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Failure Modes and Effects Analysis for Wireless and Extreme Fast Charging

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7. Authors Emre Gurpinar,* Mostak Mohammad,* Utkarsh Kavimandan,* Erdem Asa,* Veda Prakash Galigekere,* Burak Ozpineci,* Subho Mukherjee,* Leon Tolbert,† Hua Bai,† Yunting Liu† * Oak Ridge National Laboratory † University of Tennessee, Knoxville		**8. Performing Organization Report No.**
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16. Abstract

Wireless charging systems (WCS) and extreme fast charging (XFC) are considered two of the important research topics in the field of electro-mobility that have potential to significantly reduce charging times and improve charging convenience. However, people view range anxiety, considerably long charging times, the limited availability of chargers, and the inconvenience of possibly plugging in every day as significant barriers to further market penetration of electric vehicles (EVs). This report focuses on the assessment and failure mode and effects analysis (FMEA) of various concept architectures as static charger, and extreme fast charger for high-power wireless and wired EV charging systems. A better understanding of the nature of these newer charging systems can help better manage new risks they may introduce for the people or vehicles when the charging systems are in use. In addition, future vehicles may charge at points along the road (stop sign, bus stop, traffic light) or even while moving. The report is divided into two main sections: WCS and XFC systems for EVs.

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Executive Summary

Wireless charging systems (WCS) and extreme fast charging (XFC) are considered two of the important research topics in the field of electro-mobility that have potential to significantly reduce charging times and improve charging convenience. However, people view range anxiety, considerably long charging times, the limited availability of chargers, and the inconvenience of possibly plugging in every day as significant barriers to further market penetration of electric vehicles (EVs).

This report focuses on the assessment and failure mode and effects analysis (FMEA) of various concept architectures as static charger, and extreme fast charger for high-power wireless and wired EV charging systems. A better understanding of the nature of these newer charging systems can help better manage new risks they may introduce for the people or vehicles when the charging systems are in use. In addition, future vehicles may charge at points along the road (stop sign, bus stop, traffic light) or even while moving.

The report is divided into two main sections, WCS and XFC systems for EVs. The WCS section describes the operation principle of a static WCS, followed by discussion of commonly used compensation networks, grid-interface systems, and coil architectures. Electro-magnetic field emissions for different coil topologies, coil alignment and airgap variations, and extreme fast wireless charging conditions are discussed. Shielding design techniques to suppress electro-magnetic field emissions are reviewed for different power levels and coil topologies along with the interoperability of vehicle and ground systems based on different coil shape and alignment scenarios. Overviews of the codes and standards for design, testing, and safety of the WCS, along with codes and standards applicable to individual components and subsystems, are presented. Three conceptual WCSs were identified based on power levels—medium power (3.3–22 kW), high power (22–120 kW), and XFC (120–350 kW)—and were analyzed in FMEA. The FMEA study showed that compensation networks, coil design, and topology strongly affect failure modes and potential hazards, especially at XFC power levels. Furthermore, the grid side system and subsystems should be designed considering existing standards and grid requirements in case of any failure conditions.

The XFC systems section discusses expected power levels, and compares charging structures based on different resonant and non-resonant power converter topologies and architectures. Possible grid interface systems and potential multilevel power factor correction circuits are presented for megawatt (MW)-level charging systems. Design and potential challenges with medium-voltage, high-frequency transformers are highlighted, and existing communication protocols for EV charging systems are compared. The FMEA study for a conceptual MW-level XFC system was conducted for subsystems and individual components. The main takeaway from the FEMA for XFC systems is that during the design of these systems, a comprehensive systemic analysis is needed to consider all the failures and their effects on individual components and on coupled subsystems. Many of the failures can be mitigated through design, and the failures themselves can potentially be detected and isolated if sufficient sensing, monitoring, and control are incorporated into the systems.

1. Introduction of Wireless Power Transfer System for Electric Vehicle Charging

The fundamental concept of wireless charging of EVs is based on the transfer of power from the source (e.g., grid) to the load (e.g., battery) via high-frequency air core transformers. The ground side (transmitter) coil is stationary, and the vehicle side (receiver) coil is located on the vehicle. The typical structure of a wireless power transfer (WPT) system is presented in Figure 1.1 (Covic & Boys, 2013; Onar et al., 2018; Li et al., 2015; Miller, Jones, et al., 2015; Galigekere, Onar, et al., 2018; Miller, Onar, et al., 2015). For transfer of power, the AC voltage at the grid is first rectified and transferred to the primary side DC link. Then, the high-frequency inverter converts the DC voltage to a high-frequency AC voltage and transfers power from the DC link to the resonant network formed by compensation components (resonant inductor and capacitors) and the coils. The coil operates at high frequency and is designed to resonate at the given high frequency to minimize the effect of loose coupling between the transmitter and receiver coils and maximize power delivery and efficiency. Once the power is transferred to the secondary side (receiver coil), it is rectified by the vehicle side rectifier and then delivered to the DC link of the vehicle. Wireless charging eliminates cable connection between the primary side charging unit and secondary side vehicle unit, so no plugging and unplugging of a connector/cable occurs to charge the vehicle.

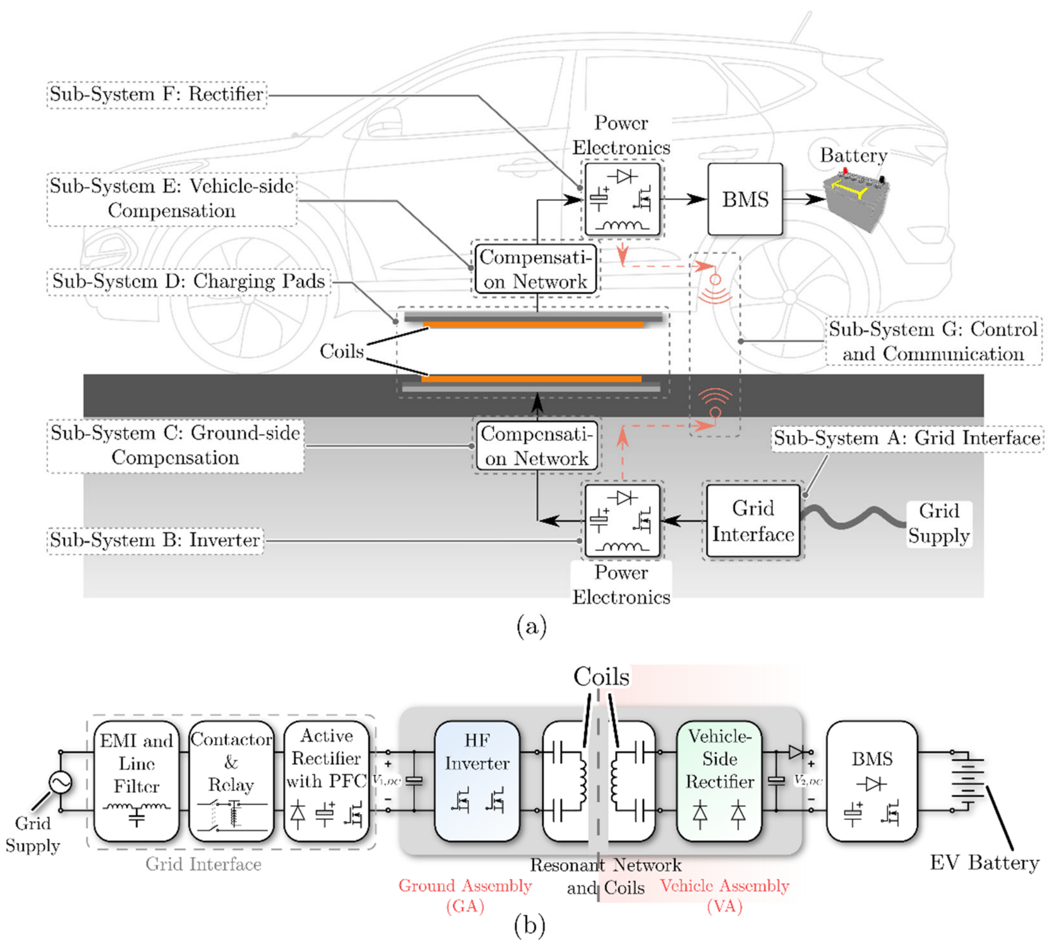


Figure 1.1. (a) Typical WPT system for EV charging; (b) block schematic of WPT system for EV charging. BMS = battery management system; EMI = electromagnetic interference; PFC = power factor correction; HF = high-frequency

A circuit schematic of the WPT system is shown in Figure 1.2. For different WPT systems, the resonant network and coils (also known as the compensating network) are different and are systematically discussed later. The figure also shows a typical control architecture for WPT systems. Depending on the control requirements, the output voltage and/or current is sensed and fed back to the primary side via a wireless communication link. A digital control architecture is implemented in the microcontroller to modulate the primary side switches to maintain either constant output voltage or current. The control architecture depends on the wireless communication and any delays and latencies in the wireless data transfer (Xu et al., 2017) adversely affect the performance of the controller and the overall system. The signals are sensed using the corresponding voltage and current sensors. Thus, sensor accuracy and reliability are critical for the controller performance.

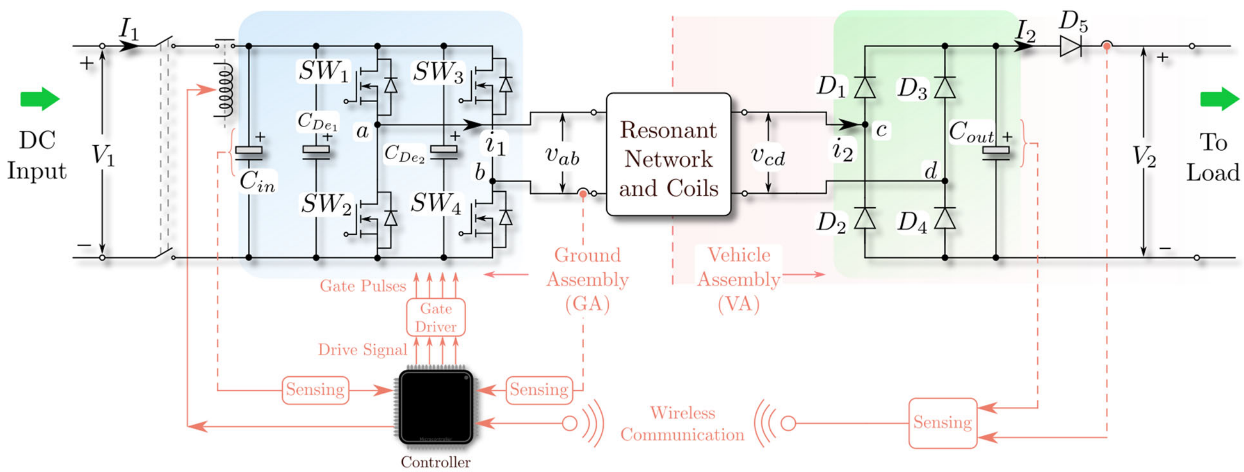


Figure 1.2. DC-to-DC circuit schematic of a WPT system

2. Compensation Topologies

2.1 Series–Series Compensation

A typical series-series compensation network for a WPT system is shown in Figure 2.1a. The resonant network incorporates series-connected capacitors (C1 and C2) on both the ground assembly (GA) and vehicle assembly (VA) coils (Onar et al., 2018). The series capacitors help to compensate for the reactive current drawn by the coils. Each capacitor is tuned to the self-inductance of the corresponding coil. At the resonance frequency, this topology behaves as a constant current source and can be conveniently used for battery charging applications. However, to reduce the switching losses, the desired operating point is slightly higher than the resonance frequency, which helps in natural zero-voltage switching (ZVS) turn-on of the primary side switches. A major concern with this topology is that it always needs a load at its output since it behaves as a constant current source. At no-load conditions, high voltages are induced at the output capacitor, thereby leading to catastrophic failure of the capacitor and/or the VA side diode rectifier. Representative current and voltage waveforms for the series-series compensation network are shown in Figure 2.1b. Because the series capacitors are in resonance with the self-inductances of the coils, they are subjected to high-voltage stress. The GA and VA coils are also subjected to sharp changes in the voltage, which increases electromagnetic interference (EMI) issues and is also detrimental to coil insulation. For the series-series compensation topology, catastrophic fault conditions can be summarized as (1) the inability to withstand no-load conditions, (2) high-voltage stress across the series-compensating capacitors, and (3) high-voltage stress across the GA and VA coil insulation.

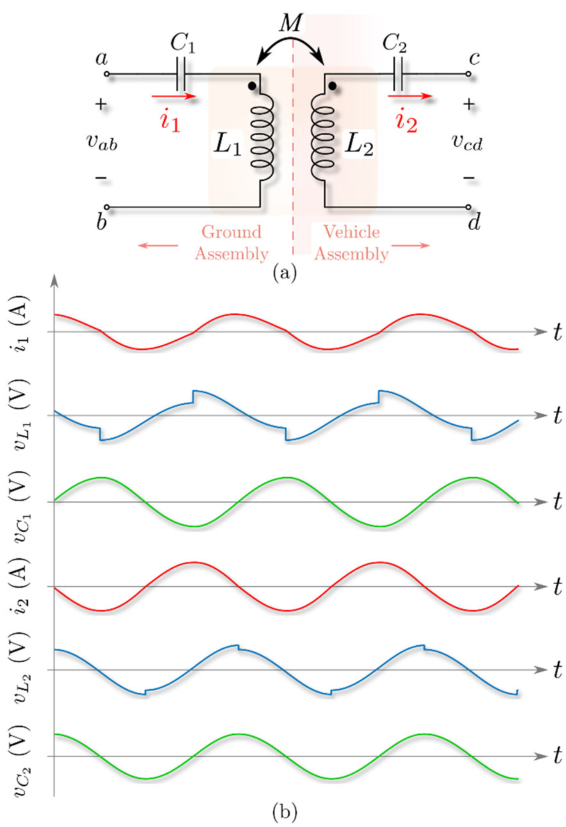


Figure 2.1. (a) Equivalent circuit of WPT system with series-series compensation; (b) representative figures from top to bottom: GA: coil current, coil voltage, and series capacitor voltage; VA: coil current, coil voltage, and capacitor voltage

2.2 LCC-Series Compensation

The LCC-series compensation (as shown in Figure 2.2 (a)) involves additional passive components on the primary side. Equivalent circuit of WPT system with LCC-series compensation (b). The inductor Lf1 is tuned to Cf1 to maintain constant primary coil current, while the primary series capacitor C1 is tuned to L1–Lf1 (Galigekere, Onar, et al., 2018). The secondary side is series-compensated. Unlike the series-series topology, the LCC-series behaves as a constant voltage source and can be operated under wide load conditions. As with the series-series compensation, the desired operating point is slightly higher than the resonance frequency, which helps in natural ZVS of the primary side switches.

Representative current and voltage waveforms for the LCC-series compensation network are shown in Figure 2.2. Equivalent circuit of WPT system with LCC-series compensation (b). b. The series capacitor C1 is subjected to higher voltage stress than the parallel capacitor Cf1. The GA coil assembly is subjected to a pure sinusoidal voltage, but the VA coil assembly is subjected to sharp changes in voltage, which is detrimental to its winding insulation. For the LCC-series compensation topology, catastrophic failure modes can be summarized as (1) the high-voltage stress across the series-compensating capacitors and (2) high-voltage stress across the VA coil insulation.

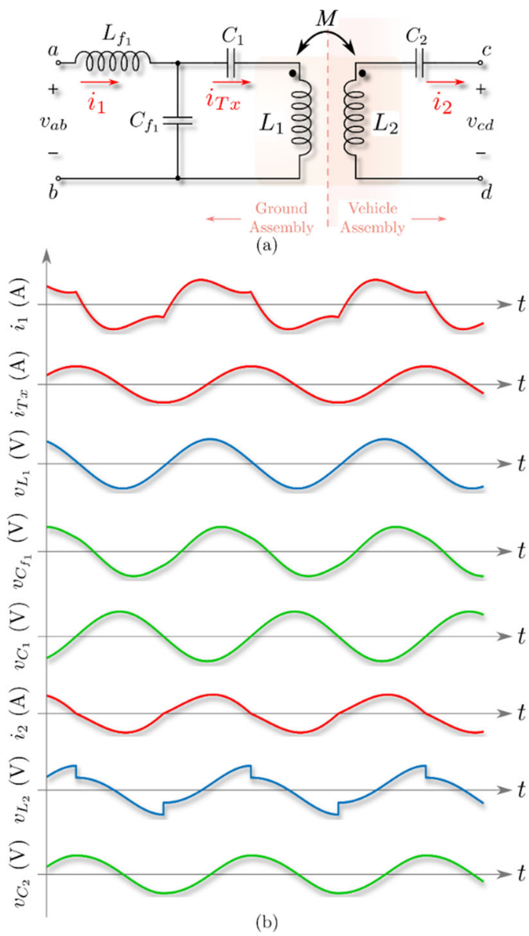


Figure 2.2. (a) Equivalent circuit of WPT system with LLC-series compensation; (b) representative figures from top to bottom: GA: inductor current, coil current, coil voltage, parallel capacitor voltage, series capacitor voltage; VA: coil current, coil voltage, and capacitor voltage

2.3 LCC-LCC Compensation

The LCC-LCC compensation (as shown in Figure 2.3a) involves further addition of passive components compared with the LCC-series topology. The compensation network is symmetric on both the primary and secondary sides [3(Li et al., 2015)]. On the primary side, Lf1 is tuned to Cf1, while the primary series capacitor C1 is tuned to L1–Lf1. On the secondary side, Lf2 is tuned to Cf2, while the primary series capacitor C2 is tuned to L2–Lf2. The topology at resonance behaves as a constant current source and needs a minimum load connected at the output to avoid excessive high voltages at the output, which can be catastrophic for the output capacitor and diode rectifier of the VA unit. The desired operating point is slightly higher than the resonance frequency, which helps in natural ZVS of the primary side switches. The voltage gain of the LCC-LCC compensation is least sensitive to the variations in the load, operating frequency, and coupling coefficient. Consequently, the LCC-LCC compensation is more suitable in achieving the constant voltage output independent of the changes in operating parameters with closed-loop control since the output voltage variations occur in a narrow voltage-range. In addition, the LCC-LCC compensation achieves better power transfer efficiency at the rated load conditions (Lu et al., 2019).

Representative figures for the LCC-LCC compensation network are shown in Figure 2.3b. Unlike the series-series or LCC-series compensation, both the GA and VA coil units are subjected to pure sinusoidal voltage waveforms without any sharp change in the voltage. The smooth coil waveforms are achieved at the cost of added passive components on both the GA and VA units. For the LCC-LCC compensation topology, catastrophic fault conditions can be summarized as (1) the inability to withstand no-load conditions and (2) high-voltage stress across the series-compensating capacitors.

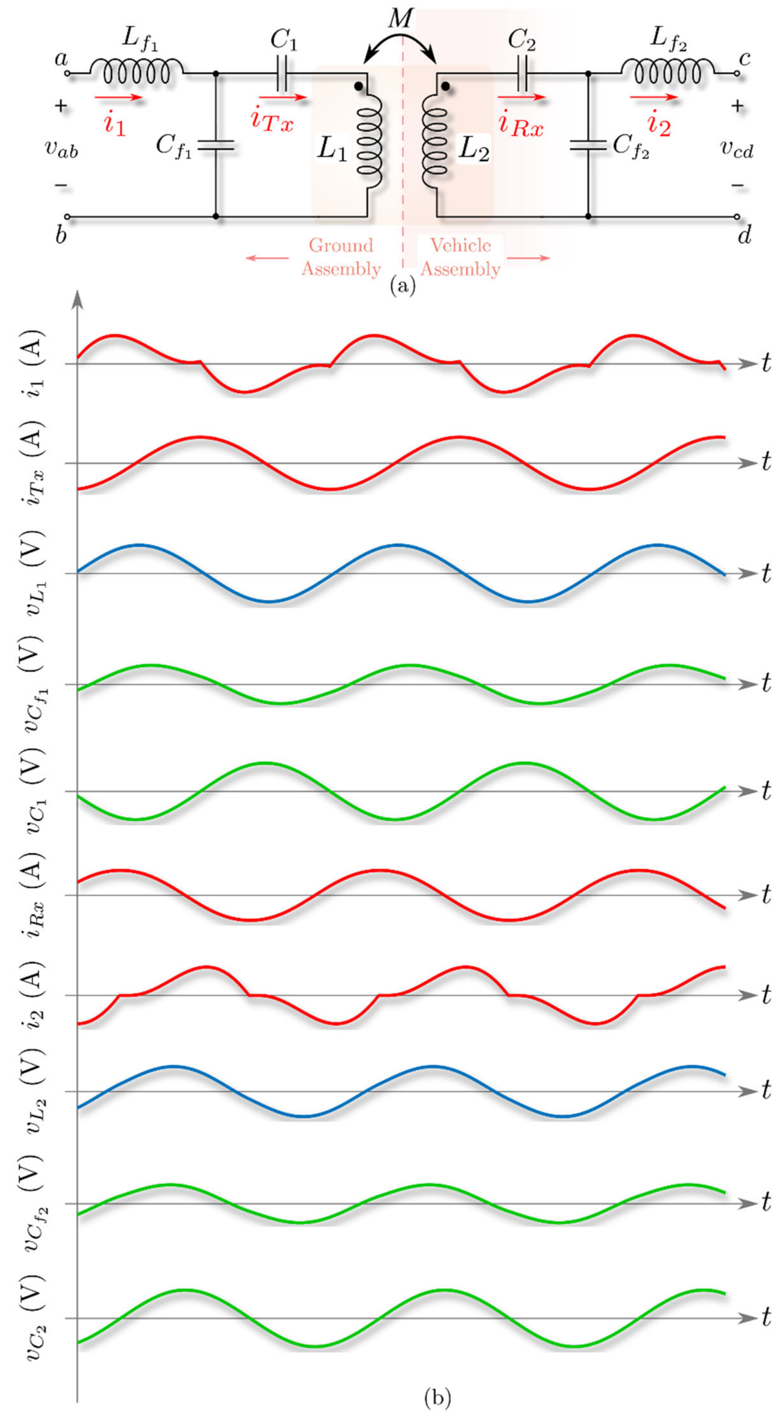


Figure 2.3. (a) Equivalent circuit of WPT system with LLC-LLC compensation; (b) representative figures from top to bottom: GA: inductor current, coil current, coil voltage, parallel capacitor voltage and series capacitor voltage; VA: coil current, inductor current, coil voltage, parallel capacitor voltage and series capacitor voltage

2.4 Series-Parallel Compensation

The series-parallel compensation (as shown in Figure 2.4a) has the VA capacitor in parallel to the VA coil. The series-parallel topology is more robust to the GA and VA coil misalignment compared with series-series topology. However, for the same output power, the GA current for series-parallel compensation is much higher than series-series or LCC-series compensation. The voltage stress across the GA series capacitor and the current stress on the GA coil is high. The desired operating point is higher than the resonance frequency, which helps in natural ZVS of the primary side switches. Representative figures for the series-parallel compensation are provided in Figure 2.4b. The VA coil is subjected to a pure sinusoidal voltage, but the GA coil is subjected to sharp changes in voltage, which is detrimental to its winding insulation.

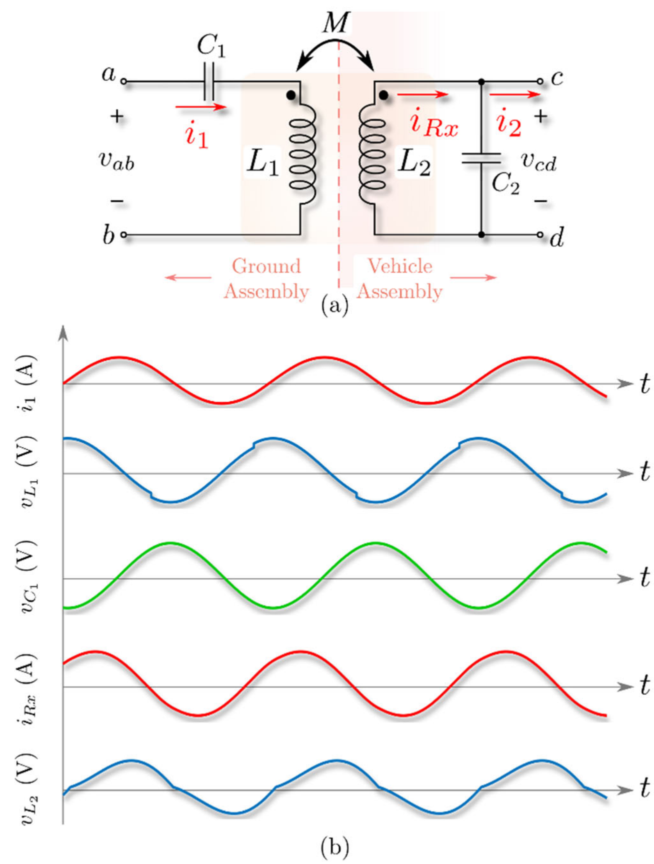


Figure 2.4. (a) Equivalent circuit of WPT system with series-parallel compensation; (b) representative figures from top to bottom: GA: coil current, coil voltage, and series capacitor voltage; VA: coil current and coil/capacitor voltage

2.5 Summary

The four compensation network topologies (series-series, LCC-series, LCC-LCC, and series-parallel) are presented in the previous sections. The series-series and LCC-LCC compensation networks show load-independent constant current source characteristics and hence cannot be operated at no-load conditions. On the contrary, the LCC-series and series-parallel compensation networks exhibit constant voltage characteristics and are safe to operate at no-load conditions. Failure modes are associated with the voltage and current stress across the inductor and capacitors and the voltage stress across the GA and VA coils. Depending on the compensation network, the GA and VA coil (as in series-series and LCC-series) is subjected to high-voltage stress and sharp changes in the voltage. The addition of passive components across the GA and VA helps to decrease the voltage change rate across the corresponding coil assembly (as in LCC-LCC compensation) at the cost of increased component count.

Other topologies aside from the four topologies reviewed here are described in the literature (Samanta & Rathore, 2015; Samanta et al., 2017; Chwei-Sen et al., 2004; Li et al., 2012). However, these topologies are modifications of the previously mentioned topologies or are still in the research phase and need more analysis for practical implementation. Discussions on the grid side, the GA and VA coil architectures, and emissions are presented in the following sections.

3. Grid-Interface System

3.1 Introduction

Electrified transportation systems rely on transfer of energy from the electric grid for charging the energy storage system on board (e.g., batteries) the vehicle. Consequently, all EV battery charging equipment requires an interface to draw energy from the electrical grid (60 Hz single-phase or three-phase). Power factor correctors interface the electric grid with the EV charging equipment and are required by standards to maintain integrity of the grid by limiting current harmonics drawn by the charger and ensuring the power factor drawn is near unity. SAE Standard J2954, "Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology" (2016), which is a Technology Information Report, has classified the power levels for wireless EV charging in the United States based on the input kilovolt-amperes.

The wireless EV charging system draws energy from the grid via the active power factor correction (PFC) circuit as shown in Figure 3.1. The purpose of an active PFC is to draw sinusoidal current at a near unity power factor, limit input current harmonics, and convert the current drawn from the grid to a stable DC output voltage for the downstream DC high-frequency inverter. International Electrotechnical Commission (IEC) 6100-3-2 and IEC 6100-3-12 mandate that the maximum allowed current harmonics magnitudes up to the 40th harmonic for line currents must be lower than 16 A (IEC 6100-3-2) and 75 A (IEC 6100-3-12).

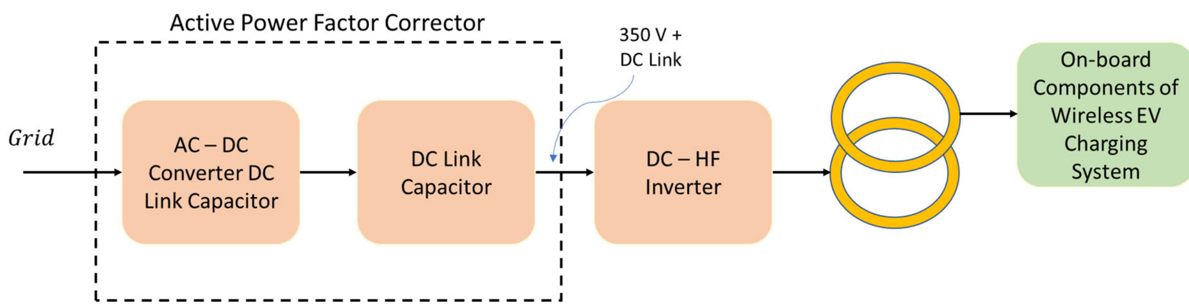


Figure 3.1. Functional representation of generic wireless EV charging system. HF = high-frequency

Although the primary purpose of the PFC is to mitigate the current harmonics to limit EMI and compatibility issues, there is also an underlying safety consideration. If the harmonics are unconstrained, odd, triplen harmonics (e.g., 3rd, 9th) flow through the neutral wire and can be a thermal hazard and potentially overheat the system.

3.2 Power Factor Corrector Topologies

Although some of the basic pulse width modulated (PWM) DC-DC converters can be used to function as an active power factor corrector, the PWM boost converter is the industry preference for single-phase or two-phase (dual phase) connections because:

- Input current is continuous,
- The boost inductor also mitigates the voltage EMI by absorbing it, and
- It does not require high-side gate drivers (gate drives are ground referenced).

Figure 3.2 depicts a generic single-phase active PFC circuit. It consists of a full-bridge AC-to-DC diode rectifier followed by a PWM boost converter, which can be operated in the continuous or discontinuous conduction mode. The PWM control can be implemented by using analog or digital control schemes. The advantages and disadvantages of analog and digital control as applied to PFC are listed in Table 3.1.

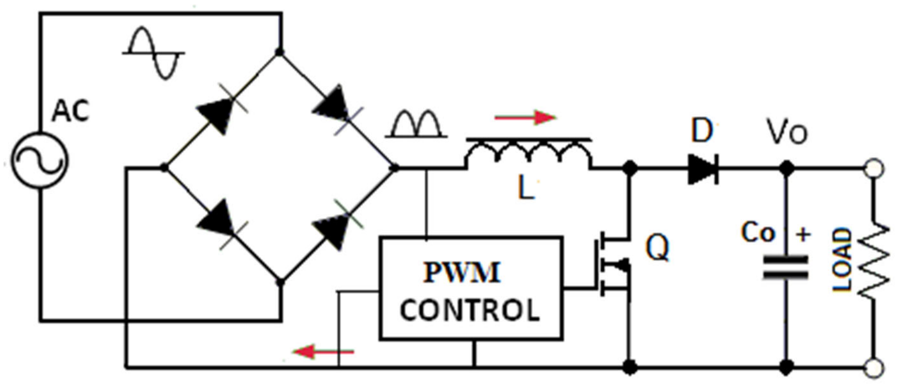


Figure 3.2. Schematic of single-phase PWM boost AC-to-DC power factor corrector (International Electrotechnical Commission, 2021)

Table 3.1. Advantages and disadvantages of analog and digital control for PFC

	Advantages	Disadvantages
Analog control scheme	• Mature technology with dedicated off-the-shelf controllers, which include advanced safety and protection mechanisms • Control bandwidth not limited by propagation delays	• Control scheme is hardwired and not flexible • Sophisticated or intelligent control schemes are difficult to implement
Digital control scheme	• Easy-to-implement advanced control such as variable or intelligent control • Flexible architecture • Insensitive to parameter variation	• Limited bandwidth can hamper transient response • Quantization error can lead to limited resolution on duty cycle • Propagation delay can restrict phase margin and safety implementation

For high-power systems in which a three-phase connection is used for grid connection, three-phase active rectifiers are commonly used. The schematic of an insulated-gate bipolar transistor (IGBT)–based three-phase PFC rectifier is presented in Figure 3.3. The grid side inductors (L_{AC}) are used along with the two-level three-phase IGBT module to boost and rectify the grid voltage (V_{AC}) to the DC link-voltage while maintaining total harmonic distortion of the input current within grid limits.

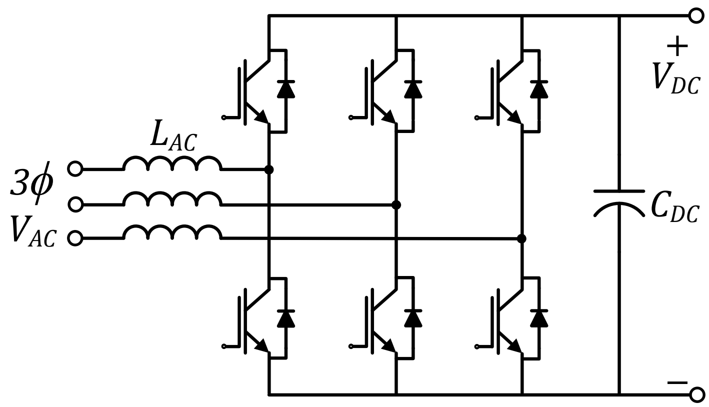


Figure 3.3. Schematic of three-phase active PFC rectifier

3.3 EMI in Wireless Charging Systems

3.3.1 Conducted and Radiated EMI

An overview of a conventional WPT EV charger system deployment is illustrated in Figure 1.1. A general concept of grid voltage to EV charging is achieved through an EMI filter, AC-DC PFC, DC-AC resonant inverter, wireless coupler coils, and AC-DC rectifier as shown in the figure.

All power conversion systems generate a noticeable amount of EMI that must be contained by an EMI filter if the interference is above the limits based on the accepted standards. The EMI filter is to limit any conductive or radiated electromagnetic disturbance that can cause catastrophic failure problems in the electronics or electrical equipment. EMI system malfunctions can lead to safety issues, such as disrupting electrical arcing protection in EV charging or causing inadvertent switching that can lead to short circuits in the charging station or EV. To define the limits for interference emission and immunity, EMC standards were established in many countries by organizations such as the International Special Committee on Radio Interference (CISPR) (International Electrotechnical Commission, 2021), Federal Communications Commission (FCC) (FCC, n.d.), and Voluntary Control Council for Interference (VCCI Council, n.d.).

CISPR and FCC cover conductive interference and radiative emission and establish various standards widely. The measurement of EMI results might differ based on the test layout because of equipment, configuration, cabling, grounding, and so on. These standards help to improve the measurement accuracy by establishing prescribed testing procedures. The needs of industrial and residential equipment are different; thus, standards are classified into two classes: Class A for industrial environments and Class B for the residential environments. The conductive interference and radiative emission limits are shown for CISPR and FCC standards in Figure 3.4.

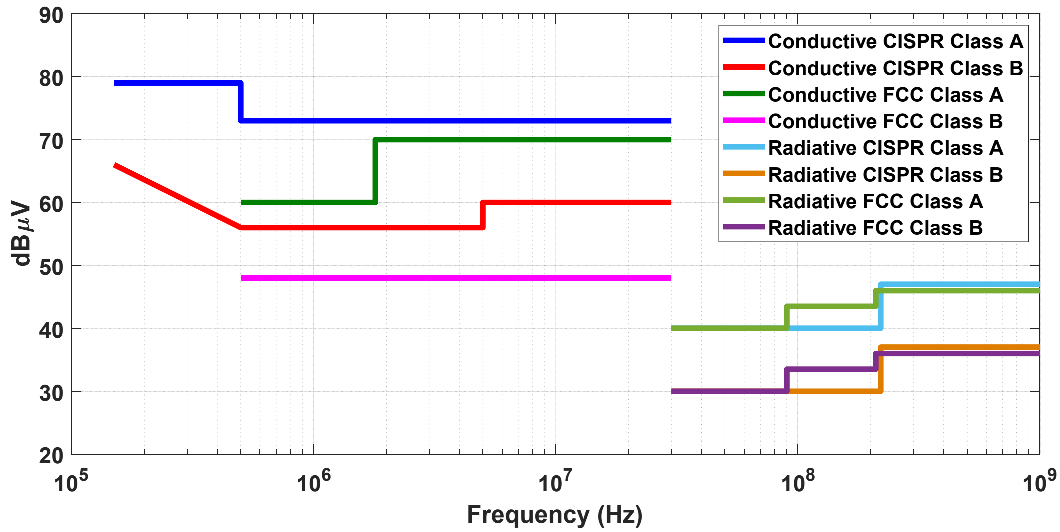


Figure 3.4. Conductive and radiative emission limits according to CISPR (International Electrotechnical Commission, 2021) and FCC (FCC, n.d.) standards

A conventional AC line EMI filter is shown in Figure 3.5. As seen from the schematic, the filter includes a common-mode choke in series with the line and neutral wires, X capacitors connected between line to neutral, and Y capacitors connected between line and neutral to the chassis ground.

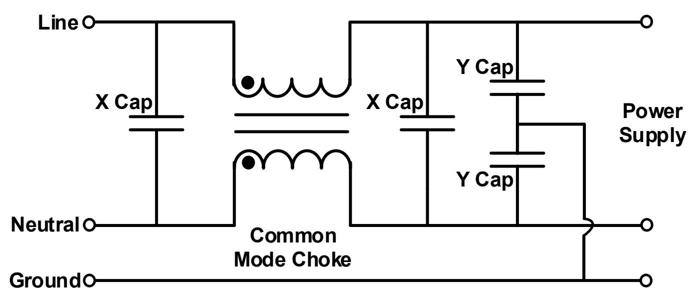


Figure 3.5. A typical AC line EMI filter with a common-mode choke, X capacitors, and Y capacitors

Leakage inductance of a common-mode choke with X capacitance might resonate if the design is not accurate. If this happens, high-voltage/current ringing can occur, which causes instability in the system and may eventually lead to failure. Also, high current oscillation might saturate the common-mode choke such that the EMI filter no longer functions appropriately, which might cause catastrophic failure because of excessive interference in electronic and electrical systems.

An inaccurate design might require so much X capacitance across the line that the EMI filter inrush current would trip the circuit breaker because of excessive capacitor charging current. Also, surge or pulse current due to a distant lightning strike or grid transmission switch opening/closing in the grid might cause arcing in the filter, which can cause the filter to malfunction and/or eventually fail by exposing high voltages, currents, or voltage and current change rates.

High-quality factor "Q" filter circuit design can cause the filter to heat the capacitors because of a high-energy conversion between inductor and capacitors. This will increase the temperature of the capacitor and might eventually lead to failure of the capacitor and hence failure of the filter. Then, it will cause failure by excessive interference to the electronic and electrical system.

To avoid excessive ground current, the value of the common-mode Y capacitor is usually limited by standards. Depending on the equipment application, maximum ground currents are specified by safety agencies such as Underwriter Laboratories. Designs need to comply with these standard values; otherwise, they might cause ground circuit faults, electrical shock, and hazards in the system. Table 3.2 shows the ground current limitations based on major standards.

Table 3.2. Maximum ground leakage currents by major standards

Standards	Maximum Y capacitor	Ground current limits
British Standard (BS) 2135	3.2–64 nF	0.25–5 mA @ 250 V/50 Hz
Canada (C) 22.2	110 nF	5 mA @ 120 V/60 Hz
IEC 335-1	9.5 nF	0.75 mA @ 250 V/50 Hz
Underwriters Laboratories (UL) 478	110 nF	5 mA @ 120 V/60 Hz
UL 1283	11–77 nF	0.5–3.5 mA @ 120 V/60 Hz
VDE (in English, Association of Electrical Engineering) 0804	6.4–44.6 nF	0.5–3.5 mA @ 250 V/50 Hz

A ground leakage current test circuit is demonstrated considering required standards in Figure 3.6 (Billings & Morey, 2011). As seen from the figure, the ground current measurement can be carried from the line and neutral to the ground connection by using a current transformer.

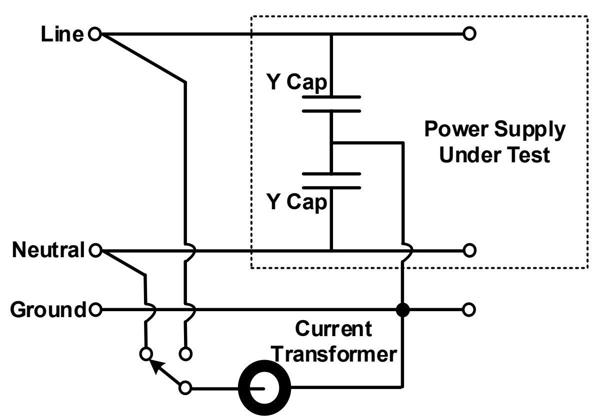


Figure 3.6. Ground leakage current test circuit (Billings & Morey, 2011)

According to the Middlebrook criterion (Middlebrook, 1976), the designed filter must also provide lower output impedance than the switching regulator input impedance. If the design does not obey this rule, the system may lose stability and degradation of transient response will occur. As a result, the switching regulator and battery will be damaged.

4. Wireless Charging Pads

A typical WCS in EV applications has two charging pads: a transmitter, which is put on the floor of a parking area, and a receiver, which is mounted under the vehicle. Each of the charging pads consists of a coil, core, and shield. The coil is excited by a high-frequency AC source, the core guides the flux and increases the self- and mutual-inductance, and the backplate shield suppresses the leakage magnetic field and provides a base for the pad. The basic diagram of unipolar-circular and bipolar- double-D (DD) pads consisting of coil, core, and shields are shown in *Figure **4.1***(a) and (b), respectively.

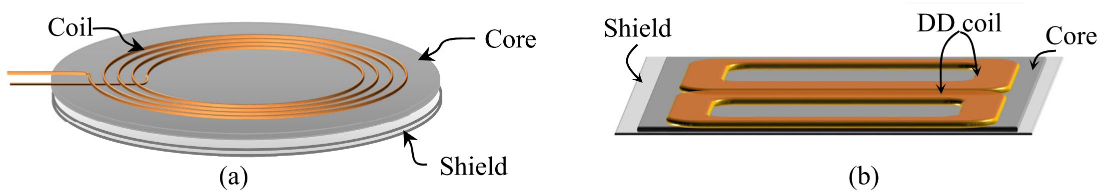


Figure 4.1. Comparative view of (a) a circular and (b) a DD coil–based charging pad with a copper coil, ferrite core, and aluminum backplate shield

In the following sections, detailed descriptions of the coil, core, and shield are presented. Also, their purpose of use, geometry, material constituents, and potential design, fabrication, and maintenance challenges are described.

4.1 Coil in High-Power WCS

Circular, rectangular, DD, and bipolar coils are the most widely used coil topologies in EV WCS. The lumped modes of different coil topologies are shown in Figure 4.2. Fundamentally, the windings of these coils can be divided into two categories: unipolar and bipolar. A few other coil topologies combine these two topologies. The magnetic flux pattern of these two coil topologies are widely different, and they have many advantages and disadvantages considering EMF emissions and eddy current-induced thermal behavior.

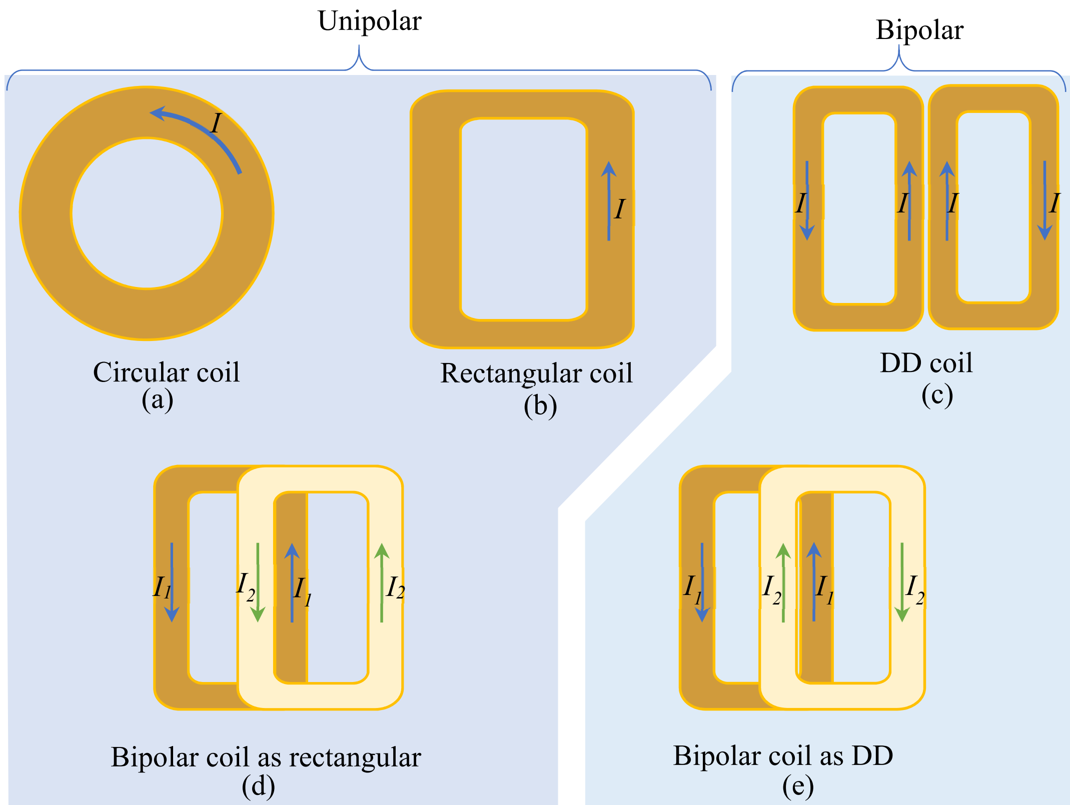


Figure 4.2. Most popular coil topologies used in EV WCSs

4.1.1 Coil Topology for Extreme Power Levels (100 to 350 kW)

This section considers the special requirement needed for XFC systems, such as the dominant thermal and electromagnetic constraints. Processing and transmitting a significantly large amount of power using a compact system requires increasing the power density by efficient thermal management. Increasing the pad size, using multiple coils, using a polyphase system, and adding forced air cooling or liquid cooling are just a few of the most practical options to accommodate the fast wireless charging.

The three most prominent pad structures for XFC are shown in *Figure 4.3*. Only a few WCS have been demonstrated at or above the 100 kW power level (Foote & Onar, 2017). The U.S. Department of Energy's Oak Ridge National Laboratory's (2018) 120 kW system adopted a high-power, single pad-based structure (Samanta et al., 2017), while ORNL's 50 kW system adopted a three-phase structure (Mohammad., Pries, et al., 2019), which is one of the most prominent candidates for XFC. Momentum Dynamics uses a modular multi-pad in its high-power WCS for electric buses.

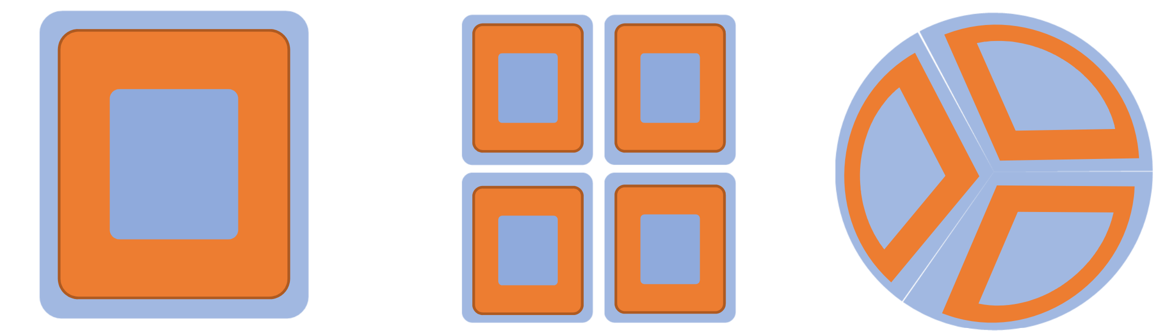


Figure 4.3. Illustration of different pad topologies for extreme fast wireless chargers

4.2 EMF Emissions in WCS

In this section, the risk of EMF emissions from the WCS is discussed for different failure mode operations in vehicle applications. As the power is transferred from transmitter (Tx) to the receiver (Rx) through the magnetic field over a large air gap, the EMF tends to spread around the charging pads, which are referred to as EMF emissions or leakage fields. These EMF emissions consist of different ratios of the electric and magnetic fields. In an inductive WCS, the leakage magnetic field is much higher than the electric field; whereas in a capacitive WCS, the leakage electric field is much higher than the magnetic field. The leakage magnetic and electric fields above a certain limit can cause health or safety hazards; therefore, these fields must be kept below a safe limit under all operating conditions.

4.2.1 Health and Safety Hazards due to Failure to Control EMF Emissions

There are several guidelines for the safety limits on the EMF emissions. In an EV application, the latest guideline of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is followed. According to the ICNIRP guideline, two different limits are imposed on the electric and magnetic field: first, the general public exposure limit, which applies to publicly accessible areas, such as inside and around a vehicle; and second, occupational exposure, which concerns limited access to a restricted area (International Commission on Non-Ionizing Radiation Protection, 2011). The limits of the magnetic field for these two exposure conditions are shown in Figure 4.4.

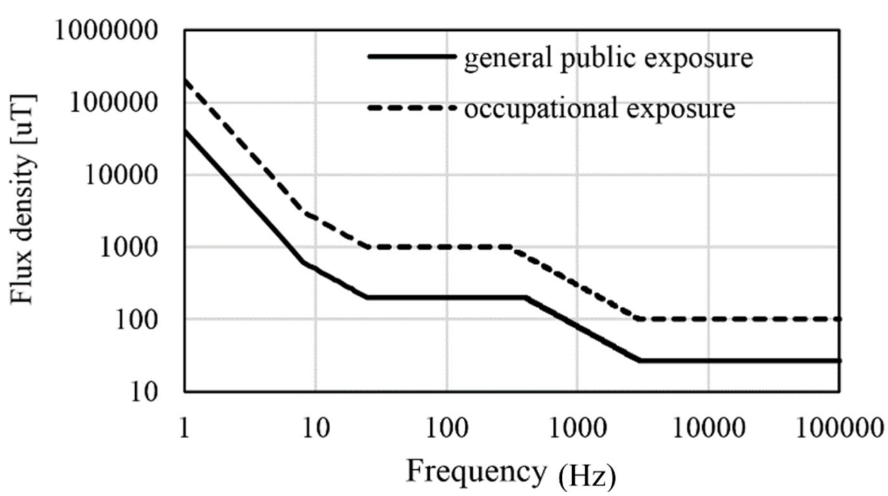


Figure 4.4. ICNIRP 2010 limits on magnetic field leakage for the general public and occupational exposure (Mohammad., 2019)

According to Figure 4.4, the limits of EMF emissions depend on

1. the accessibility of a certain area inside, under, and around the vehicle; and
2. the frequency of the EMF, which is the same as the operating frequency of a WCS.

Therefore, different limits apply for different regions inside and around the vehicle. The transmitter is installed either on the ground or just beneath the ground, and the receiver is mounted under the vehicle undercarriage as shown in *Figure **4.5**. The WCS with (a) on-the-surface and (b) under-the-surface installation of the transmitter pad (Mohammad., 2019)*

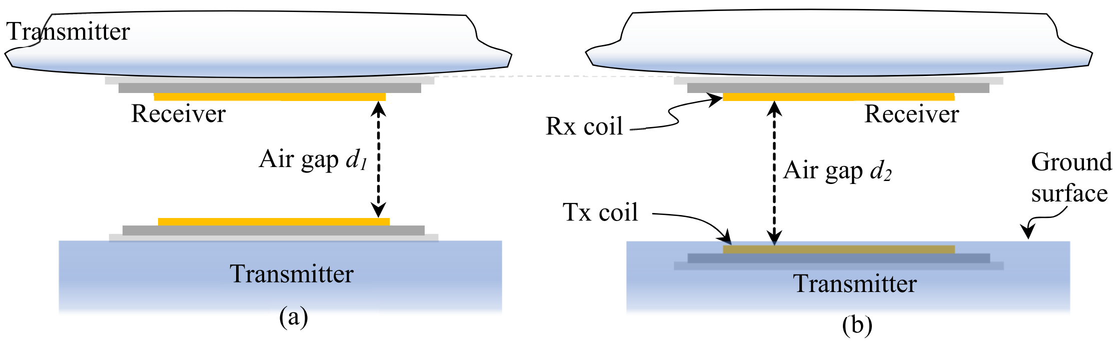


Figure 4.5. The WCS with (a) on-the-surface and (b) under-the-surface installation of the transmitter pad (Mohammad., 2019)

To identify the exposure limits for different regions around the EV charging area, the space around the WCS pad and EV is categorized into three regions:

1. region 1: under the vehicle,
2. region 2: sides of the vehicle, and
3. region 3: inside the vehicle.

Region 1 has an extremely high magnetic field, which is essential for effective power transfer. Therefore, region 1 is not subject to the strict limit of magnetic field emission; rather, accessibility in this region is observed and restricted for safe operation. This mechanism is called "foreign object detection," which is a critical safety feature for high-power EV WCSs.

Regions 2 and 3 are considered publicly accessible, so they are subject to the ICNIRP public exposure limits. Region 2 has two sub-regions as shown in Figure 4.6: Region 2(a), which is near the ground area and commonly has a higher leakage magnetic field; and Region 2(b), which has a comparatively lower leakage field. The leakage magnetic field limit for region 2(a) for the EV WCS is summarized in Table 4.1.

Region 2(b) and Region 3 can potentially have an occupant with a body-implanted pacemaker; therefore, those two regions have an even stricter limit of 15 µT.

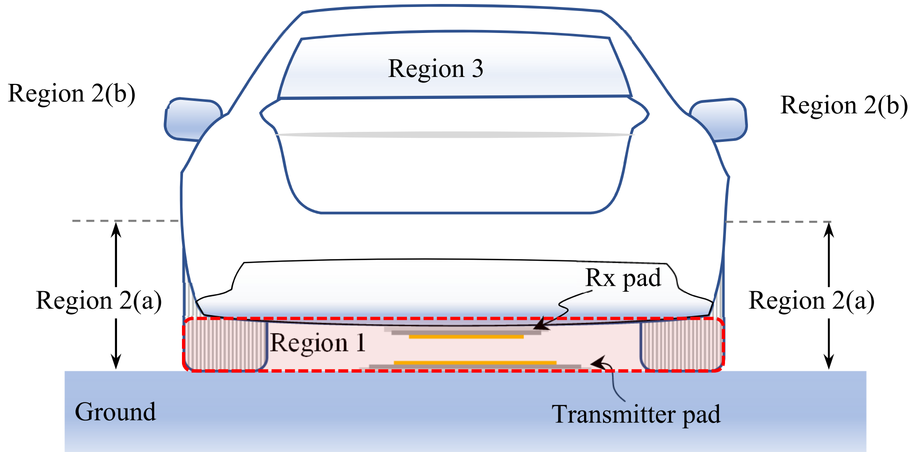


Figure 4.6. Different regions inside, below, and around the vehicle concerning the EMF emissions from a WCS (Mohammad., 2019)

Table 4.1. ICNIRP 2010 limits on the low-frequency EMF (SAE Standard J2954, 2016)

Field type	General public reference limit (applicable for regions 2 and 3)
Magnetic field	RMS 27 µT or peak 38 µT
Electric field	RMS 83 V/m

Table 4.2. SAE International recommendation for an area with a pacemaker (SAE Standard J2954, 2016)

Field type	Limit considering the presence of a pacemaker (applicable for regions 2(b) and 3)
Magnetic field	RMS 15 µT

4.2.2 EMF Emissions From Different Coil Topologies

Different coil topologies have different winding patterns, and the orientation of the coil winding shapes the pattern and distribution of the EMF around the charging pads. In the following sections, the EMF emissions from the two most common coil topologies, unipolar and bipolar coil, are discussed. Also, the effects of air gap and alignment variation on the EMF emissions are discussed.

4.2.2.1 EMF Emissions From the Unipolar Pad

The unipolar charging pads have one magnetic pole inside the pad and one outside the pad. Circular and rectangular pads with single spiral coils, as shown in *Figure 4.2*(a) and (b), are the most common unipolar pads. A bipolar pad with a reverse current in the center arms, as shown in *Figure 4.2* (e), also behaves as a unipolar pad. The most prominent geometry of the unipolar pads is the rectangular pad, which has been adopted in the designs of SAE International (SAE Standard J2954, 2016). The leakage magnetic field of the unipolar charging pad can be effectively suppressed using an aluminum backplate in the transmitter and receiver pad and an aluminum plate above the receiver. Although the aluminum plate suppresses the leakage magnetic field, it causes a significant localized eddy current loss in it (Mohammad., Wodajo, et al., 2019). Considering the thermal loss and shielding effectiveness, the aluminum plate is safe and effective for up to 3 to 5 kW of output power. For power above 10 kW, the loss tends to become so high that it creates an extremely high-temperature region in the shield, which causes high loss and raises high-temperature hazards near the vehicle undercarriage (Schneider at al., 2019). The effect of such a hazard on the EV battery requires further study.

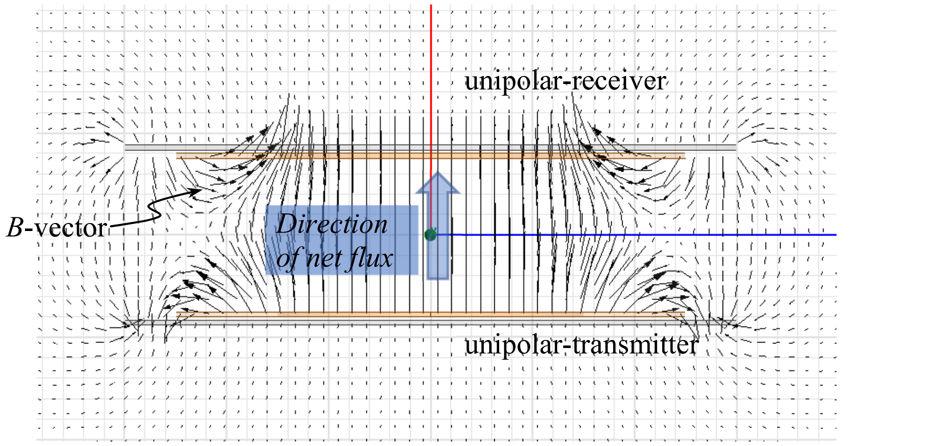


Figure 4.7. The magnetic field vector distribution of the unipolar coil-based WCS

4.2.2.2 EMF Emissions from the Bipolar Pad

The bipolar pads are known to have lower magnetic field emission than the unipolar pads (Budhia et al., 2013). Therefore, 3 to 5 kW bipolar pads are considered safe without much concern of the leakage magnetic field. However, the leakage field from the bipolar pads for more than 5 kW tends to exceed the safety limits (Schneider et al., 2019), and research is limited on effective shield design for the high-power wireless bipolar coil-based WCS. Therefore, the bipolar pads cannot be used for higher-power applications unless a highly effective shield is designed for bipolar charging pads. ORNL has made significant progress in developing an extremely high-power bipolar coil-based WCS and its shield design to keep the system safe (Mohammad., Pries, et al., 2019).

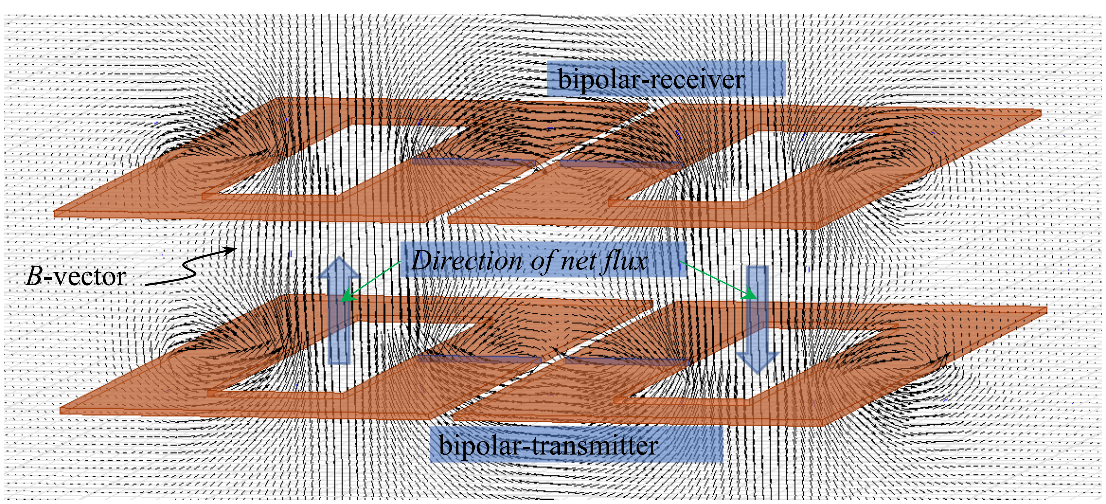


Figure 4.8. The magnetic field vector distribution around the DD coil-based air-core WCS

4.2.3 EMF Emissions for Alignment and Air Gap Variation

With the variation of the alignment of the vehicle and the air gap between the pads, the EMF around the vehicle in region 2 changes significantly. According to the SAE Standard J2954 (2016), the WCS must satisfy the EMF limits at 800 mm away from the center of the receiver on light-duty vehicles. To satisfy this limit, an observation plane is commonly chosen at 800 mm away from the sides of the vehicle as shown in *Figure **4.9***(a) and (b). According to the ICNIRP guideline and the SAE International recommendation, the EMF on the observation plane must be below the limits outlined in Table 4.1.

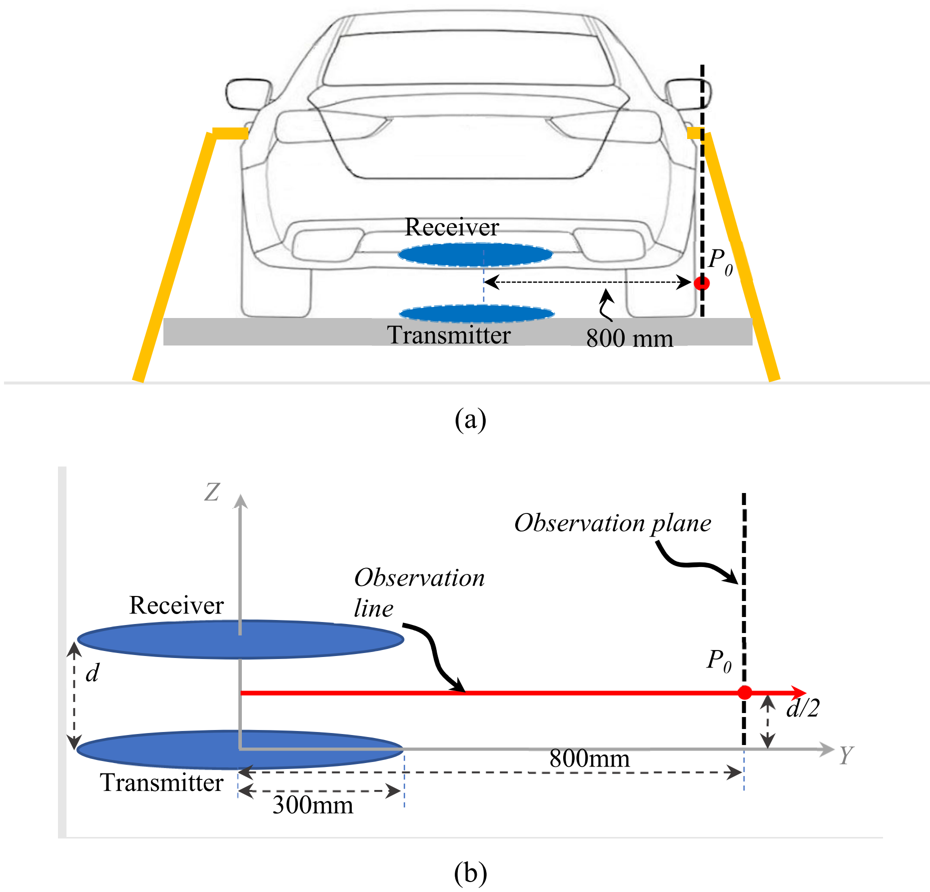


Figure 4.9. (a) Typical alignment scenario in manual vehicular parking and (b) corresponding observation plane and observation line

Because of the limited accuracy in aligning the two coils with manual parking of vehicles, misalignment between the transmitter and receiver is a common scenario for EV charging. The misalignment has a detrimental effect on the efficiency and leakage field of a WCS.

The misaligned parking reduces the effective distance between the transmitter and the accessible region around the vehicle as shown in *Figure **4.10***. Under a misalignment Δ, although the distance of the observation plane to the receiver remains the same at 800 mm, the distance to the transmitter gets reduced to 800 mm − Δ). Therefore, under a misalignment, an additional area with a higher EMF gets exposed outside the vehicle and can raise a critical safety concern.

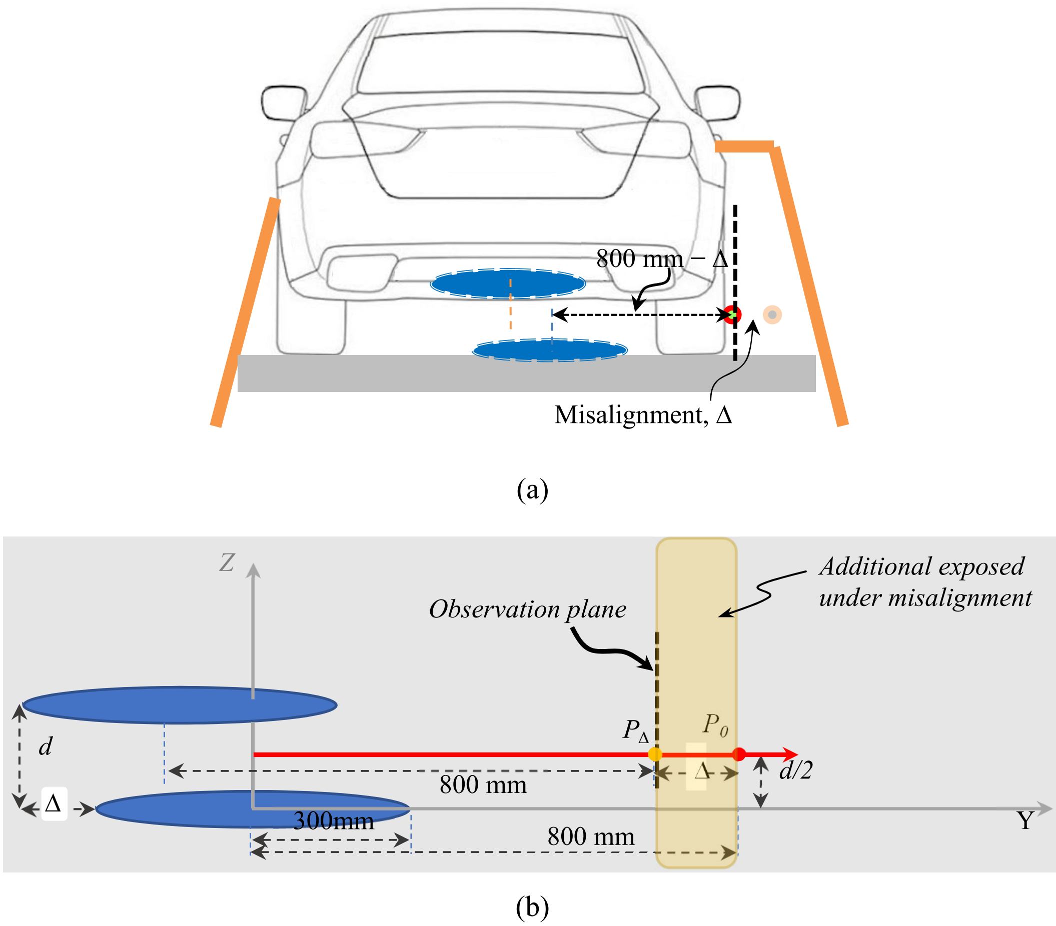


Figure 4.10. (a) Typical misalignment scenario in vehicular parking and (b) proposed observation points and line considering misalignment

Misalignment reduces the coupling between the transmitter and the receiver pad. A typical range and trend of variation of the coupling coefficient (*k*) with different degrees of misalignment are illustrated in *Figure **4.11***. Coupling coefficient is defined by:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{4.1}$$

Where M is mutual inductance, L_1 and L_2 are self-inductance of transmitter and received coils. Because the coupling coefficient reduces under misalignment, to transfer the same amount of power, a misaligned pad requires more current than the aligned pad. The higher current through the coil causes a higher loss in the coil, core, and shield. Moreover, the higher current causes higher EMF emissions.

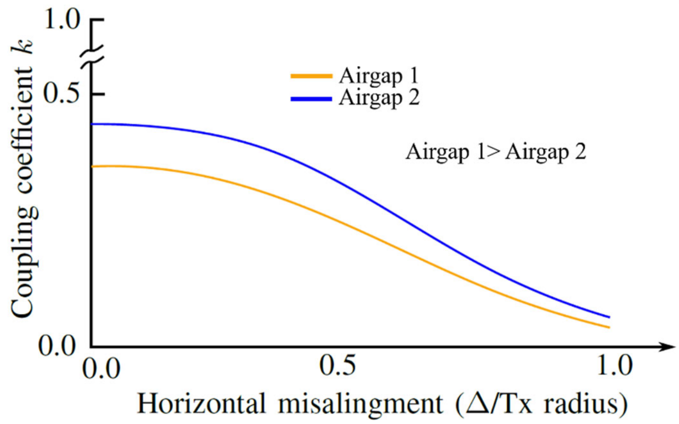


Figure 4.11. Variation of the coupling coefficient with the horizontal misalignment

Similar to the alignment variation, the air gap variation has a similar effect on the coupling coefficient (*k*) shown in *Figure **4.11***. As the air gap increases, the efficiency decreases and the EMF emissions increase. Different vehicles have different ground clearance heights, which cause different air gaps from a transmitter to a receiver. With the same transmitter and receiver pads, a vehicle with higher ground clearance has a lower mutual inductance than a vehicle with lower ground clearance. Therefore, the vehicle with higher ground clearance requires a higher current in the coils to transmit the same amount of power compared with the vehicle with lower ground clearance. In summary, a higher air gap gives lower efficiency and higher EMF emissions.

4.2.4 EMF Emissions for Extremely Fast Wireless Charging

XFC is essential to charge the large-capacity EV battery while meeting the demand of rapid charging. To meet that demand, the current plug-in charging ranges up to several hundred kilowatts, and a higher-capacity charging system is under investigation. Wireless charging also needs to meet the demand for XFC. Several high-power stationary WCSs have been demonstrated for light- and medium-duty vehicles; a brief list of the recent high-power (>30 kW) WCSs is given in *Table 4.3* (Foote & Onar, 2017).

Table 4.3. Demonstration of a high-power stationary WCS

Institute	Power (kW)	Efficiency (%)
ORNL (Pries et al., 2018; Oak Ridge National Laboratory, 2018)	120	97
WAVE (Wu & Masquelier, 2015)	50	92
ETH Zurich (Bossard & Kolar, 2017)	50	95.8
Fraunhofer (Goeldi et al., 2015)	22	97
Conductrix Wampfler (Bossard, 2017)	120	90
Showa Aircraft Co (Shinohara et al., 2013)	30	92

Although the EMF emissions for 3 to 7 kW power have been studied widely in the literature, the study of EMF emissions for extremely high-power WCSs is limited. Currently, SAE International J2954 shows the detailed design of WCSs for up to 11 kW. Galigekere, Wiles, et al. (2018) conducted an extensive study on the EMF emissions of those SAE International–recommended WCSs, both for circular and DD pads. The result of this paper showed that as the power increases to more than 5 kW, the EMF emissions tend to exceed the ICNIRP limits under various operating conditions. For higher power, the tendency of exceeding the ICNIRP limit increases significantly. These results indicate how challenging it would be to meet the safety limits under all operating conditions, including aligned, misaligned, low air gap, and high air gap.

The study and test of a 100 kW WCS at ORNL showed, with advanced shield design, that the EMF emissions can be limited for below the safety limits under the aligned operation of the transmitter and receiver [24, 26, (Mohammad et al., 2019; Pries et al., 2018; Galigekere, Wiles, et al., 2018). Further study and tests are still required to design the shield such that it meets the ICNIRP safety limits under all the diverse operating conditions of vehicular charging.

4.2.5 Thermal Hazard due to EMF around the Charging pad

A high EMF field around the charging pad generates eddy current and loss in nearby conductive and magnetic materials, such as the aluminum and steel frame of the EV body, nuts and bolts, and so on. This loss causes a temperature rise in the vehicle body parts. Compared with the highly conductive parts (e.g., aluminum alloy, copper), the steel has a much higher permeability. Therefore, the loss in the steel parts is much higher than the loss in the aluminum. The steel nuts and bolts within 3 in. around the charging pads are particularly vulnerable to extremely high loss. Unless charging pads and shield are carefully designed, the temperature in the steel parts could reach an extremely high temperature and cause thermal hazards. While designing the EMF shield, the EMF emissions and the temperature rise in the EV body must be considered.

4.2.6 Shield Design to Suppress Magnetic Field Emissions

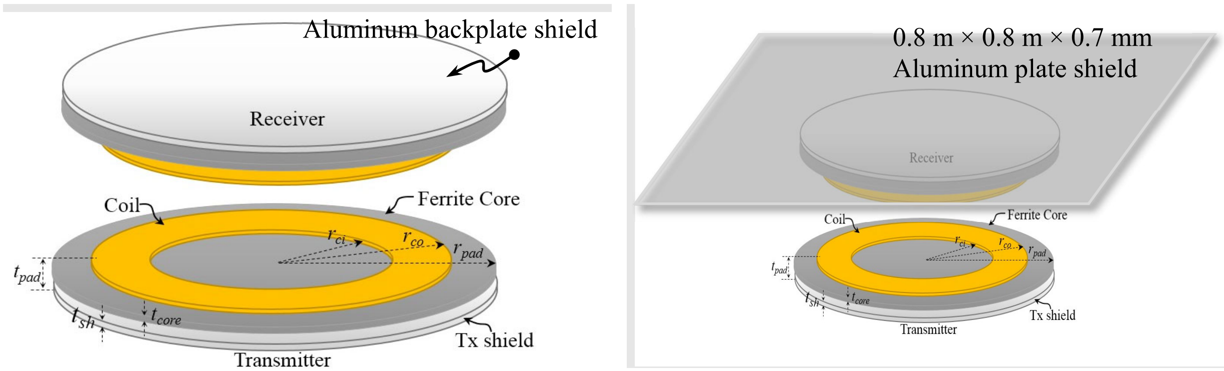
To suppress the magnetic field emission from the inductive WCS, different types of shield designs have been studied. These shield designs can be separated into several categories: passive shield, active shield, reactive shield, and magnetic shield.

4.2.6.1 Passive Shield

The passive shields are made of conductive aluminum plate. The passive shield is the most widely used shield topology in inductive WCSs (Batra & Shaltz, 2015; Jo et al., 2014). The most basic passive shield is the aluminum backplate, as shown in Figure 4.12(a), which is also required for mechanical support of the pad. However, in an EV application, the backplate shield is not sufficient. In an EV application, SAE International proposed a large aluminum plate above the receiver as shown in Figure 4.12(b) (SAE Standard J2954, 2016). The large aluminum plate has the following advantages:

1. It effectively suppresses the leakage magnetic field from the unipolar charging pads; however, it is not very effective for bipolar charging pads.
2. It effectively prevents the leakage magnetic field from entering the vehicle for all pad types.
3. It blocks the strong leakage field around the charging pad from reaching the vehicle undercarriage, which would otherwise cause a significantly large loss (Mohammad, Pries, et al., 2019).

Considering all these advantages, the aluminum shield is recommended for use in all cases of shielding in WPT systems. The basic passive shield can be further enhanced with a reactive and active shield to get better shielding effectiveness at different targeted regions.



(a) **(b)**

Figure 4.12. (a) The aluminum backplate shield and (b) the SAE International–recommended large aluminum plate shield to suppress the magnetic field from a unipolar WCS

4.2.6.2 Reactive Shield

The reactive shield consists of a partially compensated coil around the charging pad as shown in Figure 4.13. The partial compensation enables inducing a higher current in the shield coil, which gives higher shielding effectiveness. The reactive shield allows control of the shielding effectiveness, but it also causes high loss in the canceling coil.

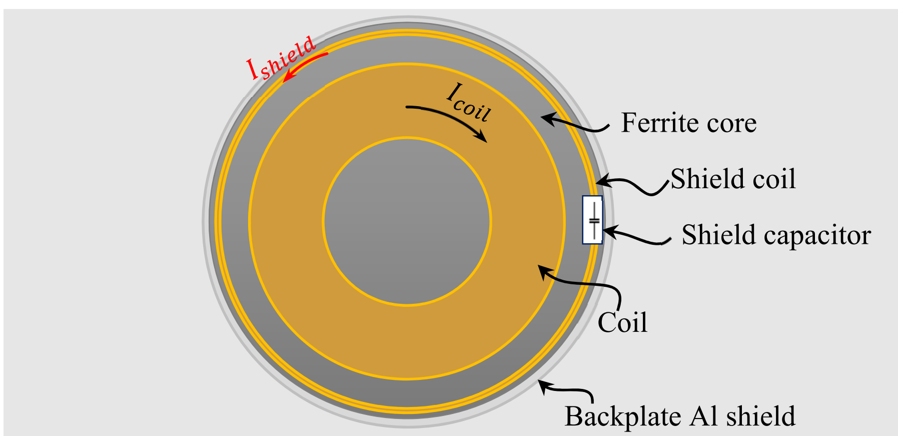


Figure 4.13. A circular nonpolar pad with a partially compensated passive reactive shield

4.2.6.3 Active Shield

Similar to the reactive shield, the active shield consists of an additional coil around the charging pad, as shown in Figure 4.14 (Campi et al., 2019; Choi et al., 2014). The coil of the active shield typically consists of one or more turns depending on the required shielding effectiveness. Unlike the reactive shield, the active shield coil is excited by an external source, which could be the same source as the primary inverter or another AC source. The active shield can potentially provide significantly high shielding effectiveness, but it increases the design complexity and requires additional components.

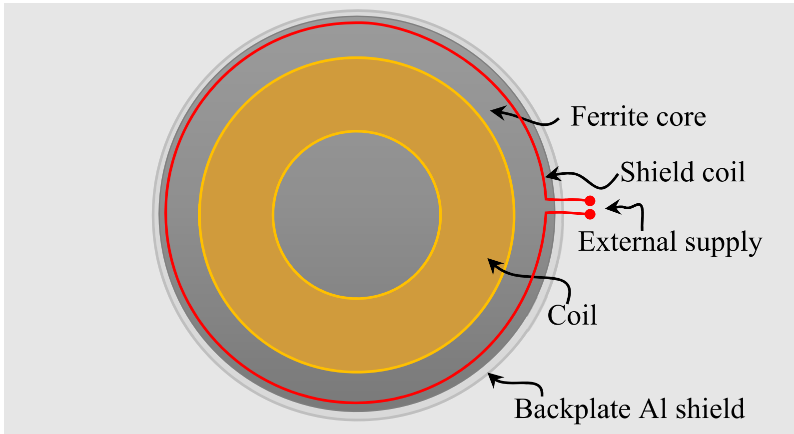


Figure 4.14. A circular nonpolar pad with an externally powered active shield

4.2.6.4 Magnetic Shield

Magnetic shields are made of high-permeability material (e.g., ferrite, steel). The magnetic shield provides a low reluctance path for the leakage flux and diverts it from a targeted region. While the active, passive, and reactive shields rely on flux canceling, the magnetic shield relies on flux-shunting. Therefore, in many ways, the magnetic shield is advantageous for the WCS.

Although magnetic shields are commonly used for shielding electronics components, they have not been widely studied for high-power WCSs. Partially, the ferrite core of a WCS pad helps to shield the leakage magnetic field. However, in the traditional design of a WCS pad, the ferrite core is mainly designed to enhance the mutual inductance, not to suppress the leakage flux. That partial consideration of the core design even increases the leakage magnetic field. A proper design of the ferrite core can increase the mutual inductance as well as work as a magnetic shield. The design of such a magnetic shield is shown in Figure 4.15 and its effective suppression of the magnetic field for bipolar pads is explained by Mohammad et al. (Mohammad, Pries, et al., 2019).

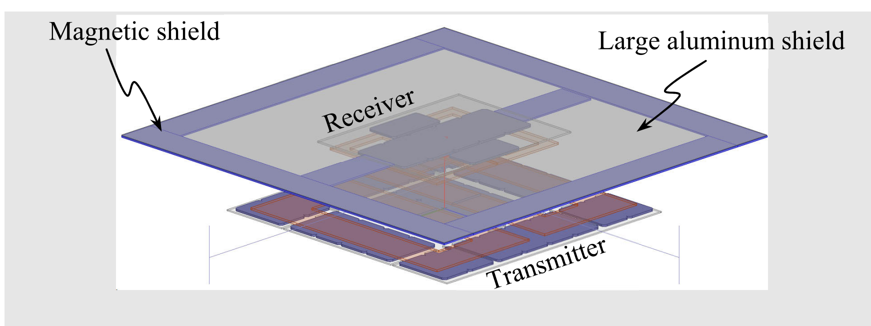


Figure 4.15. Design of a ferrite-based magnetic shield for a bipolar coil-based WCS

4.3 EMF Emissions Under Failure Modes of Different Compensation Topologies

The compensation circuit is one of the key blocks of the WCS. It is a four-terminal circuit, formed by capacitors and inductors, that enables achieving resonance at the targeted operating frequency. Consisting of the compensation circuit and the coil, the resonant tank of a WCS is rated for three to four times higher power than the output power to enable power transfer over a large air gap with a low coupling coefficient.

The position of the compensation circuit in a WCS relative to the primary and secondary coils is shown in Figure 4.16.

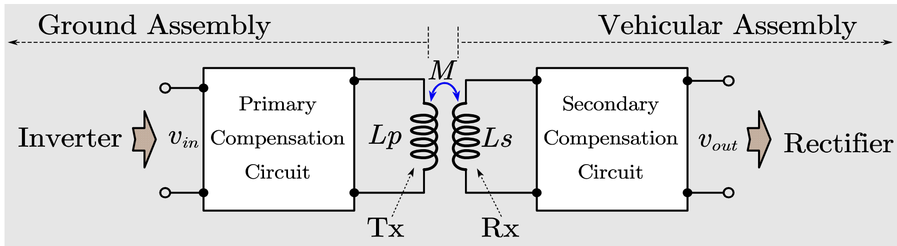


Figure 4.16. Block diagram showing the relative position of the compensation circuit in the transmitter and receiver of a resonant tank in a WCS

Several widely used compensation topologies are used in an EV WCS, which are shown in Figure 4.17. Different resonant circuits with coupled transmitter and receiver have different behavior when faced with open- or short-circuit faults at their input and output terminals.

The fault at the terminals of the resonant tank, which is located either in the primary side inverter or the secondary side rectifier, is typically either an open-circuit or a short-circuit fault. Depending on the compensation topology, the open- and short-circuit faults may increase the current through the coils above the rated current and increase the leakage field above the safety limit.

Operating beyond the normal or safe operating region of the mutual inductance and the battery current-voltage would cause extremely high current through the coils and increase the EMF emissions above the safety limits.

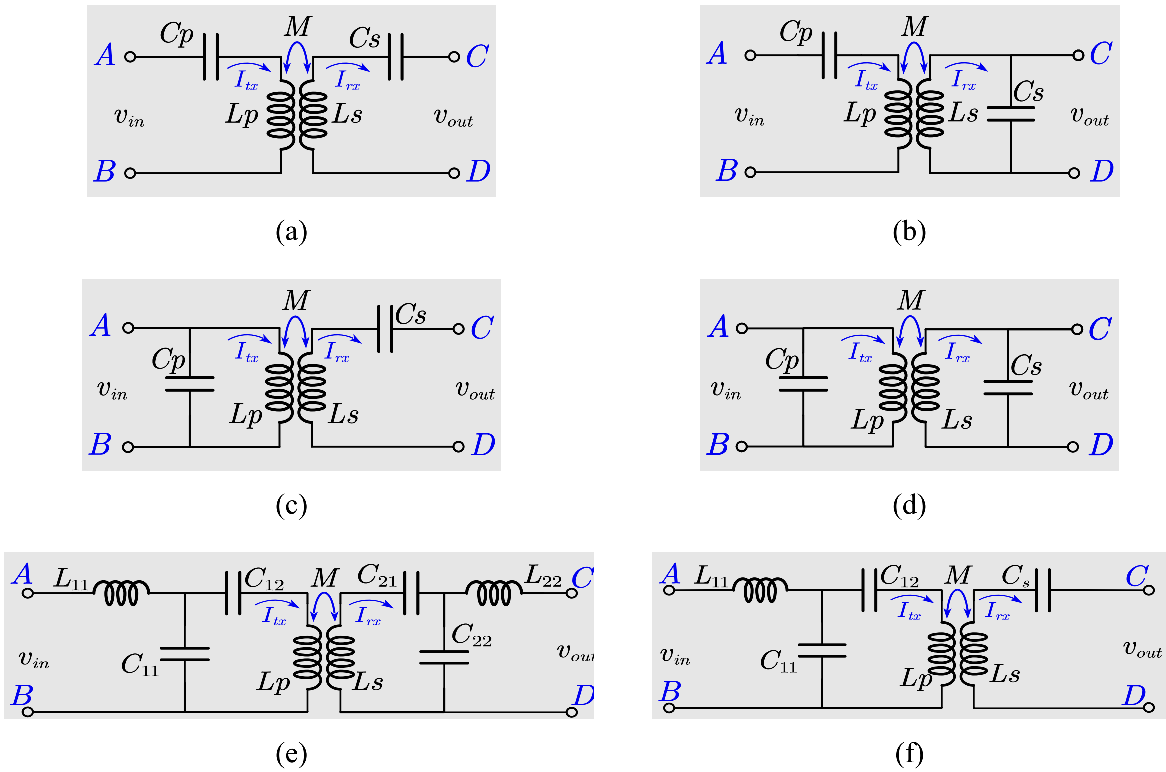


Figure 4.17. Common resonant compensation networks: (a) series-series, (b) series-parallel, (c) parallel-series, (d) parallel-parallel, (e) LCC-LCC, and (f) LCC-series

Some potentially hazardous conditions for the compensation system are the open-circuit fault, short-circuit fault, extremely low mutual inductance, and component failure. The combination of some of these operating conditions and compensation network can significantly increase the EMF emission and cause safety hazards.

4.3.1 EMF Emissions Under Extreme Variation of Mutual Inductance

Series-series compensation is the most widely used compensation topology used in laboratory prototypes of WCSs. It is simple to build but is highly sensitive to the variation of the coupling coefficient and load. The coil currents of the series-series compensation can be given as

$$I_{tx} = \frac{V_{CD}}{\omega M} \qquad\qquad I_{rx} = \frac{V_{AB}}{\omega M} \tag{4.2}$$

where, I_p and I_s are the primary and secondary coil currents, respectively, M is the mutual inductance, ω is angular frequency, and V_{AB} and V_{CD} are the terminal voltages marked in *Figure 4.17*. Equation (4.2) indicates that the coil currents in a series-series compensation are inversely proportional to the mutual inductance. The coupling coefficient varies with the alignment of the coils. As the coupling coefficient reduces, the coil current increases, which increases the EMF emissions. Commonly, WCSs are designed to operate up to a certain minimum coupling coefficient. If the misalignment is too large, the coupling coefficient will reduce below the minimum range and the coil currents will increase to a significantly high level. Therefore, the EMF emissions would increase beyond the safety limit. Therefore, it is essential to have an integrated current sensor designed to not only protect the system but also limit the current to keep the EMF emissions below the safety limit.

For the LCC-LCC compensation, the coil currents can be expressed as

$$I_{tx} = \frac{V_{AB}}{\omega L_{11}} \qquad I_{rx} = \frac{V_{CD}}{\omega L_{22}} \tag{4.3}$$

which indicates that the coil currents are independent of the mutual inductance; hence, the EMF emissions of the LCC compensation are less sensitive to the mutual inductance variation.

4.3.2 EMF Emissions Under Extreme Variation of Load Impedance

The effective load impedance of a WCS varies with the state-of-charge (SOC) of the EV battery. Therefore, as different vehicles with different battery capacities and SOCs couple with a ground transmitter pad, the resonant tank will see different load impedances. Different compensation topologies of the resonant tank have different sensitivities to the load impedance variation. Depending on the compensation topology, the coil current shows different sensitivity to the variation of the load impedance. Consequently, the EMF emissions vary accordingly.

4.3.3 EMF Emissions for Open-Circuit and Short-Circuit Fault in a Resonant Tank

An open-circuit fault at the secondary output terminal of the series-series (SS) compensation will lead to a large current in the primary coil; on the other hand, a short-circuit fault at the secondary output terminal will lead to high current in the secondary coil. The open- or short-circuit fault at the input or output of a series-series compensation generates an unsustainable operating condition, either forcing a system shutdown or leading to system-level failure. Therefore, although the steady-state condition after the failure will be safe, during the transient period of the failure, the coil current will increase to a much higher level and exceed the EMF emissions.

4.3.4 EMF Emissions for Component Failure in a Resonant Tank

From the perspective of EMF emissions, the series-series compensation system is safe from component failure. Any complete or partial failure in the primary or secondary component (L_p, L_s, C_p, C_s) will detune the system from the resonance frequency and reduce the coil currents. Similar to the series compensation, a fault in the primary or secondary side resonant tank will detune the resonance and reduce the coils currents; therefore, it would not increase EMF emissions.

LCC compensation is comparatively more sensitive to component failure. The tuning inductors L_{11} and L_{22} are also the determinant of the coil currents I_p and I_s. Specifically, the coil currents are inversely proportional to the tuning inductor. Therefore, any fault that will cause either a reduction in the inductance or a short circuit of the inductor will increase the coil current and increase the EMF emissions.

4.3.5 Emissions From Third and Fifth Harmonics

Compared with series compensation, the LCC compensation generates less third and fifth harmonics current in the transmitter coil. The coil currents of the series-compensated and LCC-compensated primary coil is given in Figure 2.1b (first waveform) and Figure 2.2b (third waveform), respectively, which shows that the coil current of the series-compensated transmitter coil has a significant distortion due to third and fifth harmonics. Therefore, the third and fifth harmonics emissions are much lower for the LCC compensation circuit.

5. Interoperability of Vehicle and Ground Side Charging Systems

- **Wireless control and sensing**

The objective of closed-loop control in WPT systems is to control the output voltage or current of the WPT system. The most common way to do this is by

a. varying the input DC voltage of the GA.
b. varying the phase shift between the phase legs of the high-frequency inverter on the GA.
c. varying the switching frequency of the high-frequency inverter on the GA.

Sensing of the output voltage or current is done using precise current and voltage sensors. Some examples of sensors used for the purpose include the LEM Hall effect current sensor (LF 510-S) and the LEM Hall effect voltage sensor (CV 3-1500). Sensor failure or loss of the sensed signal in any way is a catastrophic failure for the WPT system and will be addressed in detail in the failure mode effects and analysis (FMEA) tables.

- **Communication between VA and GA**

Wireless communication from the VA side to the GA side and vice versa forms an integral part in closed-loop control architecture for WPT charging systems. The most commonly used wireless communication are classified as follows:

a. Bluetooth: The range is limited to 33 ft (about 10 m). The communication frequency is at 2.45 GHz.
b. Wireless Fidelity (Wi-Fi): Range is limited to 150 ft (about 50 m). The communication frequency is at 2.4 GHz.
c. Dedicated short-range communication (DSRC): Range is around 1 km. The communication frequency is 5.9 GHz. Most DSRC radios are equipped with wireless, LAN, 3G/4G/LTE, GPS/navigation, Bluetooth, and so on, with many added functionalities.

Generally, the GA and VA side microcontrollers and sensing systems cannot directly be connected to the wireless communication network and require additional interfaces. The commonly used interface is a combination of controlled area network (CAN) and ethernet. Serial communication can also serve as an alternate mode of interface if serial ports (RS 232 or RS 245) are available.

Regardless of the wireless communication used, the minimum delay in communication is about 100 ms. This delay is only between the wireless units and is further increased by the serial, CAN, and ethernet interfaces. This delay severely limits the maximum achievable bandwidth of closed-loop control architectures for WPT systems.

In addition to the closed-loop feedback controls, wireless communications are also used for starting and stopping the charging process. The other function of the wireless communication is that a centralized controller may send charge commands and parameters to the primary side from a central location or via internet.

- **Compensation network compatibility**

Compensation network compatibility is important in case of any failure in the system. The different compensation topologies in the existing different electrical car models might cause severe hazards and failures in the system. SAE International proposes some practical applications for the coil design and dimensions; however, specific information about the compensation topologies is not provided. For example, from the simple impedance matching theory, if the primary side compensation impedance is lower than secondary side impedance, this condition can eventually cause system instabilities, especially at high power levels. Other issues are related to the compensation quality factor, which is basically energy storage in the oscillating resonator to energy dissipation during each cycle of operation. If the system compensation quality factors provide too much peak damping, this will also cause closed-loop control issues, and these problems will eventually cause catastrophic instability and failure issues in WPT systems.

Also, each vehicle might have different protocols, such as CCS, CHAdeMO,[1] and Tesla supercharger, which make it difficult to develop a universal charging infrastructure for all EVs on the road. Although CAN bus communications are common in all EVs, compatibility to battery management systems is different depending on the EV model. Unfortunately, these protocols cannot check the topological network compatibility in each EV. The major obstacle between wireless chargers is that compensation network compatibility might cause issues for WPT systems.

5.1 Coil Shape and Interoperability

The most common coil topologies are shown in *Figure **4.2***. Other than those, a vast number of different charging pad structures is being actively investigated with different coil geometries, winding patterns, core geometries and orientations, shielding technologies, and numbers of coils and phases (Pries et al., 2018; Kim et al., 2017; Matsumoto et al., 2014; Ahmad et al., 2019; Pries et al., 2019). Although most of the charging pads consist of a single coil, a few have multiple coils to enhance performance. Similarly, some pads have single-phase coils as well as poly-phase coils. Some of the pads are circular, some are rectangular, and some are hexagonal in overall geometry.

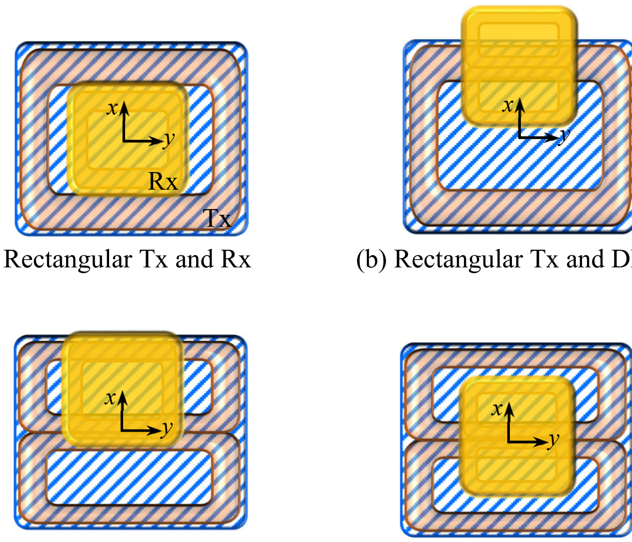
All the coil shapes and pad geometries are not fully interoperable to each other. For best interoperability, the transmitter and receiver pads must provide a significant amount of magnetic flux-linkage so that the required magnetic coupling can be achieved. Although new coil topologies arrive every few months through active research, understanding the full extent of their interoperability requires further study.

5.2 Coil Alignment

To achieve the best performance of a WCS, the transmitter and receiver pad need to be aligned such that they give the maximum coupling coefficient. If the transmitter and receiver are of the same topology—circular, rectangular, DD, DDQ, and so on—aligning them concentric to the same central vertical axis gives the maximum coupling coefficient.

Currently, unipolar-rectangular and bipolar-DD coils are the two most widely used coil topologies and they are conditionally interoperable. The aligned condition of different transmitter and receiver unipolar and DD pads are shown in *Figure **5.1***.

[1] CHAdeMO is the trademarked name of a fast-charging method for battery electric vehicles. It is an abbreviation of "CHArge de Move," equivalent to "move using charge," "move by charge," or "charge 'n' go," referring to it being a fast charger. The name is derived from the Japanese phrase "Ocha demo ikagadesu ka," translated as "How about a cup of tea?", referring to the time it would take to charge a car. The CHAdeMO Association was formed by the Tokyo Electric Power Company (TEPCO), Nissan, Mitsubishi, and Fuji Heavy Industries (now Subaru Corporation). It now has some 430 member organizations.



(a) Rectangular Tx and Rx
(b) Rectangular Tx and DD-Rx
(c) DD-Tx and rectangular -Rx
(d) DD-Tx and DD -Rx

Figure 5.1. Aligned condition for similar and inter-operable coil topology

There are a few other coil topologies, including tripolar, and polyphase charging pads. From the previous discussion, these coils can be assumed to be compatible with each other under certain conditions. The EV WCS has an alignment mechanism by which it is possible to maintain the optimal alignment.

However, different combinations of transmitter and receiver pads have different interoperability regarding power transfer efficiency and EMF emission. An exhaustive test of interoperability among different SAE International–recommended DD and rectangular transmitters and receiver pads is given in (Schneider et al., 2019). It indicates that the rectangular transmitter with DD receiver gives less emission than the DD transmitter with a rectangular receiver. This study provides a few sets of results for very specific sets of pads; however, a vast analysis would need to be undertaken to understand the potential risks and advantages of all available coil topologies.

For the light-duty WCS, the maximum misalignment outlined by the SAE International standard is 100 mm along the side and 75 mm along the front of the vehicle. Under that given misalignment, the minimum 80% efficiency must be maintained. While the 15 percent loss is manageable for a low-power WCS, it is a significant loss for high-power WCSs (15 to 20 kW). That loss occurs in three major subsystems: inverter, rectifier, and coupler pads. The high loss creates a significant thermal challenge that requires extensive thermal management. Therefore, the flexibility of misalignment that is allowed for light-duty charging may not be allowed for XFC.

Another challenge of the misalignment is the increased EMF emissions. EMF emissions are already a critical limit for the high-power WCS. Therefore, the strict limit on EMF emissions, which must be maintained for all power levels, will put a strict limit on the allowed misalignment for XFC. Maintaining alignment requires precision position sensing for manual parking as well as automated parking. Therefore, the alignment sensor and protocol that is recommended for the heavy-duty WCS vehicle may need further advances compared with a light-duty WCS.

6. Review of FMEA and Related Codes and Standards

Table 6.1. Overview of the codes and standards for design, testing, and safety of the WCS

Standard	Title	Scope	Issued
SAE RP J2954	Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology	Discusses the general requirements of the WCS, including interoperability, electromagnetic compatibility, EMF emission, operating frequency, safety, testing, and alignment for grid-to-vehicle stationary 3.3 to 11 kW WCSs	2019-04-23
IEC 61980-1	Electric vehicle wireless power transfer (WPT) systems—Part 1: General requirements	Discusses the general requirements of the WCS in an EV application, including the requirements for operational safety and protection, EMF emissions and safety, touch current, and mechanical safety and reliability	2015-07-24
IEC 61980-2	Electric vehicle wireless power transfer (WPT) systems—Part 2: Specific requirements for communication between electric road vehicle (EV) and infrastructure	Discusses the communication method between the electric road vehicle and WCS considering supply voltage up to 1,000 V_{AC} and up to 1,500 V_{DC}.	2019-06-13
IEC 61980-3	Electric vehicle wireless power transfer (WPT) systems – Part 3: Specific requirements for the magnetic field wireless power transfer systems	Discusses the specific requirement for electrical safety, communication required for ensuring safety under any fault, and specific EMS requirements for an inductive WCS	2019-06-13
UL 2750	Outline of Investigation for Wireless Power Transfer Equipment for Electric Vehicles	Covers SAE International J2954–based WCS equipment considering a maximum input voltage of 600 $V_{AC,}$ including the requirement of monitoring of the critical system components for proper functionality, reliability, and safety	2020-03-13
SAE RP J2847-6	Communication between Wireless Charged Vehicles and Wireless EV Chargers	Discusses the requirements and specifications for communications messages between wirelessly charged EVs and the wireless charger	2015-08-05

RP: recommended practice.

Table 6.2. Component- and subsystem-level scope of the codes and standards related to FMEA of the EV WCS

Scope	SAE International J2954	IEC 61980-1	IEC 61980-3	UL 2750
Grid interface circuit	Harmonic requirements are referred to IEC 61000-3-2 or IEC 61000-3-12. Voltage fluctuation and flickers are also referred to IEC 61000-3-3 and IEC 61000-3-11.	Harmonic requirements are referred to IEC 61000-3-2 or IEC 61000-3-12. Voltage fluctuation and flickers are also referred to IEC 61000-3-3 and IEC 61000-3-11.	Degrees of protection, LV switchgear and control gear, residual current operated circuit breakers without/with overcurrent protection are referred to IEC 60529, IEC 60947-2, IEC 61008-1, and IEC 61009-1, respectively.	The requirements for protection refers to the UL 1077, UL 60691, UL 248-1, UL 248-11, UL 4248-1, and UL 4248-11. Also, it refers UL 489 for circuit breakers.
Inverter	Operating frequency of the inverter system is referred as a table in the file.		Operating frequency of the inverter system is referred to as a table in the file.	The circuit operation of leakage current test and the capacitor discharge test are described in the file.
Pad design	SAE International J2954 proposed two different coil topologies: unipolar and bipolar for up to 11 kW power. It also gave the nominal, maximum, and minimum range of the inductance of each charging pad. It has also presented the shield design and interoperability criteria. The design of the transmitter pads is dominated by the interoperability requirement with different receiver pads. However, the design of the receiver pads is made much smaller than the transmitter pads.	Out of scope	For light-duty vehicles, IEC 61980-3 provided the same pad design as of SAE International J2954. Additionally, IEC 61980-3 briefly discusses the pad design criteria for the heavy-duty vehicles, such as an electric bus.	Out of scope
Compensation network	SAE International J2954 recommended different compensation circuits, including series, parallel, and LCC.	Out of scope	IEC 61980-3 provided the same compensation network as of SAE International J2954.	Out of scope

Table 6.2. Component and subsystem level scope of the codes and standards related to FMEA of the EV WCS (continued)

Scope	SAE International J2954	IEC 61980-1	IEC 61980-3	UL 2750
Testing and evaluation	SAE International J2954 proposed a benchtop testing guideline including an EV-mimicking aluminum plate. The main focus of the testing guideline is to verify the efficiency of the system, misalignment tolerance, interoperability between unipolar and bipolar pads, and EMF emissions. SAE International J2954 gave a detailed guideline to evaluate both the EMF emission and EMI interference.	IEC 61980-1 covers the operational safety and reliability of the WCS pad under diverse operating conditions. It summarized all the general requirements that a WCS must meet for indoor and outdoor use. It discusses the specific requirements of the WCS, including touch current measurement, insulation resistance, thermal safety testing, and protection against mechanical incidents. UL 2750 discusses the environmental conditions of an EV WCS, potential hazards, and required protection standards.	IEC 61980-3 provided the same testing method as of SAE International J2954.	UL 2750 presented an extensive testing and evaluation method for commercial use of the WCS. It provides the required characteristics of the metallic and nonmetallic materials of different components of a WCS considering flammability, moisture resistance, and mechanical durability. UL 2750 provides a detailed testing requirement of input test, leakage current test, capacitor discharge test, dielectric strength test, humidity, temperature test, impact test, vehicle drive over test, drop test, mounting test, chemical stress test, and different production-line tests.

Table 6.3. Subsystems and components

System	Subsystem	ID#	Component	Comments
Grid interface	**EMI filter**	**A.1**	Common-mode choke	
		A.2	Y capacitor	
		A.3	X capacitor	
		A.4	Shielding	
	Line filter	**A.5**	Filter inductor	
		A.6	Filter capacitor	
	Pre-stage protection and regulations	**A.7**	Fuse	
		A.8	Contactor	
		A.9	Soft start circuit	
		A.10	Inrush current limiter circuit	
	Rectifier/PFC	**A.11**	IGBT/MOSFET power module	Failure modes of IGBT and MOSFET are listed separately in FMEA table
		A.12	Diode module	Diodes may be integrated into IGBT/MOSFET package
		A.13	DC link capacitor	
		A.14	Cooling unit (heat sink and chiller)	
		A.15	Gate driver circuitry	
		A.16	DC voltage sensor	
		A.17	Grid voltage sensor	
		A.18	Grid current sensor	
		A.19	Temperature sensor	
Solid-state transformer	**High-frequency inverter**	**B.1**	Semiconductor power module (generally MOSFETs)	
		B.2	Diode module	Diodes may be integrated into IGBT/MOSFET package
		B.3	DC link capacitor	
		B.4	Gate driver circuitry	
		B.5	Cooling unit (heat sink and chiller)	
		B.6	DC voltage sensor	DC voltage sensor for the series DC capacitor
		B.7	Temperature sensor	
	MV transformer	**B.8**	Litz wire coil	
		B.9	Nanocrystalline core	
		B.10	Metallic enclosure	
		B.11	Temperature sensor	

Table 6.3. Subsystems and components (continued)

System	Subsystem	ID#	Component	Comments
	High-frequency rectifier	**B.12**	Resonant capacitor	
		B.13	Resonant inductor	
		B.14	Semiconductor power module (generally MOSFETs)	
		B.15	Diode module	
		B.16	DC link capacitor	
		B.17	Gate driver circuitry	
		B.18	Cooling unit (heat sink and chiller)	
		B.19	Output current sensor	
		B.20	Temperature sensor	
Vehicle side	**DC-DC converter**	**C.1**	DC link capacitor	DC-DC converter is optional depending on the battery voltage and the solid-state transformer output range
		C.2	Semiconductor power module (generally MOSFETs)	
		C.3	Diode module	
		C.4	Filtering inductor	
		C.5	Gate driver circuitry	
		C.6	Cooling unit (heat sink and chiller)	
		C.7	Input DC voltage sensor	Back-up sensor. The input DC voltage sensor for the DC-DC converter is the same measurements as output DC voltage sensor of solid-state transformer
		C.8	Output voltage sensor	
		C.9	Output current sensor	
		C.10	Temperature sensor	
	EMI filter	**C.11**	Common-mode choke	
		C.12	Y capacitor	
		C.13	X capacitor	
Charging system control and communication	**Sensors**	**D.1**	Grid voltage sensor	
		D.2	Grid current sensor	
		D.3	DC voltage sensor	
		D.4	Temperature sensor	
		D.5	Output voltage sensor	
		D.6	Output current sensor	
	Controller	**D.7**	FPGA	Optional
		D.8	PFC/SST controller unit	

Table 6.3. Subsystems and components (continued)

System	Subsystem	ID#	Component	Comments
		D.9	DC-DC converter controller unit	Optional, depending on the presence of DC-DC converter
	Communication	**D.10**	Communication circuit	Serial or CAN interfaces are aggregated as one unit
	Vehicle connecting cable	**D.11**	Heavy duty charging cable	

7. FMEA Methodology for Static WPT Systems

FMEA is a commonly used tool for understanding and evaluating the potential issues of a system composed of multiple subcomponents. It can help engineers and designers to identify the weak points in a system and help to develop safety tests. In this section, the methodology used for FMEA will be explained for static WPT systems.

The FMEA methodology is based on the analysis of conceptual WCSs at different power levels. For each conceptual system, the subsystems are identified, and each subsystem is broken down into individual components for the FMEA study. In addition to component analysis, the potential interaction between components and subsystems that may trigger certain failure modes are identified and considered for the system FMEA analysis. For each component and subcomponent interaction, potential failure modes are listed and scored based on the likelihood and consequence of the failure. The score for each component and subcomponent interaction is then ranked based on the risk score, which is the multiplication of likelihood and consequence score.

Table 7.1. Likelihood scores

Rating	Description
5	Almost definite
4	Highly likely to occur
3	Likely to occur
2	Rarely likely to occur
1	Unlikely to occur

Table 7.2. Consequence scores

Rating	Description
5	Potential harm or death to the user/operator, system requires replacement
4	Major injuries, medium/severe repair, system requires major repair time
3	Minor injuries, minor/medium repair, system can restart in reasonable time
2	No injuries, minor repair, system can restart in a short time
1	No injuries, no repair, system can restart

Table 7.3. Risk matrix (green = low risk, blue = medium risk, yellow = high risk, and red = extreme risk)

		Consequence score				
		1	**2**	**3**	**4**	**5**
Likelihood score	**1**	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

7.1 Light-Duty Static Wireless Charger (3.3–22 KW) Concept System, Subsystem, and Components

Table 7.4. List of subsystems and components

Subsystem	Sub-subsystem	ID#	Component	Comments
A. Grid interface	A.1. EMI filter	A.1.1.	Common-mode choke	
		A.1.2.	Y capacitor	
		A.1.3.	X capacitor	
		A.1.4.	Shielding for EMI filter of the system	
	A.2. Pre-stage protection and regulations	A.2.1.	Fuse	
		A.2.2.	Contactor	
		A.2.3.	Soft start circuit	
	A.3. Line filter	A.3.1.	Filter inductor	
		A.3.2.	Filter capacitor	
	A.4. Rectifier	A.4.1.	Rectifier power module	
		A.4.2.	Capacitor	
		A.4.3.	Heat sink	
	A.5. PFC	A.5.1.	Boost inductor	
		A.5.2.	IGBT power module	
		A.5.3.	Gate driver	
		A.5.4.	Capacitor	
		A.5.5.	Grid voltage sensor	
		A.5.6.	Grid current sensor	
		A.5.7.	Temperature sensor	
B. High-frequency inverter	B.1. Inverter and gate driver	B.1.1.	Semiconductor power module (generally MOSFETs)	
		B.1.2.	Gate driver circuitry	
		B.1.3.	Cooling unit (heat sink and chiller)	
		B.1.4.	High-frequency decoupling capacitor	
C. Compensation circuit	C.1. Ground side inductors and capacitors	C.1.1.	Series capacitor	
		C.1.2.	Parallel capacitor	
		C.1.3.	Inductor (not required for series-series and series-parallel compensation)	
	C.2. Vehicle side compensation network	C.2.1.	Series capacitor	
		C.2.2.	Parallel capacitor	
		C.2.3.	Inductor (not required for series-series and series-parallel compensation)	

Table 7.4. List of subsystems and components (continued)

Subsystem	Sub-subsystem	ID#	Component	Comments
D. Wireless charging pads	**D.1. High-power magnetic components**	D.1.1.	Litz wire–based coil	
		D.1.2.	Ferrite core	
		D.1.3.	Backplate shield	
		D.1.4.	EMF shield	
	D.2. Sensors and enclosure	D.2.1.	RF sensor for alignment	
		D.2.2.	Foreign object detection coil	
		D.2.3.		
		D.2.4.	Nonmagnetic enclosure	
		D.2.5.	Nonmagnetic coil and core holders	
E. Rectifiers	**E.1. High-frequency rectifier**	E.1.1.	Diode rectifier bridge	
		E.1.2.	Cooling unit (heat sink and chiller)	
		E.1.3.	High-frequency decoupling capacitor	
	E.2. Output filter	E.2.1.	Filter inductor (typically required for parallel compensation in secondary)	
		E.2.2.	Filter capacitor	
F. Control and communication	**F.1. Sensors**	F.1.1.	Input voltage sensor	
		F.1.2.	Output voltage sensor	
		F.1.3.	GA coil current sensor	
		F.1.4.	Output current sensor	
		F.1.5.	GA side high-frequency inverter temperature sensor	
		F.1.6.	Vehicle side high-frequency rectifier temperature sensor	
		F.1.7.	Ambient and other passives temperature sensor	Certain situations might require monitoring ambient temperature or the temperature of the passive components in the GA and VA side resonant networks
	F.2. Controller	F.2.1.	Micro controller unit	
	F.3. Communication	F.3.1.	Communication circuit (wireless communication together with serial or CAN interfaces are aggregated as one unit)	

7.2 Static Wireless Public Charger (22–120 KW) Concept System, Subsystem, and Components

Table 7.5. List of subsystems and components

System	Subsystem	Component	Comments
Grid interface	EMI filter	Common-mode choke	
		Y capacitor	
		X capacitor	
		Shielding for EMI filter of the system	
	Pre-stage protection and regulations	Fuse	
		Contactor	
		Soft start circuit	
	Line filter	Filter inductor	
		Filter capacitor	
	Rectifier	Rectifier module	
		Capacitor	
		Heat sink	
	PFC	Boost inductor	
		IGBT power module	
		Gate driver	
		Capacitor	
		Grid voltage sensor	
		Grid current sensor	
		Temperature sensor	
Basic subsystems of a WCS	High-frequency inverter (ground side)	Semiconductor power module (generally MOSFETs)	
		Gate driver circuitry	
		Cooling unit (heat sink and chiller)	
		High-frequency decoupling capacitor	
	Compensation network	Compensation capacitor	
		Compensation inductor (not required for series-series and series-parallel compensation)	
	Couplers	Litz wire–based coil	
		Ferrite core	
		Backplate shield	
		EMF shield	
		RF sensor for alignment	
		Foreign object detection coil	
		Nonmagnetic enclosure	
		Temperature sensor	
		Cooling system for charging pad (optional)	

Table 7.5. List of subsystems and components (continued)

System	Subsystem	Component	Comments
Vehicle side	**High-frequency rectifier**	Diode rectifier bridge	
		Cooling unit (heat sink and chiller)	
		High-frequency decoupling capacitor	
	Output filter	Filter inductor (typically required for parallel compensation in secondary)	
		Filter capacitor	
Control and communication of a WCS	**Sensors**	Input voltage sensor	
		Output voltage sensor	
		GA coil current sensor	
		Output current sensor	
		GA side high-frequency inverter temperature sensor	
		Vehicle side high-frequency rectifier temperature sensor	
		Ambient and other passives temperature sensor	Certain situations might require monitoring ambient temperature or the temperature of the passive components in the GA and VA side resonant networks
	Controller	Micro controller unit	
	Communication	Communication circuit (wireless communication together with serial or CAN interfaces are aggregated as one unit)	

7.3 Static Wireless Extreme Fast Charger (XFC) (120–350 KW) Concept System, Subsystem, and Components

Table 7.6. List of subsystems and components

System	Subsystem	Component	Comments
Grid interface	**EMI filter**	Common-mode choke	
		Y capacitor	
		X capacitor	
		Shielding for EMI filter of the system	

Table 7.6. List of subsystems and components (continued)

System	Subsystem	Component	Comments
	Pre-stage protection and regulations	Fuse	
		Contactor	
		Soft start circuit	
	Line filter	Filter inductor	
		Filter capacitor	
	Rectifier	Rectifier module	
		DC link capacitor	
		Heat sink	
	PFC	Boost inductor	
		IGBT power module	
		Gate driver	
		Capacitor	
		Grid voltage sensor	
		Grid current sensor	
		Temperature sensor	
WCS	**High-frequency inverter (ground side)**	Semiconductor power module (generally MOSFETs)	Generally, three-phase system is used to transfer the higher power, so component count will increase
		Gate driver circuitry	
		Cooling unit (heat sink and chiller)	
		High-frequency decoupling capacitor	
	Compensation network	Compensation capacitor	
		Compensation inductor (not required for series-series and series-parallel compensation)	
	Couplers	Litz wire coil	
		Ferrite core	
		Backplate shield	
		EMF shield	
		RF sensor for alignment	
		Foreign object detection coil	
		Nonmagnetic enclosure	
		Temperature sensor	
		Cooling system for charging pad	

Table 7.6. List of subsystems and components (continued)

System	Subsystem	Component	Comments
Vehicle side	**High-frequency rectifier**	Diode rectifier bridge	Generally, three-phase system is used to transfer the higher power, so component count will increase
		Cooling unit (heat sink and chiller)	
		High-frequency decoupling capacitor	
	Output filter	Filter inductor (typically required for parallel compensation in secondary)	
		Filter capacitor	
WPT system control and communication	**Sensors**	Input voltage sensor	
		Output voltage sensor	
		GA coil current sensor	
		Output current sensor	
		GA side high-frequency inverter temperature sensor	
		Vehicle side high-frequency rectifier temperature sensor	
		Ambient and other passives temperature sensor	Certain situations might require monitoring ambient temperature or the temperature of the passive components in the GA and VA side resonant networks
	Controller	Micro controller unit	
	Communication	Communication circuit (wireless communication together with serial or CAN interfaces are aggregated as one unit)	

7.4 Summary of FMEA Tables for Wireless Charging Systems

The FMEA tables for wireless charging systems can be summarized for three key sections of the system: high-frequency inverter/rectifier and compensation networks, grid side system, and wireless charging pads.

The compensation network in WCS is typically designed to transfer nominal output power to the vehicle battery while maintaining a resonant operating point (or near resonance operation) throughout the charging process. The different failure modes in the compensation network components (capacitors and inductors) typically affect the DC output power delivered to the battery. Moreover, the failure modes may increase the GA side (input) currents, resulting in short circuit conditions depending on the type of failure mode. The characteristics of the compensation networks are unique, and therefore, different combinations of the failure mode must be considered to design the protective action. Consequently, the modules and sub-modules' protection is carried out using fast response current and voltage sensors, appropriate network design, fault communication to operate the input circuit breaker or contactor, and fault communication to the BMS. In high-power XFC and WCSs, a careful design of the compensation networks must be carried out (to ensure considerable safety margins in voltage and current ratings) based on the summary of failure modes due to the increase in nominal current value and module/component parallelization.

The grid-side system and subsystems should be designed considering existing standards and grid requirements in case of any failure conditions. Especially for high-power XFC WCSs, the grid side requirements are more important and must be carefully designed as summarized potential failure mode conditions. Because the grid side system is similar to wired XFC and existing charging systems, lessons learned from these solutions can be to develop grid friendly and robust high-power WCSs.

Finally, wireless charging pads are commonly installed in parking spaces, in home garages, and under vehicles; therefore, they must be designed considering strict safety requirements, robustness, and durability. Faulty design and improper operation of the wireless charging pads may cause high losses, unsafe electromagnetic field emissions, and high temperatures. While the design and operation must meet the safety requirements, the system also needs to be equipped with numerous monitoring systems, including current sensors, temperature sensors, EMF sensors, foreign object detectors, living object detectors, vehicle arrival detectors, and so on.

8. XFC System for EVS

XFC systems have been proposed for EVs for them to have charging times comparable to the time required to fill the tank on a conventional internal combustion vehicle (3 to 10 min).

8.1 Expected Voltage and Power Levels

To accomplish complete battery charging in a short time period, power levels of at least 350 kW and up to 1 MW are needed for conventional passenger vehicles. These power levels are comparable to small electric utility substations, especially for a location that has multiple XFCs to charge multiple vehicles simultaneously. Therefore, most proposed designs involve the primary of the charger system connected to an electric utility's distribution system at a medium voltage (e.g., 12.4, 13.2, 13.8 kV). The XFC then must step down the voltage to a voltage level compatible with the battery pack (200 to 400 V) and regulate the voltage and current during the charging process.

Because of the costs required to upgrade the utility system's infrastructure to accommodate the power levels expected with XFC, most proposals are for sites where multiple XFC chargers can be deployed so that utility costs are spread over several charging stations. This also allows for ease in scheduling the charge demanded to avoid drawing too high of peak power from the utility.

To maximize the profitability of XFC stations, significant up-front modeling will be required to assess where to locate these within the electric system such that minimum system modifications are needed. Many have also posited that because of the large power required at these locations, power sources such as photovoltaics (PV) and energy storage (batteries) will need to be integrated to help reduce the demands on the grid. Researchers have proposed integrating local generation and/or storage at the XFC site to mitigate some of the demands that would be placed on the utility when charging a vehicle at a high charging rate (Tu et al., 2019). This allows the upstream charging equipment to not necessarily be rated for the peak charging load since some of the power demanded would be supplied locally. The main generation sources that have drawn interest are PV and, to a lesser degree, wind. The main energy storage being considered is a large utility-scale battery or using the collective energy of the vehicles' batteries themselves. Some researchers have also proposed using bidirectional chargers to transfer charge among vehicles or to provide grid support when needed, but this option may face opposition from vehicle manufacturers as the additional battery cycling may reduce the overall battery lifetime.

Significant communication capabilities will also be required between the charger systems and the electric grid to coordinate the charging among multiple units and minimize their overall effect on the grid. The two main topologies that are being considered is an AC connection (Figure 8.1) and a DC connection (Figure 8.2) (Tu et al., 2019).

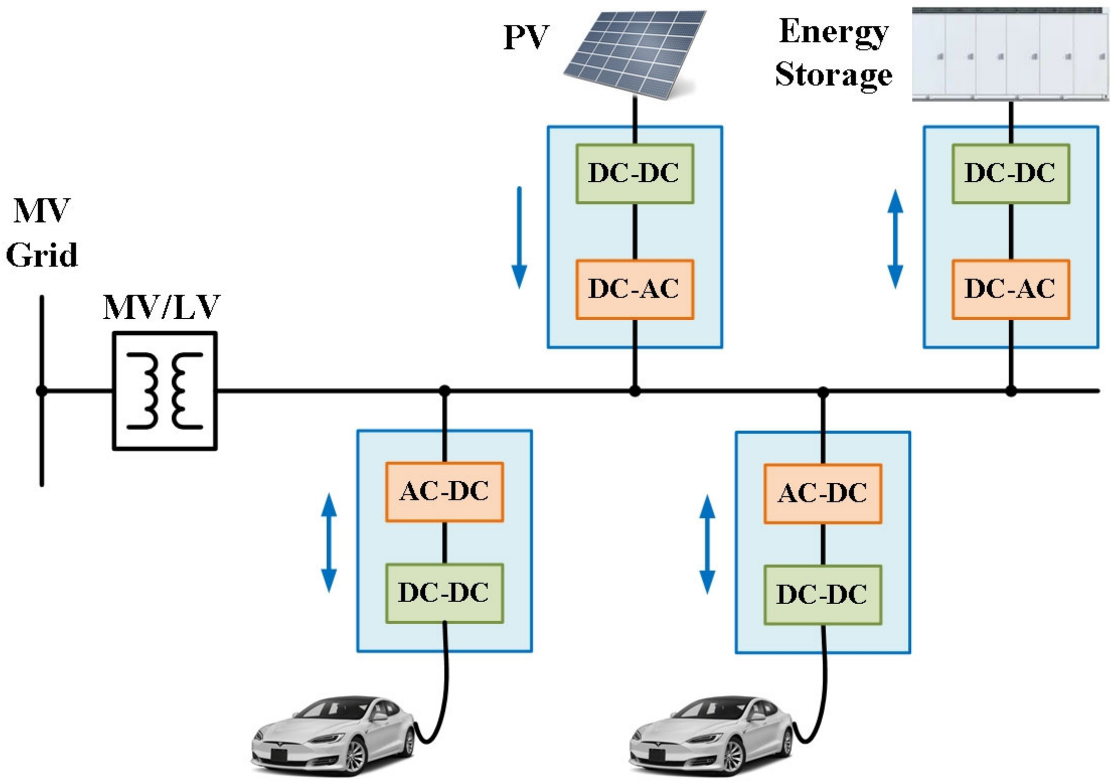


Figure 8.1. AC-connected XFC station (Tu et al., 2019). MV = medium-voltage; LV = low-voltage

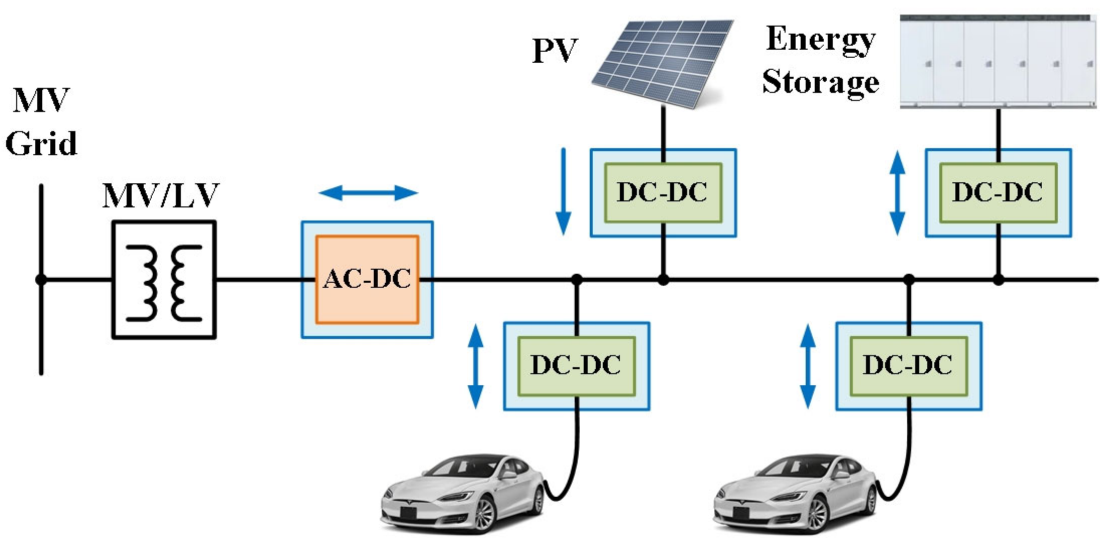


Figure 8.2. DC-connected XFC station (Tu et al., 2019). MV = medium-voltage; LV = low-voltage

One advantage of the DC-connected XFC station is that a single AC interface has to synchronize and exchange power with the AC grid. This arrangement would also allow partial DC-DC converters to be used where a portion of the vehicle charge goes directly to the vehicle without passing through the DC-DC charger. However, this scheme would not meet the isolation requirements to comply with today's standards. DC distribution between the chargers and power sources presents the challenges of DC fault protection and also coordination between protection devices.

The grid-connected AC-DC converters shown in Figures 8.1 and 8.2 are required to draw current with little distortion and typically at a unity power factor or controllable power factor. The voltage supplied to the DC link (typically around 400 to 1,000 V) also has requirements in terms of little ripple and specified voltage regulation.

XFC charging stations that have incorporated generation and/or storage would fall under the regulations for distributed energy resources and thus would be required to comply with Institute of Electrical and Electronics Engineers (IEEE) 1547 or a similar standard, which most utilities have adopted for their own requirements. This will require the charger to be able to ride through short duration/momentary faults and voltage sags and perhaps even provide voltage or frequency support to the grid during fault or extreme system events. IEEE 1547 also provides recommended protection that should be incorporated into the distributed energy resource such that it can detect a fault on the system and know when grid support should be provided or when the load should be interrupted to preserve the grid stability and reliability.

Enabling an XFC station to provide ancillary services to the electric grid—such as reactive power support for voltage regulation, frequency regulation, and energy arbitrage—makes the XFC station more acceptable for the utilities on which they would be placed. For short durations when there is a shortage of generation on the grid due to the tripping of a large generator or the addition of a large load, the frequency of the grid may decrease beyond allowable levels, triggering the need for additional power supply or load shedding to bring the frequency back within close range to 60 Hz. Because of the large battery packs on EVs, a fraction of this energy could be provided to the grid to mitigate dynamic drops in frequency. This would require the charging systems to be bidirectional such that power could be drawn from the batteries and supplied to the grid.

Other ancillary services that draw or supply reactive power to the grid include PFC, voltage regulation, and utility-scheduled reactive power support. These services do not necessitate drawing power from the vehicles' batteries but rather use a current that circulates between the three phases to provide reactive power demanded by a controller.

Figure 8.3 shows several front-end topologies for fast chargers (Tu et al., 2019). Figure 8.3(a) shows the most widely used topology, the active rectifier with LCL filter. The advantages of this topology are the ability to draw high-quality (near sinusoidal) waveforms from the utility and controllable power factor. This topology also boosts the voltage to the DC link of the rectifier. This topology also allows for bidirectional current flow so that the charger could provide real power to the grid if needed. Other three-phase PFC (AC-DC) topologies have also been investigated by Tu et al. (2019) as shown in Figure 8.3(b)–(d).

Their performance metrics are summarized in Table 8.1 (Tu et al., 2019).

Overall, the topology from Figure 8.3(a)—three-phase PWM rectifier—is a favorable candidate, which has the following advantages:

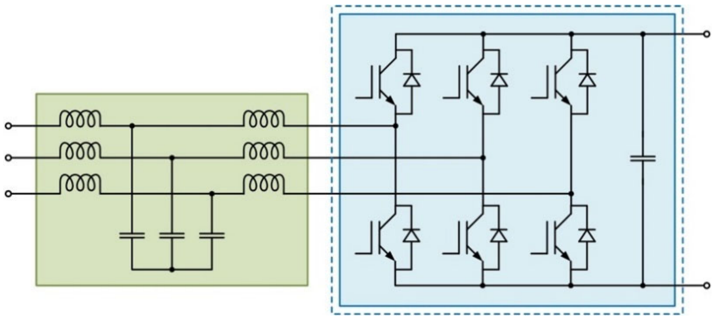
1. Lower cost by using less switches and diodes

2. Ease of control, given various control strategies have previously been developed, such as space vector PWM, discontinuous PWM (DPWM), and active zero state PWM, without any neutral point unbalance unlike for topologies in Figure 8.3(b) and (c);

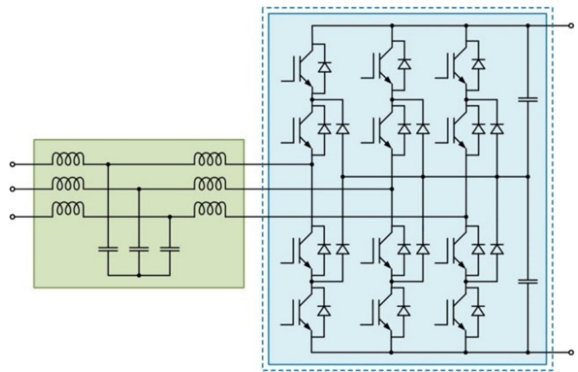
3. Higher efficiency—Current in each phase only flows through one switch/diode, yielding much lower conduction loss compared to other topologies. Meanwhile, a DPWM algorithm has been investigated and tested, which can avoid the switching actions around the peak current and reduce the number of

switching actions by one-third (i.e., lower switching losses). A typical DPWM waveform is shown in Figure 8.4 (Bai et al., 2012).

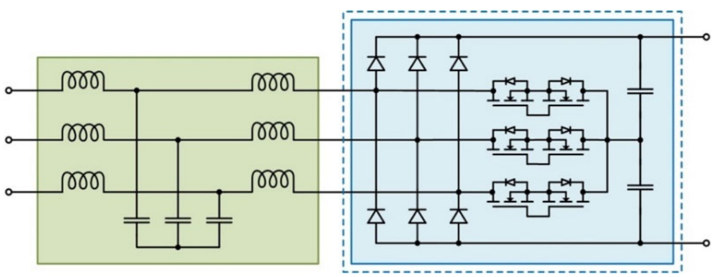
4. Bidirectional—For topologies in Figure 8.3(c) and (d), all diodes have to be replaced with active switches to realize the bidirectional power flow, which adds more cost.



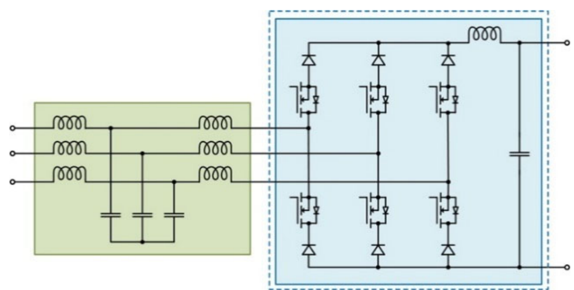
(a) Three-phase PWM rectifier



(b) NPC rectifier



(c) Vienna rectifier



(d) Buck-type rectifier

Figure 8.3. Three-phase AC-DC front-end topologies for fast chargers (Tu et al., 2019)

Table 8.1. Performance metrics for AC-DC converters for DC fast chargers shown in Figure 8.3 (Tu et al., 2019)

	a	b	c	d
Number of switches	6	12	6	6
Number of diodes	0*	6	6	6
Number of gate drives	6	12	6	6
Switch voltage ratings (V)	>900	>600	>600	>900
DC cap voltage ratings (V)	>900	>900	>900	<600
Control difficulty	Easy	Easy	Medium	Difficult
Input power factor range	Wide	Wide	Limited	Limited
Neutral-point imbalance	No	Yes	Yes	No
Grid current total harmonic distortion	Low	Low	Low	Low
Loss	Low	Medium	Medium	Medium
Bidirectional	Yes	Yes	No	No

* can use the switch body diodes.

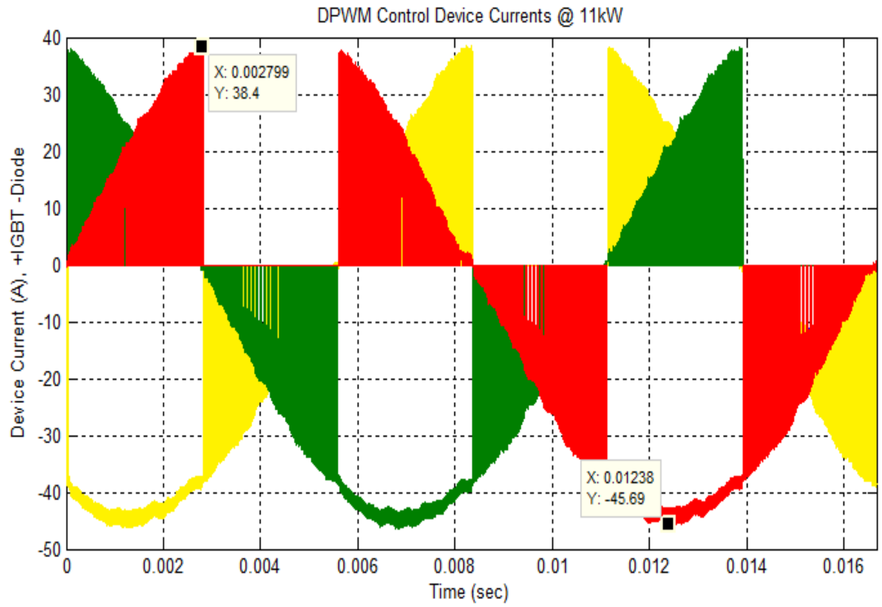


Figure 8.4. IGBTs/diodes current with DPWM control (Bai et al., 2012)

For the DC-DC stage, although original equipment manufacturers are exploring non-isolated topologies, because the battery pack on the EV is floating with respect to ground, there must be galvanic isolation between the grid and the battery pack. One way to achieve this isolation is through the use of a high-frequency transformer that is part of a DC-DC converter that takes power from the front-end rectifier and provides power to the battery. Four types of isolated DC-DC converters were compared by Tu et al. (2019) as shown in Figure 8.5.

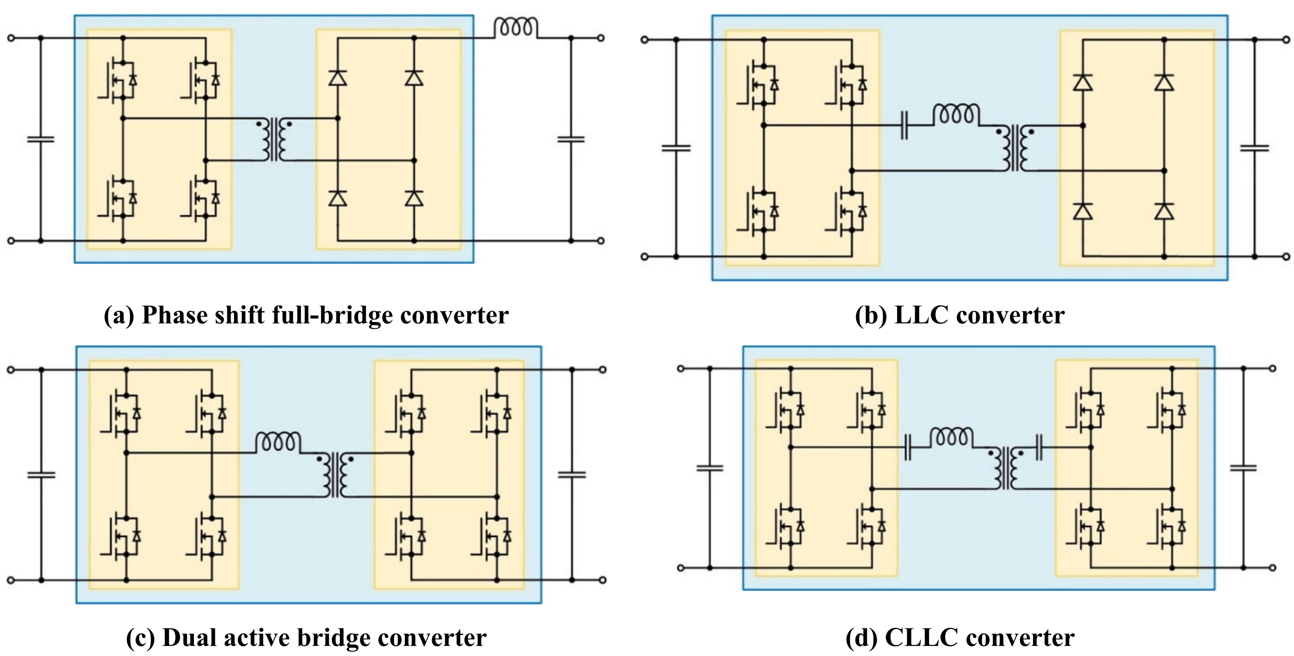


Figure 8.5. Isolated DC-DC converter topologies for DC fast chargers (Tu et al., 2019)

The performance metrics for the DC-DC converter topologies depicted in Figure 8.5 are summarized in Table 8.2.

Table 8.2. Performance metrics for isolated DC-DC converters for DC fast chargers shown in Figure 8.5 (Tu et al., 2019)

	a	b	c	d
Number of switches	4	4	8	8
Number of diodes	4	4	0	0
Number of gate drives	4	4	8	8
Voltage-gain range	Limited	Limited	Wide	Limited
Control difficulty	Easy	Easy	Medium	Medium
Soft-switching range	Narrow	Medium	Wide	Wide
In need of extra resonant circuit	No	Yes	No	Yes
Switching loss	High	Low	High	Low
Bidirectional	No	No	Yes	Yes
Ease for parallelization	No	No	Yes	No

* can use the switch body diodes.

Overall, the topology in Figure 8.5(c)—dual active bridge (DAB)—is the most favorable candidate, which has the following advantages:

1. Bidirectional, which facilitates using the vehicle to provide power in applications such as vehicle-to-grid, vehicle-to-home, and vehicle-to-load

2. Wide soft switching range—Although conventional single-phase shift control can lose ZVS at light loads, recent research has explored other advanced phase shift controls, such as dual-phase shift (DPS) control or triple-phase shift (TPS) control, which can extend the ZVS application to the full power range (IEEE Standard 1547-2018, 2018). Figure 8.6 illustrates how soft switching can be achieved even at light loads using DPS and TPS.

3. Wide output voltage range—For the DAB topology, the single-phase-shift control follows Eq. 8.1. Here, P_1 is the power supplied, I is the average current, V_1 is the input voltage, V_2 is the battery voltage, D is the phase shift between primary and secondary sides, f_s is the switching frequency, L_s is the leakage inductance of the transformer, and n is the transformer turns ratio.

$$P_1 = nV_1\bar{I} = \frac{nV_1V_2}{2f_sL_s}D(1-D) \tag{8.1}$$

Theoretically, as long as the phase shift is imposed between the two sides, there will be power flow regardless of the input or output voltage values. Therefore, DAB can realize very wide voltage ranges, making it suitable for EV charging, where the battery voltages can range from 200 to 500 V for passenger cars depending on the vehicle model and SOC. On the other hand, LLC and CLLC topologies are both frequency selective with limited voltage range.

4. No resonant tank required—Resonant converters, such as in Figure 8.5(b) and (d), shift the electrical stress from the main switches to the resonant components. Because of the high resonant voltage and current, multiple capacitors, film types are usually put in series and parallel, adding to the size and cost. The DAB topology in Figure 8.5(c), on the contrary, does not require resonant tanks. It only uses the leakage inductance of the transformer to realize the power flow.

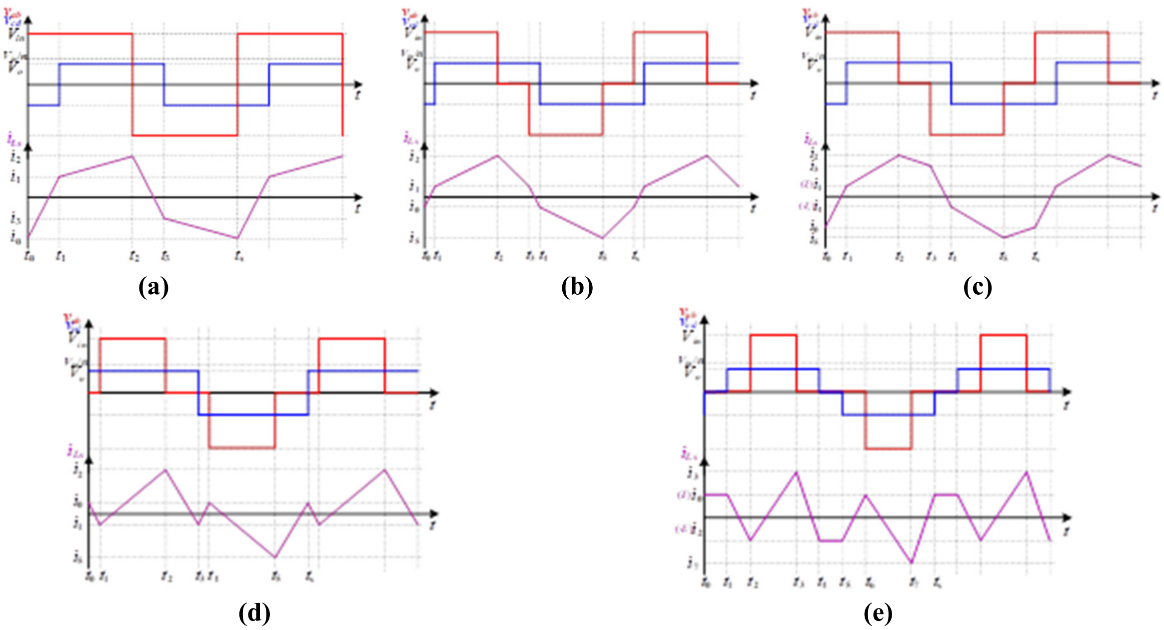


Figure 8.6. Switching modes when the power is (a) 22 kW, SPS; (b) 15 kW, DPS; (c) 10 kW, DPS; (d) 5 kW, DPS; and (e) 1 kW, TPS (Yan et al., 2020)

To undertake higher input voltage (e.g., single-phase 8 kV), a modular design is a better candidate such that voltage blocking can be divided among multiple devices/modules. In addition to the two-level design using >6 kV devices, Zhu proposed a multilevel converter as shown in Figure 8.7 (Zhu, 2019). Both the PFC stage and DC-DC stage use a three-level topology as shown in the figure. 1200 V silicon carbide MOSFETs or silicon IGBTs can be used on both primary and secondary sides to save on cost.

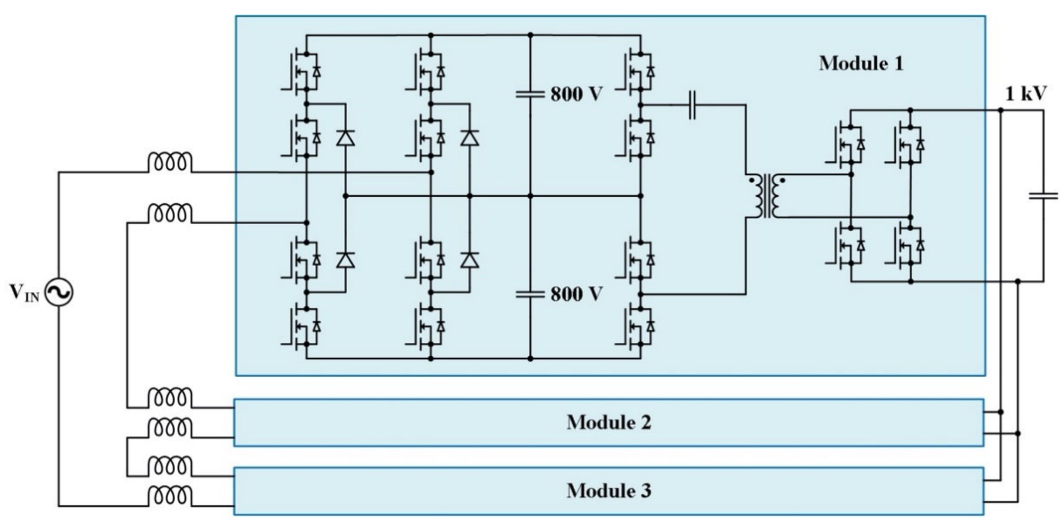


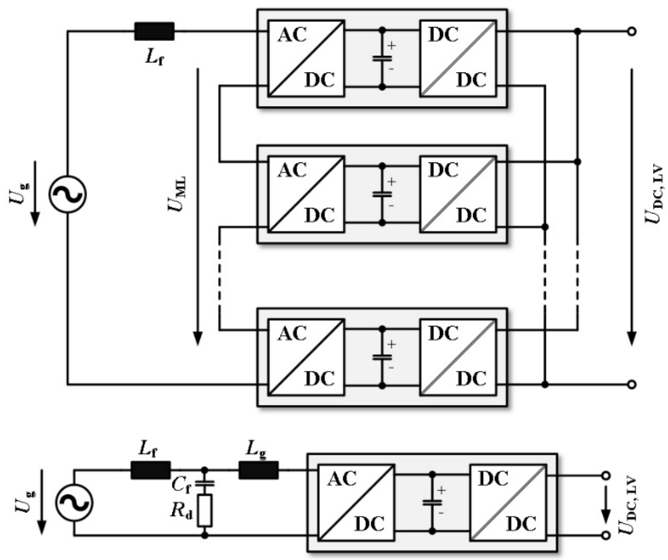
Figure 8.7. Modular design for EV fast charger using the multilevel (three-level) topology (Zhu, 2019)

With LLC employed at the DC-DC stage, ZVS can be realized to save the switching loss. The challenge, however, remains as the large module numbers. With single-phase 8 kV, assuming the DC-bus voltage of each module to be 1.6 kVdc, the input of each module should be less than 1 kVac, which needs at least 8 such modules to form the input-series output-parallel (ISOP) system. Timely communication and control among these >8 such modules are needed to properly share/balance the currents and voltages among the modules.

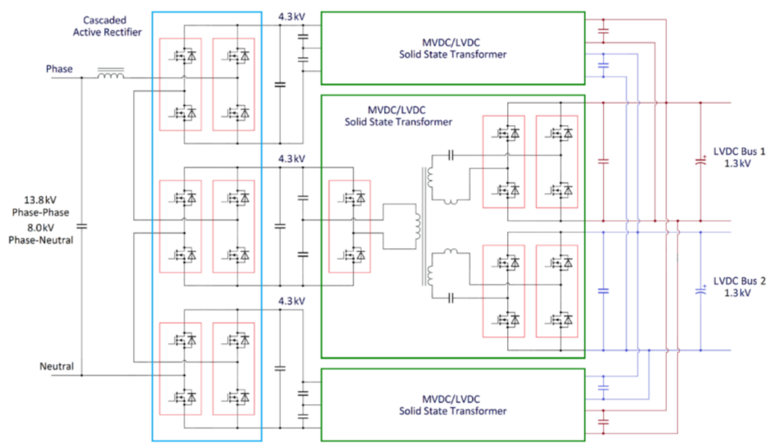
8.2 Transformerless Wired Extreme Fast Charger Structures

The fundamental concept of transformerless XFC for EVs is to directly step down the transmission medium-voltage (MV) AC to the battery voltage via the AC-DC stage and isolated DC-DC stage, without incorporating a line-frequency MV/low-voltage (LV) transformer (60 Hz transformer) like that shown in Figure 8.1 or 8.2. In addition to using a multilevel topology (Figure 8.7) for the XFC, ISOP is another popular candidate as shown in Figure 8.8(a) (Rothmund et al., 2019). ("Transformerless" typically means that no 50/60 Hz transformer is used, but many times still incorporates a high frequency [>10 kHz] transformer that is much more compact in size and weight.)

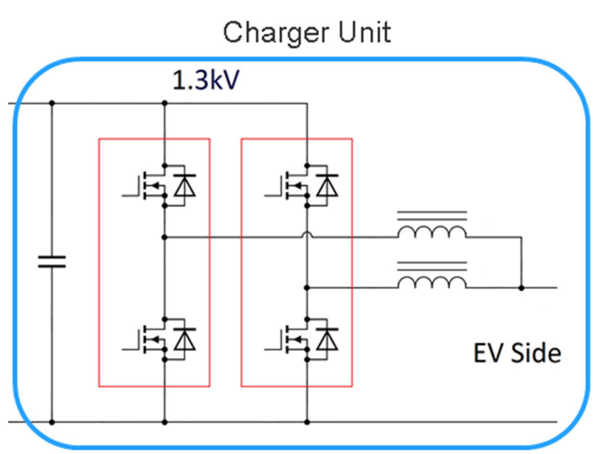
One exemplary ISOP XFC is presented in Figure 8.8(b) (Liang et al., 2020). To transfer the power, the AC voltage at the grid is first rectified and transferred to the primary side DC link, such as 4.3 kVdc in Figure 8.8(b). The number of series-connected H-bridges on the grid side is determined by the AC-grid voltage and the switch voltage rating. Then, the high-frequency inverter converts the DC voltage to high-frequency AC voltage and transfers power from the DC link to the resonant network formed by compensation components (resonant inductor and capacitors).



(a)



(b)



(c)

Figure 8.8. (a) Block diagram of an ISOP XFC (Rothmund et al., 2019), (b) exemplary design of ISOP XFC station for two vehicles, and (c) block diagram of the following 500 kW DC-DC buck converter (Liang et al., 2020)

An MV high-frequency transformer is needed for voltage isolation purposes. If only one car is charged from the XFC, the transformer secondary side only needs one winding. In this particular case, the XFC is designed to charge two cars simultaneously, so two secondary side windings are used. The secondary windings then induce a stepped-down AC voltage, which will be rectified by the LV H-bridges with output voltage being paralleled forming the LVDC bus (e.g., 1.3 kVdc). To charge regular EV batteries of ~200–450 Vdc, another buck converter is needed to step down the 1.3 kVdc to the battery voltage as shown in Figure 8.8(c).

The MVDC-LVDC stage is mainly an LC circuit, which switches at the resonant frequency. Therefore, the key control strategy lies in the AC-DC stage, which also acts as the power factor controller. A schematic of the PFC strategy is shown in Figure 8.9 (Liang et al., 2020). Take two modules with their inputs connected in series as an example. Figure 8.9(b) shows the control block of the PFC weighted output voltage balancing control, which comprises three loops: the inner current control loop, outer voltage control loop, and supplementary voltage balancing loop. The slower outer voltage control loop makes the PFC stage output voltage follow the reference voltage and supply the reference current to the inner current control loop. The reference current is generated by the averaged voltage loop output V_{voa} and the grid side voltage V_{in}. The voltage balancing loop is to finely tune the duty cycle of each AC-DC module in case of output voltage unbalance between modules.

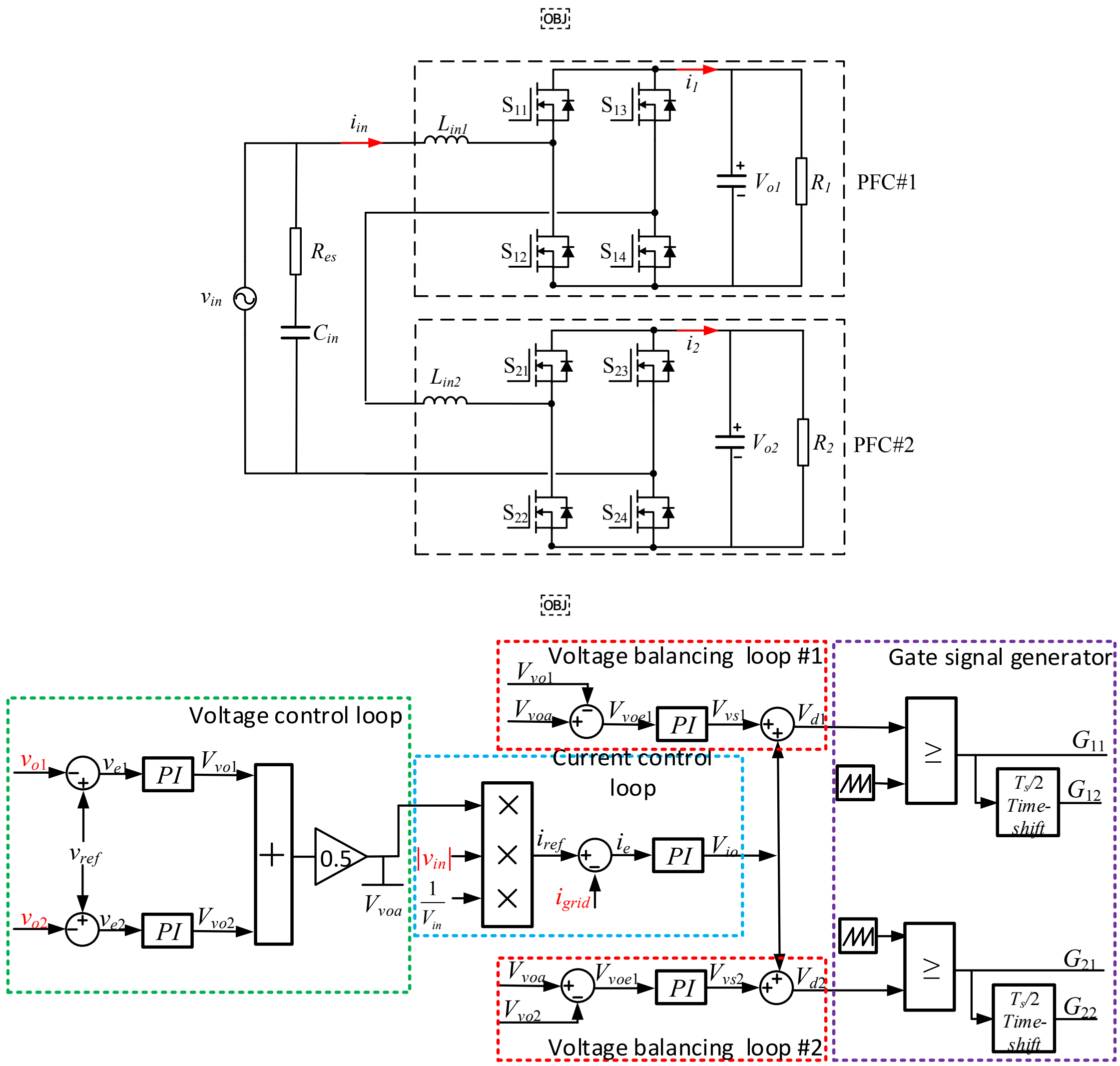


Figure 8.9. (a) Schematic of two PFC modules in series; (b) control scheme for series-connected PFC modules

8.3 MVDC-LVDC Topologies

8.3.1 Resonant Type

A typical resonant-type isolated MVDC-LVDC converter shown in Figure 8.8(a) is an LC type, which is also called DC transformer (DCX) converter (Rothmund et al., 2019). The resonant network only incorporates series-connected capacitors C and transformer leakage inductance L on the secondary side. The transformer mutual inductance is much larger than the leakage inductance. Therefore, it has little effect on the resonance. At the resonance frequency, this topology behaves as a constant voltage source. With the transformer turns ratio equal to 4.3/2:1.3, the 4.3 kVdc bus will precisely generate 1.3 kVdc output. Essentially, such DCX topology is made to eliminate the switching losses, given the switching moments all happen at current zero crossing points, which helps in natural ZVS turn on and zero-current switching turn off for both primary side and secondary side switches as shown in Figure 8.10 (Liang et al., 2020).

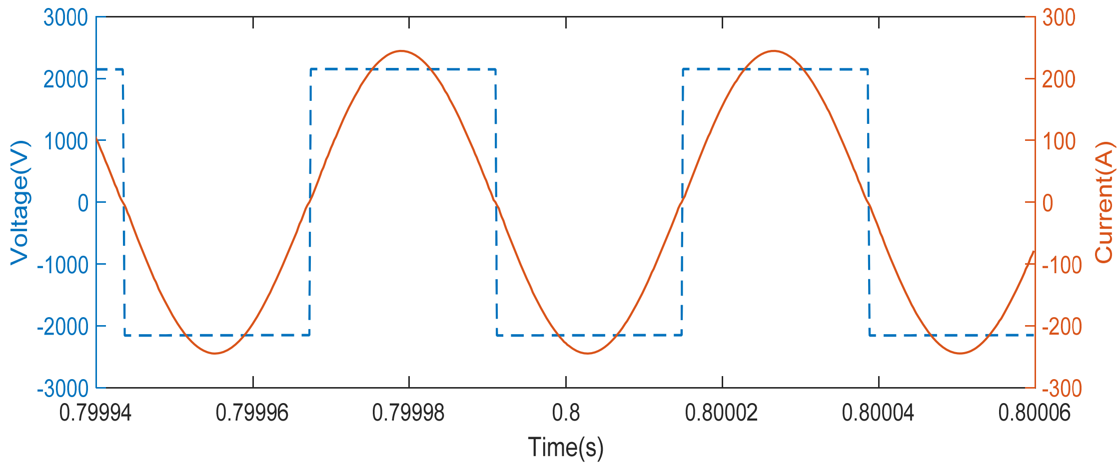
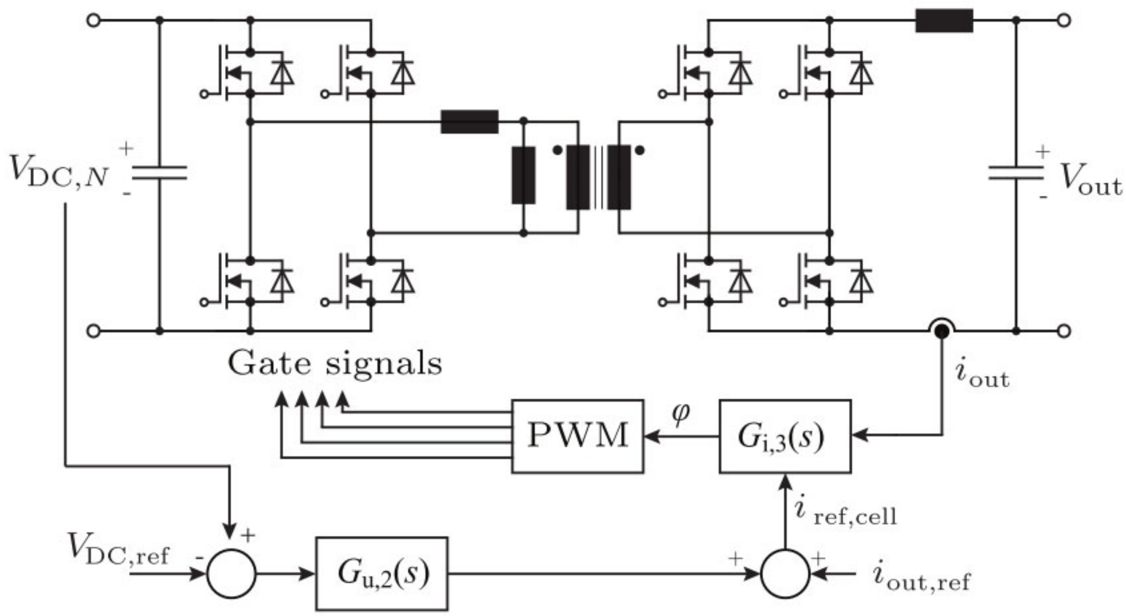


Figure 8.10. Voltage and current waveforms of the primary side of the DCX transformer (Liang et al., 2020)

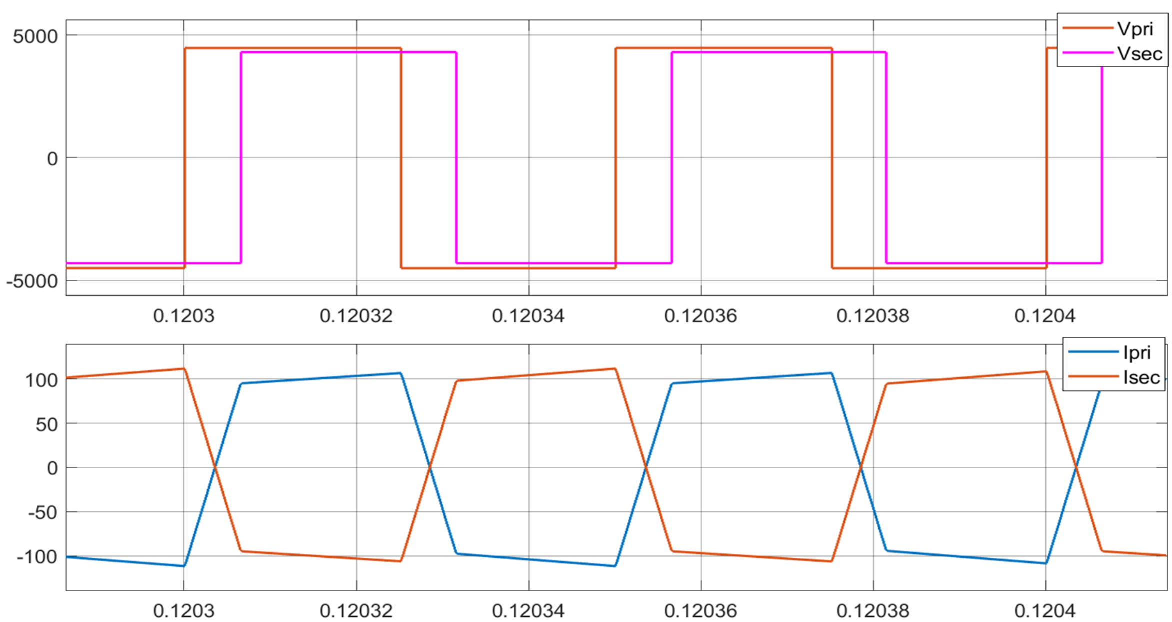
The first major concern with this topology is its resonant capacitors. High voltages at resonant frequency are induced across the resonant capacitor. Such high-voltage stress, usually multiple times of the DC-bus voltage, requires a large number of film capacitors in series and parallel, resulting in large capacitor tanks. Meanwhile, such high-frequency voltage is also subject to significant EMI issues. The second major concern lies in the MV high-frequency transformer, which has issues of partial discharge. For such resonant compensation topology, catastrophic fault conditions can be summarized as (1) high-voltage stress across the series resonant capacitors and (2) insulation failure of the MV transformer due to the partial discharge.

8.3.2 Nonresonant Type

To eliminate the large resonant tank, nonresonant type DC-DC converter can be used, such as DAB as shown in Figure 8.11(a) (Kasper et al., 2015). Two inductors at the primary side of the transformer are equivalent leakage and mutual inductors, respectively, which are integrated inside the transformer. No resonant capacitor is adopted, though the switch number is increased to eight. Each input voltage will be compared to the reference value as well as the output current compared to its reference. Essentially, such a DAB converter is a current source type, where the output current/power is controlled by the phase shift between primary and secondary sides (φ). The typical voltage and current of the transformer primary and secondary sides are shown as the top and bottom plots of Figure 8.11(b), respectively.



(a)

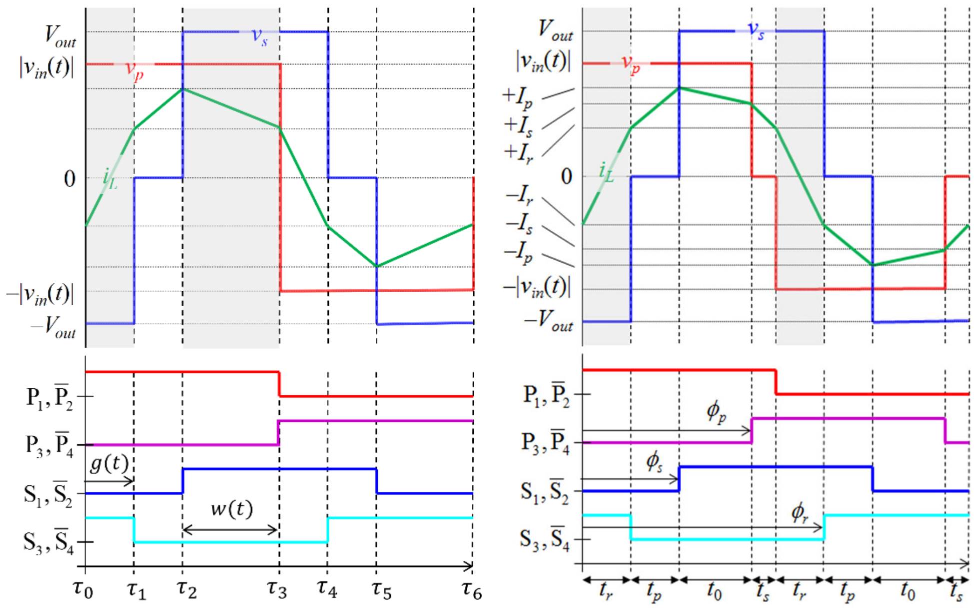


(b)

Figure 8.11. (a) Circuit and control diagram of the DAB (Kasper et al., 2015); (b) typical waveform of the DAB using single-phase-shift control

Compared with an LC resonant-type DC-DC converter, Figure 8.11(b) shows that the switching current stress of the DAB is much higher, which yields higher switching loss. At the light load condition, the switch can easily lose soft switching, yielding high switching-on loss and diode reverse recovery loss. For the DAB-based topology, catastrophic failure modes can be summarized as (1) the high switching current stress across semiconductor switches, (2) partial discharge of the MV transformer, and (3) easy-to-lose soft switching, though research has recently been conducted to introduce multi-phase shift control to secure ZVS, with the drawback of an increase in the complexity of the control (Yan et al., 2020).

In research from Yan et al. and Taylor et al. [48, 49], multi-phase shift control has been proposed (i.e., introducing TPSs for light loads, DPSs for medium loads, and single-phase shifts for heavy loads) as shown in Figure 8.12. In research from Everts et al. (2013), switching frequency acts as another variable to ensure ZVS, which challenges the design of the MV transformer to accommodate a range of frequencies.



(a) DPS control **(b) TPS control**

Figure 8.12. Other types of control of the DAB (Taylor et al., 2018)

8.3.3 Summary

The two types of the DC-DC topology (resonant type and nonresonant type) have been presented. The exemplary design of the resonant type is an LC circuit (i.e., DCX). It shows a simple control (i.e., fixing the switching frequency to the resonant one) with low switching loss. Failure modes are associated with the voltage and current stress across the resonant inductor and capacitors. On the contrary, the nonresonant type, such as DAB, exhibits large switching stress; however, it eliminates the resonant network. It can yield higher power density and lower cost, though the loss and EMI must be addressed.

Topologies in the literature other than the two topologies reviewed are also options, such as LLC and CLLC resonant. However, these topologies are modifications of the resonant-type topologies and face the same challenges/failure modes as DCX topology. Therefore, the authors in this report will not provide a detailed discussion of other resonant types.

8.4 Grid-Interface System

Similar to the wireless charger, all EV XFC equipment requires an interface to draw energy from the electrical grid (60 Hz single-phase or three-phase). A PFC interface with the electric grid is required as well. Although the majority of the PFC topologies in the wireless charger section can be used in wired XFC, to accommodate MV AC input, there are mainly two-types of PFC under consideration, one using multilevel topology to form a single PFC as shown in Figure 8.13 (Gill et al., 2019), and the other using an ISOP topology as shown in Figure 8.8(a).

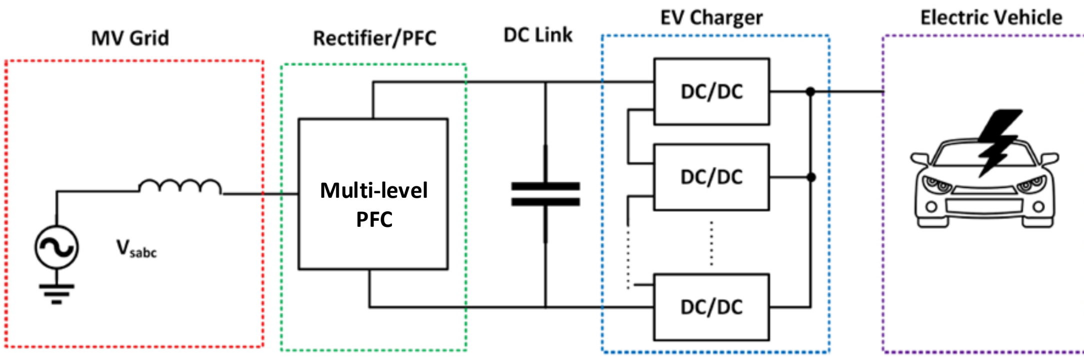


Figure 8.13. XFC using multilevel PFC and ISOP DC-DC topology (Gill et al., 2019)

The PFC stages mainly have two challenges. One is the hard switching of switches, which causes high switching loss and EMI at the MV level. The other is the bulky DC-link capacitor.

To solve the hard switching issues, Bai et al. (2012) proposed adding one LC resonant tank at the PFC stage, facilitating the realization of ZVS as shown in Figure 8.14.

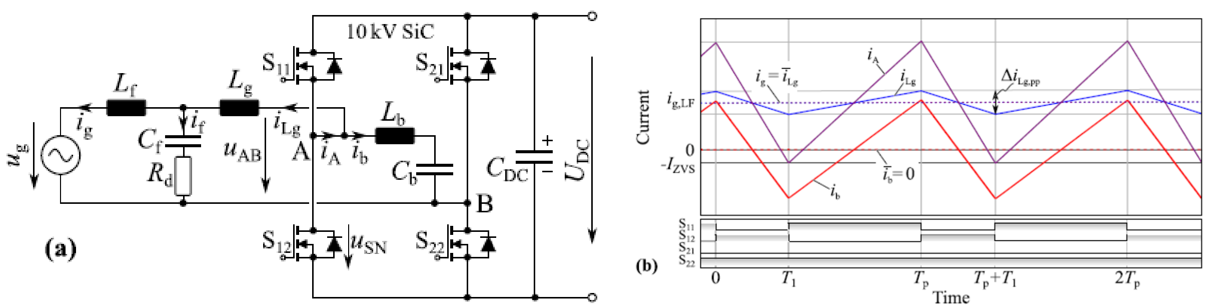


Figure 8.14. Soft switching PFC (a) topology and (b) key current waveform (Bai et al., 2012)

MV DC-link capacitor can be bulky especially for the single-phase AC input. Because the system is a single-phase AC-DC converter, the power fluctuation with twice the mains frequency has to be buffered in the DC-link capacitor. Especially for MV applications, where the electrolytic capacitors are not applicable due to their LV rating, the DC-link capacitor is one of the physically largest hardware parts. To save on capacitor size, one method to keep the required volume to a minimum and still attain a highly compact converter is to allow a larger peak-to-peak DC-link voltage ripple of 10 percent or higher (Bai et al., 2012), leading to a relatively small capacitance. Meanwhile, such MV DC-link capacitors can be realized with a series connection of multiple LV film capacitors whose voltages are passively balanced with high-ohmic resistors (MΩ level) connected in parallel to the capacitors. A typical example is the Electronic Concepts LH3 series capacitors as shown in the Table 8.3.

Table 8.3. Electronic Concepts LH3 series capacitors (Electronic Concepts, Inc., 2021)

Part number	Voltage	Cap	"H"	ESR	Rth	ESL	dv/dt	Ipk	Fres	Weight	RMS Current (10 kHz)			
	VDC	µF	mm	(Milliohms)	°C/W	(nH)	(v/us)	(AMPS)	(kHz)	(kg)	25°C	55°C	85°C	105°C
LH30CB756	2,400	85	75	1.28	1.8	9	78	6,628	182.0	1.9	187	148	95	23
LH30CB147	2,400	140	100	1.88	1.6	10	48	6,656	134.5	2.9	162	129	83	20
LH30BT906	1,600	90	50	0.44	2.2	8	112	10,098	187.6	0.9	287	228	147	35

8.5 MV High-Frequency Transformer

When increasing the operating frequency of a transformer, the authors expect to reduce the transformer size and weight, given its core cross section is reduced inversely proportionally to the frequency. Nanocrystalline cores, for instance, can be produced with sheet thicknesses as low as 13 µm, in contrast to the 350 µm thickness of conventional grain-oriented electrical steel used at the line frequency (Lyons et al., 2007). However, for MV insulation, the miniaturization of the transformer creates a direct challenge for the dielectric design, given increasing frequency does not reduce the clearance distance required for insulation. Meanwhile, because of the MV ratings required, the insulation material layer, which encapsulates the MV-winding and isolates it from the LV-winding and the core, has to be rather thick, which increases the transformer size again.

8.5.1 Core Selection

Two main families of cores are available for the MV transformer design: the powder type and the tape type. Although the powder types are generally referred to as ferrites, a variety of materials can be used in terms of loss and saturation levels. One challenge is that ferrite cores are not easily manufactured in larger sizes. Therefore, nowadays such materials are mainly applied in low-power applications. Additionally, ferrites usually have relatively low flux density saturation levels (e.g., ~0.3–0.5 T). Tape type cores, in theory, have unlimited size. Therefore, they can be produced in much larger sizes than ferrites. The main material types for these cores are amorphous, nanocrystalline, nickel iron, and cobalt iron (Isler et al., 2017). Main core parameters are shown in Table 8.4.

Table 8.4. Comparison of main core parameters (Isler et al., 2017)

	Ferrite MnZn	Amorphous (iron-based)	Amorphous (cobalt-based)	Nano crystalline	Nickel iron (50%)	Nickel iron (79%)	Cobalt iron (50%)
Core type	Powder	Tape	Tape	Tape	Powder/ Tape	Powder/ tape	Tape
Saturation induction at 20ºC (T)	0.43	1.56	0.57	1.23	1.6	0.88	2.1
Curie temperature (°C)	140	395	225	600	470	450	940
Core losses at 10 kHz (W/kg)	70.0	250.0	4.0	28.7	200.0	50.0	400.0
Saturation magnetostriction (ppm)	-0.6	27.0	1.0	0.5	25.0	12.0	70.0

8.5.2 Dielectric Design

MV transformers that operate at high switching frequencies require dielectric compounds that can withstand high electric fields by having high electrical insulation values and also can have high thermal conductivity to aid in the dissipation of heat generated by losses in the transformers.

A special silicone compound material (filled silicone rubber) with high thermal conductivity and moderate dielectric dissipation factor has been demonstrated as the insulation material to reduce the dielectric loss and the hot spot temperature for an encapsulated transformer (Tuncer & Gubanski, 2000). This insulation material is vulnerable to partial discharge and wears out gradually if air bubbles or impurities exist in the gel. Therefore, vacuum pressure potting is typically used for transformers to minimize bubbles and impurities (Rothmund et al., 2019).

Zhang et al. (2019) explored the properties of different insulation materials—namely Kapton tape, insulation paper, and silicone gel—that are commonly used in designing MV transformers. As shown in Table 8.5, Kapton tape has a high dielectric strength from the adhesive polyimide film. However, the film has very low effective thickness, which needs multiple layers to achieve the required insulation voltage. This would introduce air between each tape layer, leading to partial discharge. However, insulation paper can withstand the high voltage with sufficient thickness. Nevertheless, wrapping the transformer with thick insulation is difficult. The last material, silicone gel, has the least dielectric strength, but vacuum pressure potting enables it to tolerate high voltage. It allows for standardized manufacturing and mass production of the transformer.

Table 8.5. Comparison of insulation materials (Zhang et al., 2019)

	Kapton tape with polyimide film	Insulation paper with polyester film	Silicone gel
Dielectric constant	~3.5–3.8	~4.1–5.2	~2.8–3.2
Dielectric strength	~150–300 kV/mm	~40–60 kV/mm	~20–30 kV/mm
Effective thickness	~1–5 mil	~2–20 mil	—

8.6 Communication

One common protocol is a combined charging system (CCS) for DC fast charging only as shown in Figure 8.15a. Here DC+ and DC− are directly connected to the battery cathode and anode, respectively. The Type 2, as shown in Figure 8.15b, can accommodate three-phase AC and DC fast charging. Here, the control pilot (CP) is a post-insertion signal pin. This pin is employed to signal the charging level between the car and the XFC and can be manipulated by the connected vehicle to initiate charging as well as other information. A 1 kHz square wave at ±12 V is generated by the XFC on the CP line to detect the presence of the vehicle, communicate the maximum allowable charging current, and control charging begin/end.

The proximity pilot (PP) is a pre-insertion signal pin. It provides a signal to the vehicle's control system so it can prevent movement while connected to the EVSE, and signals the latch release button to the vehicle. The protective earth (PE) is a full-current protective earthing system pin.

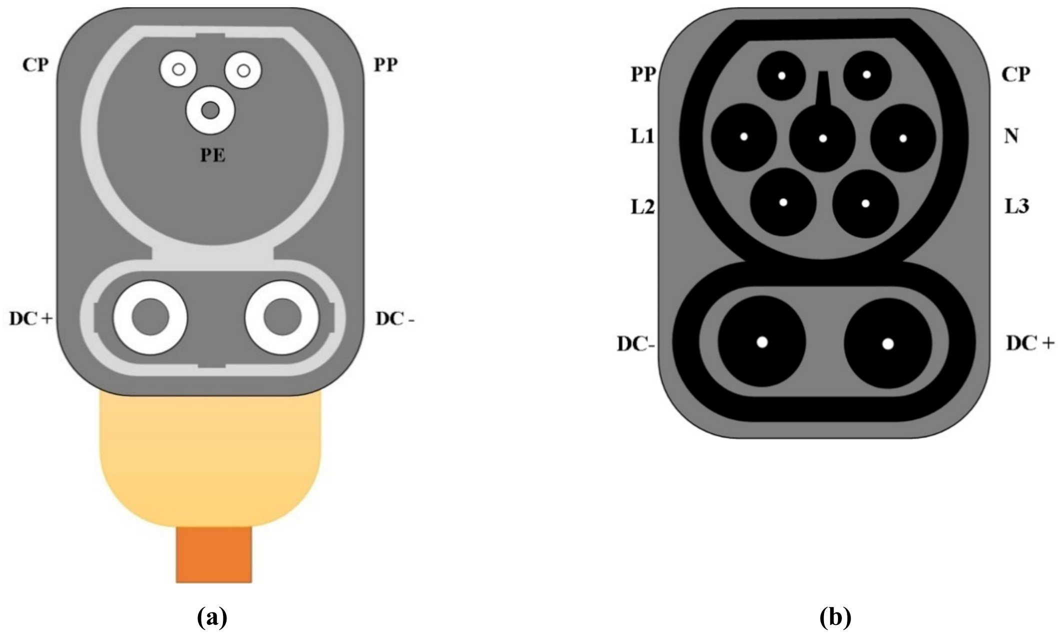


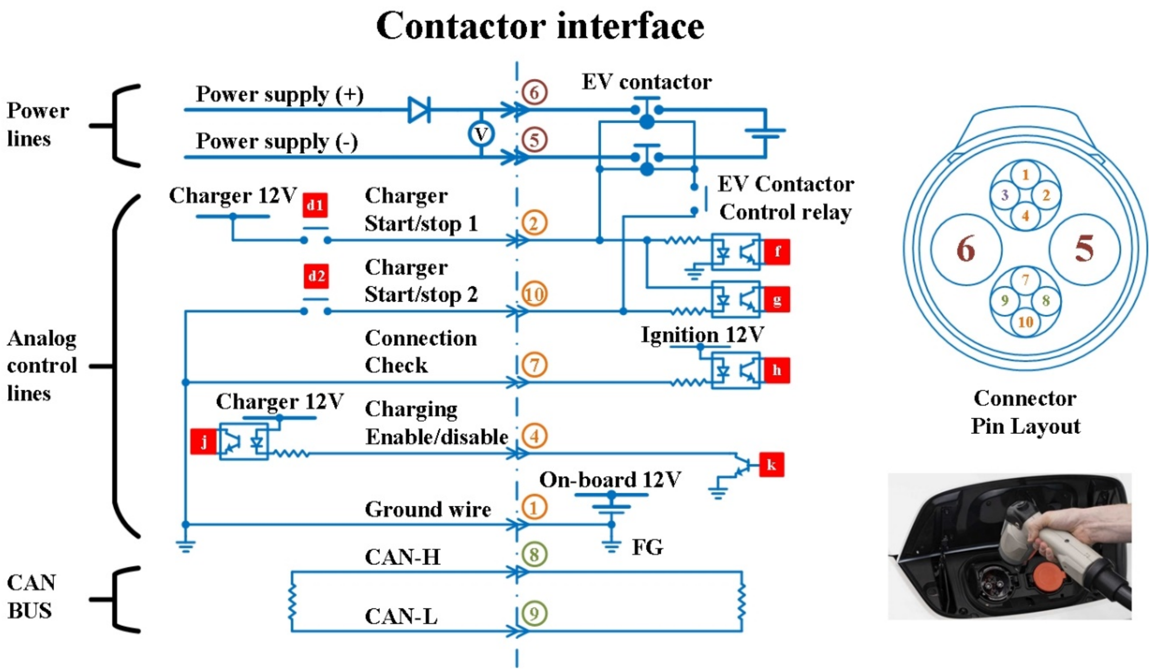
Figure 8.15. (a) CCS for DC charging only and (b) CCS for AC and DC charging (Combined Charging Systems, n.d.)

In addition to CCS, CHAdeMO (developed by CHAdeMO Association) is another popular fast charging standard for EVs, but only for DC XFC. Compared with CCS only employing three signal pins, CHAdeMO enables seamless communication between the car and the XFC. Detailed connector pin assignment is shown in Figure 8.16(a). Only Pins 5 and 6 are used to output high DC current. The other eight pins (1–4, 7–10) are employed for the communication between the connected EV and XFC. The detailed handshaking procedure is shown in Figure 8.16(b). All the communication is through a CAN.

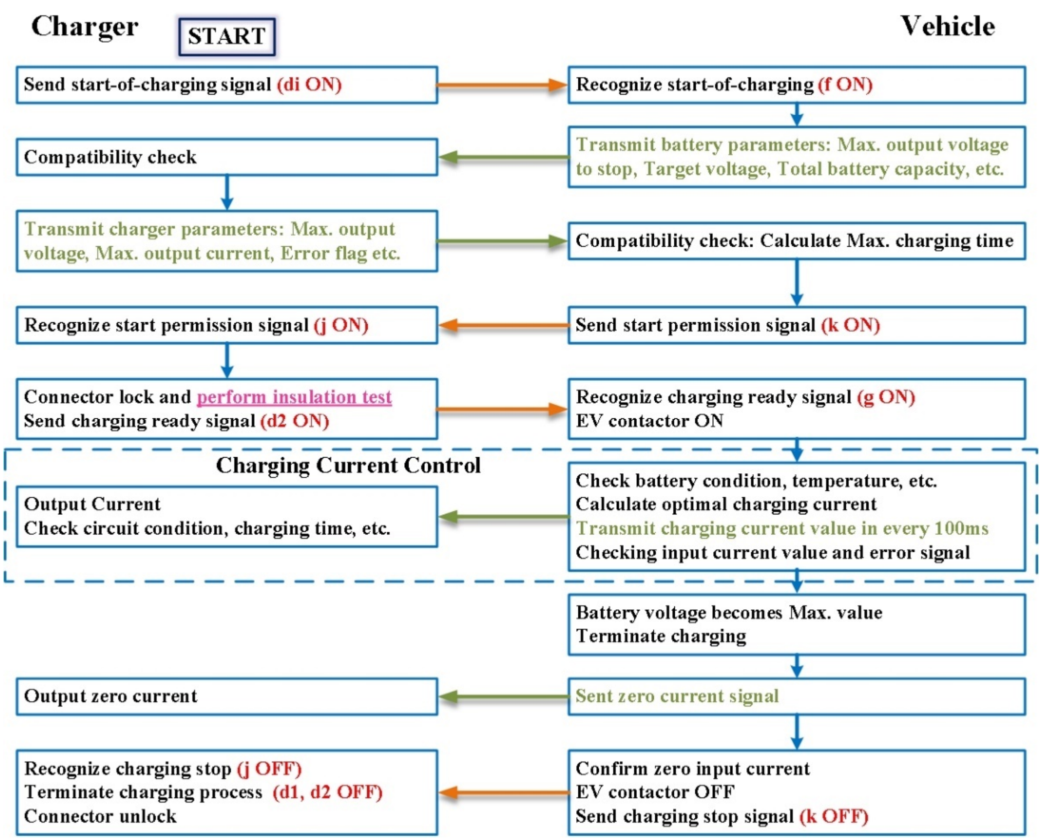
When plugged in, the XFC will turn on the relay d1 internally, generating 12 V on Pin 2, which makes the EV aware of the existence of the connected XFC. Through the CAN bus, the EV then sends the battery parameters (e.g., voltage and current ratings) to the XFC, which will check the compatibility. The XFC then sends the maximum charging voltage and current back to the EV for further confirmation.

Once confirmed, the EV grounds Pin 4 through an internal optical coupler, triggering the charging enable signal internal of XFC, which then grounds Pin 10, indicating the charging is ready. Given that the voltage difference between Pin 2 and Pin 10 is now 12 V, the EV internal charging control relay is then turned on, which closes the internal contactor. By this moment, all preparation for the charging is finished.

The EV then sends the required charging current to the XFC through the CAN bus, along with the battery status such as SOC, voltage, and temperature. When the vehicle control unit decides the end of charging, it sends zero current command to the XFC. Once zero current output is confirmed, the EV turns off the charging control contactor, which terminates the charging.



(a)



(b)

Figure 8.16. (a) CHAdeMO pin assignment (Jar et al., 2016) and (b) CHAdeMO handshaking protocol (Jar et al., 2016)

Other XFC protocols have been summarized by CHAdeMO as shown in Table 8.6 (China-Japan Joint Research Project, 2018).

Table 8.6. Comparison of EV XFC standards (China-Japan Joint Research Project, 2018)

	CHAdeMO	**GB/T**	**US-COMBO CCS1**	**EUR-COMBO CCS2**	**Tesla**
Connector					
Inlet					
	✓	✓	✓	✓	
					
	✓			✓	
	✓	✓	✓	✓	
		✓			
Protocol	CAN		PLC		CAN
Max spec power	400 kW 1,000×400	185 kW 750×250	200 kW 600×400	350 kW 900×400	?
Max market power	150 kW	50 kW	50 kW	350 kW	120 kW
First	2009	2013	2014	2013	2012

8.7 FMEA Methodology for Wired XFC Systems

FMEA is a commonly used tool for understanding and evaluating the potential issues of a system composed of multiple subcomponents. It acts as an aid for engineers and designers to identify the weak points in a system and helps in the development of safety tests that can be performed on prototype systems.

The FMEA methodology is based on the analysis of conceptual XFC systems—the exemplary design of an ISOP XFC station for two vehicles shown in Figure 8.8(b). For this conceptual system, the subsystems are identified and each subsystem is further broken down into individual components for the FMEA study. In addition to component analysis, the potential interaction between components and subsystems that may trigger certain failure modes are identified and considered for the system FMEA. For each component and subcomponent interaction, potential failure modes are listed and scored based on the likelihood and consequence of the failure. The score for each component and subcomponent interaction is then ranked based on the risk score, which is the multiplication of likelihood and consequence score.

In addition to the complete FMEA for the ISOP XFC topology, an analysis is also conducted for a three-phase PWM rectifier front-end shown in Figure 8.3(a) and for a DAB-isolated DC-DC converter shown in

Figure 8.5(c) as two additional sample subsystem topologies that show promise for being adopted in XFC systems.

8.8 Summary of FMEA Tables for Wired XFC Systems

The main takeaway from the FMEA for XFC systems is that during the design of these systems, a comprehensive systemic analysis is needed to consider all the failures and their effects on individual components and on coupled subsystems. Many of the failures can be mitigated through design, and the failures themselves can be quickly detected and isolated if sufficient sensing, monitoring, and control are incorporated into the systems. There are several suggested protection and mitigation strategies given in the following tables.

Most of the subsystems and sub-modules are not unique to XFC systems, and therefore, circuit design, control, and protection that have learned from other applications can be applied to XFC. Lessons learned in these other applications should reduce development time as well as provide a more robust, reliable circuit.

In power electronics, much of the protection depends on fast detection of a fault and then quickly isolating the fault through opening an electronic switch, relay, or circuit breaker. All the various possible fault modes need to be considered, and their quick mitigation (interruption) should be considered. Many times, the default protection is to open the main circuit breaker to interrupt power to the entire XFC system, so there is a high dependency on the main circuit breaker/relay to function when called upon.

One concern that needs more consideration in the design of XFC systems is what happens when a loss of load (the vehicle disconnects itself from the charger) occurs while the charger is providing a high charge rate (high power). This can lead to over-voltage issues in energy storage elements (DC-link capacitors), which is unique to XFC systems and needs to be fully considered in the design stage.

XFC designers should also consider the possibility of isolating local faults and the ability of the system to continue to charge a vehicle at a reduced charging capacity as opposed to completely shutting down the charging system. Modular, multilevel structures may more easily lend themselves to this capability.

Because these XFC systems will in many cases have local generation (PV, wind, fuel cells) and storage (battery) capabilities, they cannot be treated as a normal load; their effects on the grid and even perhaps their ability to help the grid when there are faults or LV conditions on other nearby parts of the grid must be fully considered. This will require considering local grid codes and working with the local utilities where XFC systems are planned to be installed.

9. References

Ahmad, A., Alam, M. S., Chabaan, R., & Mohamed, A. (2019, April 9-11). *Comparative analysis of power pad for wireless charging of electric vehicles* (SAE Technical Paper 2019-01-0865). Available at https://doi.org/10.4271/2019-01-0865. Paper delivered at the WCX World Congress Experience, Detroit, MI.

Batra, T., & Schaltz, E. (2015). Passive shielding effect on space profile of magnetic field emissions for wireless power transfer to vehicles, *Journal of Applied Physics, 117*(17).

Bai, H., Taylor, A., Guo, W., Szatmari-Voicu, G., Wang, N., Patterson, J., & Kane, J. (2012). Design of an 11 kW power factor correction and 10 kW ZVS DC/DC converter for a high-efficiency battery charger in electric vehicles. *IET Power Electronics*, *5*(9).

Billings, K., & Morey, T. (2011). *Switch mode power supply handbook* (third edition). McGraw Hill.

Bosshard, R. (2017). *Multi-objective optimization of inductive power transfer systems for EV charging*. ETH Zürich [*Eidgenössische Technische Hochschule Zürich*, Swiss Federal Institute of Technology, Zürich].

Bosshard, R., & Kolar, J. W. (2017). All-SiC 9.5 kW/dm3 on-board power electronics for 50 kW/85 kHz automotive IPT system, *IEEE Journal of Emerging and Selected Topics in Power Electronics, 5*(1).

Budhia, M., Boys, J. T., Covic, G. A., & Huang, C. Y. (2013). Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems. *IEEE Transactions on Industrial Electronics, 60*(1).

Campi, T., Cruciani, S., Maradei, F., & Feliziani, M. (2019, July 22-26). *Active coil system for magnetic field reduction in an automotive wireless power transfer system*. 2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC+SIPI), New Orleans, LA.

China-Japan Joint Research Project. (2018, November 30). *Super high power charging* (Web Page/PowerPoint). CHAdeMO Association. https://fpcj.jp/wp/wp-content/uploads/2018/11/Handout-CHAdeMO-briefing.pdf

Choi, S. Y., Gu, B. W., Lee, S. W., Lee, W. Y., Huh, J., & Rim, C. T. (2014). Generalized active EMF cancel methods for wireless electric vehicles, *IEEE Transactions on Power Electronics, 29*(11).

Combined Charging Systems. (n.d.) In Wikipedia. https://en.wikipedia.org/wiki/Combined_Charging_System

Chwei-Sen, W., Covic, G. A., & Stielau, O. H. (2004). Investigating an LCL load resonant inverter for inductive power transfer applications, *IEEE Transactions on Power Electronics, 19*(4).

Covic, G. A., & Boys, J. T. (2013). Modern trends in inductive power transfer for transportation applications, *IEEE Journal of Emerging and Selected Topics in Power Electronics, 1*(1.)

Electronic Concepts, Inc. (2021). *LH3 Series-Unlytic* (Web page). Available at www.ecicaps.com/film-capacitors/lh3-series-film-capacitor/

Everts, J., Krismer, F., Keybus, J., Driesen, J., & Kolar, J. (2013). Optimal ZVS modulation of single-phase single-stage bidirectional DAB AC-DC converters. *IEEE Transactions on Power Electronics*, 29(8).

Federal Communications Commission. (n.d.). *Equipment authorization – RF device* [Web page]. Available at www.fcc.gov/oet/ea/rfdevice

Foote, A., & Onar, O. C. (2017, June 22-24). *A review of high-power wireless power transfer.* IEEE Transportation and Electrification Conference and Expo (ITEC), Chicago.

Galigekere, V. P., Onar, O., Pries, J., Zou, S., Wang, Z., & Chinthavali, M. (2018, June 13-15). *Sensitivity analysis of primary-side LCC and secondary-side series compensated wireless charging system*. 2018 IEEE Transportation Electrification Conference and Expo (ITEC), Long Beach, CA. doi: 10.1109/ITEC.2018.8450163

Galigekere, V. P., Wiles, R., & Wilkins, J. (2018, June 13-15). *Design and implementation of an optimized 100 kW stationary wireless charging system for EV battery recharging*. 2018 IEEE Transportation Electrification Conference and Expo (ITEC), Long Beach, CA. doi: 10.1109/ECCE.2018.8557590

Gill, L., Ikari, T., Kai, T., Li, B., Ngo, K. & Dong, D. (2019, September 29-October 3). *Medium voltage dual active bridge using 3.3 kV SiC MOSFETs for EV charging application*. IEEE Energy Conversion Congress and Exposition, Baltimore, MD.

Goeldi, B., Tritschler, J., & Reichert, S. (2015, May 19-20). *Measurement results of a 22 kW bidirectional inductive charger*. Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany.

IEEE Standard 1547-2018, Interconnection & Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces (Revision of IEEE Standard 1547-2003), 2018. doi: 10.1109/IEEESTD.2018.8332112

International Commission on Non-Ionizing Radiation Protection. (2011). Guideline for limiting exposure to time-varying electric and magnetic fields (1Hz-100kHz). *Health Physics*, 99(6). doi: 10.1097/HP.0b013e3181f06c86. Erratum in: Health Physics, 2011 Jan;100(1):112. PMID: 21068601

International Electrotechnical Commission. (2021). *Electromagnetic compatibility* [Web page]. Available at www.iec.ch/emc/

Isler, S., Chaudhuri, T., Aguglia, D., & Bonnin, X. A. (2017, October 1-5). *Development of a 100 kW, 12.5 kV, 22 kHz and 30 kV insulated medium frequency transformer for compact and reliable medium voltage power conversion*. IEEE Energy Conversion Congress and Exposition, Cincinnati, OH.

Jar, B., Watson, N., & Miller, A. (2016, June 22-24). *Rapid EV chargers: Implementation of a charger.* EEA Conference & Exhibition, Wellington, NZ.

Jo, M., Sato, Y., Kaneko, Y., & Abe, S. (2014, september 14-18). *Methods for reducing leakage electric field of a wireless power transfer system for electric vehicles*. 2014 IEEE Energy

Conversion Congress and Exposition, Pittsburgh, PA. Available at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1052.6850&rep=rep1&type=pdf

Kasper, M., Chen, C.-W., Bortis, D., Kolar, J. W., & Deboy, G. (2015, March 15-19). *Hardware verification of a hyper-efficient (98%) and super-compact (2.2kW/dm3) isolated AC/DC telecom power supply module based on multi-cell converter approach*. 2015 IEEE Applied Power Electronics Conference and Exposition, Charlotte, NC.

Kim, S., Covic, G. A., & Boys, J. T. (2017). Tripolar pad for inductive power transfer systems for EV charging, *IEEE Transactions on Power Electronics, 32*(7).

Li, H. L., Hu, A. P., & Covic, G. A. (2012). A direct AC–AC converter for inductive power-transfer systems. *IEEE Transactions on Power Electronics, 27*(2).

Li, S., Li, W., Deng, J., Nguyen, T. D., & Mi, C. C. (2015). A double-sided LCC compensation network and its tuning method for wireless power transfer. *IEEE Transactions on Vehicular Technology, 64*(6.)

Liang, Z., Cirino, D. M., Jalalpour, M., & Bai, H. (2020). Deployment of a bidirectional MW-level electric-vehicle extreme fast charging station enabled by high-voltage SiC and intelligent control. *Energies*, *13*(7).

Lu, J., Zhu, G., Wang, H., Lu, F., Jiang, J., & Mi, C. C. (2019). Sensitivity analysis of inductive power transfer systems with voltage-fed compensation topologies, *IEEE Transactions on Vehicular Technology, 68*(5).

Lyons, B. J., Hayes, J. G., & Egan, M. G. (2007, February 25-March 1). *Magnetic material comparisons for high-current inductors in low-medium frequency DC-DC converters*. IEEE Applied Power Electronics Conference and Exposition, Anaheim, CA.

Matsumoto, H., Neba, Y., Iura, H., Tsutsumi, D., Ishizaka, K., & Itoh, R. (2014). Trifoliate three-phase contactless power transformer in case of winding-alignment. *IEEE Transactions on Industrial Electronics*, *61*(1).

Middlebrook, R. D. (1976, October 11-14). *Input filter considerations in design and application of switching regulators*. IEEE Industry Applications Society Annual Meeting, Chicago.

Miller, J. M., Jones, P. T., Li, J. M., & Onar, O. C. (2015). ORNL experience and challenges facing dynamic wireless power charging of EV's. *IEEE Circuits and Systems Magazine,* 15(2).

Miller, J. M., Onar, O. C., & Chinthavali, M., (2015). Primary-side power flow control of wireless power transfer for electric vehicle charging. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 3*(1).

Mohammad, M. (2019). *Optimization of inductive wireless charging systems for electric vehicles: minimizing magnetic losses and limiting electromagnetic field emissions*. (Thesis or dissertation). University of Akron. Available at https://etd.ohiolink.edu/

Mohammad, M., Pries, J., Onar, O., Galigekere, V. P., Su, G.-J., Anwar, S., Wilkins, J., Kavimandan, U. D., & Patil, D. (2019, March 17-21). *Design of an EMF suppressing magnetic shield for a 100-kW DD-coil wireless charging system for electric vehicles*. IEEE Applied Power Electronics Conference and Exposition, Anaheim, CA.

Mohammad, M., Wodajo, E., Choi, S., & Elbuluk, M. (2019, December). Modeling and design of passive shield to limit EMF emission and to minimize shield loss in unipolar wireless charging system for EV. *IEEE Transactions on Power Electronics, 34*(12). doi: 10.1109/TPEL.2019.2903788

Oak Ridge National Laboratory. (2018, October 19). *ORNL demonstrates 120-kilowatt wireless charging for vehicles* (Web press release). Available at www.ornl.gov/news/ornl-demonstrates-120-kilowatt-wireless-charging-vehicles

Onar, O. C., Chinthavali, M., Campbell, S. L., Seiber, L. E. White, C. P., & V. P. Galigekere, V. P., V. P. (2018, June 13-15). *Modeling, simulation, and experimental verification of a 20-kW series-series wireless power transfer system for a Toyota RAV4 electric vehicle*. 2018 IEEE Transportation Electrification Conference and Expo, Long Beach, CA.

Pries, J., Galigekere, V. P., Onar, O. C., & Su, G. (2019). A 50kW three–phase wireless power transfer system using bipolar windings & series resonant networks for rotating magnetic fields. *IEEE Transactions on Power Electronics, 35*(5).

Pries, J., Galigekere, V. P., Onar, O., Su, G.-J., Wiles, R., Seiber, L., Wilkins, J., Anwar, S., & Zou, S. (2018, September 23-27). *Coil power density optimization and trade-off study for a 100 kW electric vehicle IPT wireless charging system*. Energy Conversion Congress and Exposition, Portland, OR. doi: 10.1109/ECCE.2018.8557490

Rothmund, D., Guillod, T., Bortis, D. & Kolar, J. W. (2019). 99.1% efficient 10 kV SiC-based medium-voltage ZVS bidirectional single-phase PFC AC/DC stage. *IEEE Journal of Emerging and Selected Topics in Power Electronics, 7*(2),

Samanta, S., & Rathore, A. K. (2015). A new current-fed CLC transmitter and LC receiver topology for inductive wireless power transfer application: Analysis, design, and experimental results. *IEEE Transactions on Transportation Electrification, 1*(4).

Samanta, S., Rathore, A. K., & Thrimawithana, D. J. (2017). Bidirectional current-fed half-bridge (C) (LC)–(LC) configuration for inductive wireless power transfer system. *IEEE Transactions on Industry Applications, 53*(4, 2017.

SAE Standard J2954: Wireless power transfer for light-duty plug-in/electric vehicles and alignment methodology, 2016. SAE International.

Schneider, J., Carlson, R., Sirota, J., Sutton, R., Taha, E., Kesler, M., Kamichi, K., Teerlinck, I., Abeta, H., Minagawa, Y., Yazaki, S., Yoon, U., Kawashima, K., Muskett, S., Bohn, T., Mathar, S., Mikat, D., Guag, J., Seidman, S., & Reitan, R. (2019). *Validation of wireless power transfer up to 11kW based on SAE J2954 with bench and vehicle testing* (SAE Technical Paper 2019-01-0868). SAE International. https://doi.org/10.4271/2019-01-0868

Shinohara, N. (2013, January 20-23). *Wireless power transmission progress for electric vehicle in Japan*. 2013 IEEE Radio and Wireless Symposium, Austin, TX.

Taylor, A., Liu, G., Bai, H., Brown, A., Johnson, P.M., & McAmmond, M. (2018). Multiple-phase-shift control for a dual active bridge to secure zero-voltage switching and enhance the light-load performance, *IEEE Transactions on Power Electronics*, *33*(6), Tu, H., Feng, H., Srdic, S., & Lukic, S. (2019). Extreme fast charging of electric vehicles: A technology overview. *IEEE Transactions on Transportation Electrification*, *5*(4).

Tuncer, E., & Gubanski, S. M. (2000, February 28). Electrical properties of filled silicone rubber. *Journal of Physics: Condensed Matter, 12*(8).

VCCI Council. (n.d.). *What is VCCI? Electromagnetic disturbance and VCCI* [Web page]. Avialable at http://www.vcci.jp/english/general/introduction.html

Wu, H. H., & Masquelier, M. P. (2015, June 14-17). *An overview of a 50kW inductive charging system for electric buses*. 2015 IEEE Transportation Electrification Conference and Expo, Dearborn, MI.

Xu, Z., Li, X., Zhao, X., Zhang, M. H., & Wang, Z. (2017). DSRC versus 4G-LTE for connected vehicle applications: A study on field experiments of vehicular communication performance. *Journal of Advanced Transportation*.

Yan, Y., Bai, H., Foote, A. & Wang, W. (2020). Securing full-power-range zero voltage switching in both steady-state and transient operations for a dual active bridge based bidirectional electric vehicle charger. *IEEE Transactions on Power Electronics*, *35*(7),

Zhang, L., Ji, S., Gu, S., Huang, X., Palmer, J., Giewont, W., Wang, F., & Tolbert, L. M. (2019, March 17-21). *Design considerations of high-voltage-insulated gate drive power supply for 10 kV SiC MOSFET in medium-voltage application*. 2019 IEEE Applied Power Electronics Conference and Exposition, Anaheim, CA.

Zhu, C. (2019, June 13). High-efficiency medium-voltage-input, solid-state-transformer-based 400-kW/1000-V/400-A extreme fast charger for electric vehicles [Web page PowerPoint]. Delta Electronics (Americas) Ltd. Available at www.energy.gov/sites/prod/files/2019/06/f64/elt241_zhu_2019_o_4.24_9.31pm_jl.pdf

10. FMEA Worksheets

10.1 Static Wireless Charger (3.3–22 KW) Concept System, Subsystem, and Components

Table 10.1. FMEA worksheet for light-duty static wireless charger (3.3–22 kW) concept system, subsystem, and components

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A. Grid interface subsystem											
A.1.	Common-mode choke	Multi-turn common-mode inductor made of toroidal core and Litz wire usually	Filter inductor for conductive and differential emissions	High voltage insulation breakdown	• Over voltage operation due to grid surge, voltage sag, transient, and so on • Mechanical deformation • Improper manufacturing design • Over temperature • Aging of insulation	1	• Insulation breakdown between windings might cause electrical arc • Significant damage such as fire with the other components and subsystems • Increase high current at the grid and power losses at the PFC • Increase of conductive and differential emissions • User electrical and thermal safety hazard and excessive energy exposure	4	4	• Current and temperature sensors • Electrical and mechanical design requirements • Safety and quality operating conditions • Shielded enclosure to limit user access	
				Electrical open circuit	• Over temperature and breakdown winding • Mechanical failure (e.g., break of winding, disconnect from the circuit board) • Over pressure during manufacturing of windings	1	• Open circuit between live terminals might cause an electrical arc and over voltage • Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	4	4	• Current, temperature, and voltage sensors • Electrical and mechanical design requirements • Safety and quality operating conditions	
				Electrical short circuit	• Improper manufacturing electrical or mechanical design • High voltage breakdown of insulation wire • Improper isolation clearance between active wires	1	• Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • Increase high current at the grid and power losses at the PFC	4	4	• Current, temperature, and voltage sensors • Electrical and mechanical design requirements • Safety and quality operating conditions	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• High temperature across the winding leading to insulation degradation		• Increase of conductive and differential emissions, • User safety hazard and energy exposure				
				High temperature	• High core losses due to improper design • Degraded electrical property of core material • Conductivity degradation of wire • High conduction losses due to high current • Improper thermal management and design • Excessively high ambient temperature (e.g., operating outside recommended operating range)	1	• High temperature might break the winding insulation and increase the possibility of short between turns and windings • Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • Increase high current at the grid and power losses at the PFC • Increase of conductive and differential emission • User safety hazard and excessive energy exposure	4	4	• Current, voltage, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Mechanical failure	• Crash-induced mechanical failure • Degradation due to external factors (e.g., temperature, humidity, water, air pressure) • Aging of electrical and mechanical components • Excessive vibration due to transportation and mounting • Fragile components subject to mechanical shocks (e.g., crash, vibration, collapse, drop off)	1	• Mechanical damage • Potential short circuit • Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • Increase high current at the grid and power losses at the PFC • Increase of conductive and differential emissions • User safety hazard and energy exposure	4	4	• Current, voltage, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper assembly and soldering during manufacturing • Improper mechanical design						
				Component performance degradation	• High over temperature • Mechanical breakdown • Insulation failure • Core saturation • High voltage breakdown • Reduced current, voltage, and power handling capability	1	• Conductivity degradation might cause increased and power losses • Core saturation may lead to excessive current at grid • Increase high current at the grid and power losses at the PFC • Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and excessive energy exposure	4	4	• Current, voltage, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing • Lifetime assessment and estimation during the design stage	
A.2.	Y capacitor	Film or ceramic capacitor	Filter capacitor for common-mode emission	High temperature	• High ripple current • Improper design, placement, and assembly • Improper capacitor derating during the design stage	1	• High temperature might cause derating, short, open circuit, reduced lifetime, and so on • Improper functionality and damage to other components and subsystems • Electrical and thermal safety hazard • Increased ripple current and power losses • Increase of conductive and differential emissions • User safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical open circuit	• Over voltage failure due to oscillations between active phases and ground	1	• Improper functionality of the filtering	3	3	• Voltage, current, and temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Over temperature • High ripple current • Mechanical failure (e.g., solder crack, disconnect from the board) • Improper soldering and assembly during manufacturing • Improper capacitor derating during the design stage		• Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard			• Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical short circuit	• Over voltage failure due to oscillations between active phases and ground • Over temperature • Mechanical failure • Improper design due to improper voltage clearance • High ripple current • Pressure, water exposure, humidity, and so on • Improper capacitor derating during the design stage	1	• Improper functionality of the filtering • Damage to the other components and subsystems • Increase ground currents • Electrical and thermal safety hazard • Increased ripple current and power losses • Increase of conductive and differential emission • User safety hazard	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure • Degradation due to external factors (e.g., temperature, humidity, water, air pressure) • Aging of electrical and mechanical components • Excessive vibration due to transportation and mounting • Fragile components subject to mechanical shocks (e.g., crash, vibration, collapse, drop off)	1	• Mechanical broken of the component • Improper functionality of the system • Damage to the components and subsystems • Electrical and thermal safety hazard • Increased ripple current and power losses • Increase of conductive and differential emissions • User safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper assembly and soldering during manufacturing • Improper mechanical design						
A.3.	X capacitor	Film capacitor	Filter capacitor for differential mode emission	High temperature	• High voltage • High ripple current • Improper capacitor derating during the design stage • Improper design	1	• High temperature might cause reduced performance, short, open circuit, and so on • Improper functionality and damage to other components and subsystems • Electrical and thermal safety hazard • Increased ripple current and power losses • Increase of conductive and differential emission • User safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical open circuit	• Excessive voltage due to grid voltage sag, surges, and so on • Over temperature • High ripple current • Mechanical failure • Improper soldering and assembly during manufacturing • Improper capacitor derating during the design stage	1	• Improper functionality of the filtering • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical short circuit	• Over temperature • Mechanical failure, • Improper design due to improper voltage clearance on the board • High ripple current • Pressure, water, humidity, and so on	1	• Improper functionality of the filtering • Damage to the other components and subsystems • Electrical and thermal safety hazard • Increased ripple current and power losses	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper capacitor derating during the design stage		• Increase of conductive and differential emissions • User safety hazard				
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure • Degradation due to external factors (e.g., temperature, humidity, water, air pressure) • Aging of electrical and mechanical components • Excessive vibration due to transportation and mounting • Improper assembly and soldering during manufacturing	1	• Physical damage to the component • Improper functionality of the system • Damage to the components and subsystems • Electrical and thermal safety hazard • Increased ripple current and power losses • Increase of conductive and differential emissions • User safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.4.	Shielding for EMI filter of the system	Aluminum or copper cover plate or housing	Absorbs and suppresses high-frequency EMFs for EMI filter circuit	Mechanical aging and deformation	• Extreme temperature • Mechanical stress • Environmental conductions humidity, water, air pressure, and so on • Improper mechanical design and installation • Crash-induced damages • Excessive vibration during transportation and operation, and so on	1	• Mechanical deformation • Malfunctioning of the filter, and increase of conductive and differential emissions • Damage to the other components and subsystems • Electrical and user safety hazard	3	3	• Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				High temperature	• Improper thermal management • Excessive loss on the shield due to high density eddy currents	1	• Increase the temperature of other components • Electrical and thermal safety hazard • Increased power losses • Increase of conductive and differential emissions	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• User safety hazard due to high temperature exposure				
				Electrical short circuit	• Contact to electrically live terminals and components • Crash-induced damages • Mechanical aging and deformation	1	• Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • Increased current and power losses • Increase of conductive and differential emissions • User safety hazard and excessive energy exposure	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Excessive emissions and loss in the shield	• Mechanical breakdown, deformation, or crack in the shield • Improper design • Improper mechanical design and installation • High eddy current loss in shield	1	• Malfunctioning of the filter and increase of conductive and differential emissions • Damage to other components and subsystems • Increased current and power losses • Electrical and user safety hazard • Increased ambient temperature for other components • Electrical and thermal safety hazard	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.5.	Fuse	Low melting lead or zinc	Circuit current protection for high current conditions	Short circuit	• Does not function • Wrong type fuse selection • Manufacturing design error • Mechanical failure due to improper assembly or soldering	1	• Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	3	3	• Using electronic fuse • High voltage and current protection • The input relay contactor in front stage with the fault signal • Temperature sensors • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality operating conditions	
A.6.	Contactor	Relay circuit with operating switches	Connects the system to the grid and energize the subsystem	Short circuit	• Does not function • Manufacturing design error • Mechanical failure due to improper assembly or soldering	1	• Damage with the other components and subsystems when the failure happens • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection, • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.7.	Soft start circuit	Electronic circuit charging the DC link capacitor slowly through analog and digital circuits	Ramping the DC Link voltage gradually to avoid grid instabilities and transients	Short circuit (not working properly)	• Crash-induced mechanical failure • Improper design during manufacturing • Functionality is broken • Exposure to temperature, humidity, water, air pressure, and so on • Improper assembly and soldering during manufacturing	1	• High voltage and current spikes during startup • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.8.	Filter inductor	Multi-turn inductor	Filter inductor for high-frequency ripples on the grid side	High voltage insulation breakdown	• Over voltage due to problems in the grid such as surge, voltage sag, transients, and so on • Mechanical deformation (e.g., crash-induced damages) • Improper mechanical design and installation • Over temperature	1	• Insulation breakdown between windings might cause electrical arc and short circuit • Significant damage to the other components and subsystems • Electrical and thermal safety hazard • Increased current and power losses • Damage to functionality of filtering and not complying with grid requirements • User safety hazard and energy exposure	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical open circuit	• Over temperature and breakdown winding • Mechanical failure	1	• Open circuit between active energy probes • Damage to the functionality of the	3	3	• Voltage, current, and temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper assembly and soldering during manufacturing • Improper mechanical design		filter system, and other components and subsystems • Electrical safety hazard • User safety hazard			• Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical short circuit	• Improper manufacturing and design for electrical or mechanical requirements • High voltage breakdown of the wire insulation • Improper isolation clearance between the wires	1	• Damage to the functionality of the filter system, and other components and subsystems • Electrical and thermal safety hazard • Increased high current and power losses • User safety hazard and energy exposure	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				High temperature	• High core losses due to improper design • Degraded electrical property of the core material • High conduction losses due to high current and/or conductivity degradation of wire • Improper thermal design	1	• High temperature might break the wire insulation and increase the possibility of short circuit between windings • Damage to the functionality of the filter system, and other components and subsystems • Electrical and thermal safety hazard • Increased high current and power losses, • User safety hazard	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Mechanical failure	• Crash-induced mechanical failure • Degradation due to external factors (e.g., temperature, humidity, water, air pressure) • Aging of electrical and mechanical components • Excessive vibration due to transportation and mounting	1	• Mechanical damage • Short circuit • Damage grid filtering functionality and EMI filtering • Electrical and thermal safety hazard • Increased current and power losses • User safety hazard	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper assembly and soldering during manufacturing						
A.9.	Filter capacitor	Film capacitor	Filter capacitor for high-frequency ripples on the grid side	Capacitor short circuit	• Excessive voltage and current stresses • High power losses and heat dissipation across the capacitor, which may lead to dielectric failure depending on capacitor properties • Aging of the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Improper design during manufacturing	1	• The input of PFC will be shorted, resulting high current in the front stage and EMI filter • Break the functionality of EMI with the other component and subsystems • High power losses at the front stage • High temperature in the components • Electrical and thermal safety hazard • User safety hazard	4	4	• High voltage and current protection in front of the system • The input relay contactor in front stage with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Capacitor open circuit	• Excessive voltage and current stresses across the capacitor • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors and lifetime • Improper design during manufacturing	1	• Damage to the functionality of the grid requirements and EMI filtering • High power losses and temperature due to high ripple current • Damage with the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	2	2	• High voltage and current protection • The input relay contactor in front of the system for disconnection from the grid • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				High temperature	• Excessive voltage and current stresses across the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors and lifetime • Improper design during manufacturing	1	• High power losses at the front stage • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	4	4	• High voltage and current protection • The input relay contactor in front of the system for disconnection from the grid • Temperature sensors • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing	
A.10.	Rectifier module	Power module formed by housing and semiconductor diodes.	Rectifies AC voltage coming from the grid and forms DC voltage at the output.	One diode in the module shorted	• High voltage and current stresses on the rectifier module • High power losses • Over temperature • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, water flooding, pressure, humidity, and so on • Improper design during manufacturing	2	• The input AC grid half cycle will be shorted, resulting high current in the rectifier module • It might damage the rectifier module • Break the functionality of the PFC • Excessive power losses in the rectifier module • High temperature in the rectifier module • Electrical and thermal safety hazard • User safety hazard and energy exposure	3	6	• High voltage and current protection at the input of rectifier module • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Both diodes in the module shorted	• High voltage and current stresses on the rectifier module • High power losses • Over temperature • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, water flooding, pressure, humidity, and so on • Improper design during manufacturing	2	• The input AC grid will be shorted, resulting high current in the rectifier module • Might damage the rectifier module • Break the functionality of PFC • High power losses in the rectifier module • High temperature in the rectifier module • DC link component failures due to short of the DC link terminals • Electrical and thermal safety hazard • User safety hazard and energy exposure	3	6	• High voltage and current protection at the input of rectifier module • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				One diode in the module is open circuit	• Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors	1	• The input AC grid half cycle will be open • Break the functionality of PFC	3	3	• High voltage and current protection in front of rectifier module	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design during manufacturing		• Reduced DC link voltage due to limited rectification capability • User safety hazard			• The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Both diodes in the module are open circuit	• Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors • Improper design during manufacturing	1	• Open circuit to the output • System will stop working and stop functionality of the system	3	3	• High voltage and current protection in front of rectifier module • The input relay contactor in front of PFC turning off with the fault signal • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				High temperature	• Excessive voltage and current stresses across the rectifier module • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors • Improper design during manufacturing	1	• High power losses in the rectifier module • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• High voltage and current protection • The input relay contactor in front of rectifier module turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.11.	DC link capacitor	Film or electrolytic	Filtering capacitor for DC link ripple voltages after rectification	Capacitor short circuit	• Excessive voltage and current stresses • High power losses and heat dissipation across the capacitor, which may translate in	1	• The output of rectifier will be shorted, resulting high current in the rectifier module	4	4	• High voltage and current protection at the output of the rectifier • The input relay contactor in front of	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					dielectric failure depending on capacitor properties • Aging of the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Improper design during manufacturing		• Might damage the rectifier module due to excessive energy • Break the functionality of PFC and the overall system • High energy dissipation across the rectifier module • High temperature in the rectifier module, • Electrical and thermal safety hazard • User safety hazard and energy exposure			PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Capacitor open circuit	• Excessive voltage and current stresses across the capacitor • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors • Improper design during manufacturing	1	• High voltage ripple at the DC link • Might damage the functionality of the PFC • High power losses and temperature in the PFC • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	2	2	• High voltage and current protection at the output of the rectifier • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				High temperature	• Excessive voltage and current stresses across the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors • Improper design during manufacturing	1	• High power losses in the rectifier module due to increased resistance in the capacitor • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• High voltage and current protection • The input relay contactor in front of rectifier module turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										Proper derating during capacitor selection	
A.12.	Heat sink	Heat sink structure made from aluminum or copper and uses air or liquid for heat transfer	Transfers the heat from power modules used in PFC and rectifier to the coolant	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit • Improper design during manufacturing	1	• Temperature control disrupted • Lead to excessive heating of the electronic active and passive components • Increased power loss across components • Damage to the other components and subsystems	4	4	• Temperature sensors to protect overheating • The input relay contactor in front of PFC turning off with the thermal fault signal • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Failure of the coolant pump	• Electrical failure of the pump motor • Mechanical failure of the pump motor	2	• Temperature control disrupted • Lead to excessive heating of the electronic active and passive components • Increased power loss across components • Damage to the other components and subsystems	2	4	• Temperature sensors to protect from overheat • The input relay contactor in front of PFC turning off with the thermal fault signal • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit • The properties of the coolant fluid is not adequate for the operating conditions • Aging of the fluid • Lack of filter maintenance and care	2	• Temperature control disrupted • Lead to excessive heating of the electronic active and passive components • Increased power loss across components • Damage to the other components and subsystems	2	4	• Temperature sensors to protect from overheat • The input relay contactor in front of PFC turning off with the thermal fault signal • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Poor performance of the thermal	• Mechanical stress and strain due to thermal cycling	2	• Temperature control disrupted	2	4	• Temperature sensors to protect from overheat	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				interface material between the power module and cold plate	• Improper material selection during the design stage • Degradation of material properties due to aging		• Lead to excessive heating of the electronic active and passive components • Cause to increase in power losses • Damage with the other components and subsystems			• The input relay contactor in front of PFC turning off with the thermal fault signal • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.13.	Boost inductor	Multi-turn winding inductor made by Litz wire	Part of the PFC system for boosting rectified grid voltage to the desired output voltage	High voltage insulation breakdown	• Over voltage due to problems in the grid such as surge, voltage sag, transient, and so on • Mechanical deformation • Improper manufacturing design • Over temperature	1	• Insulation breakdown between windings might cause electrical short circuit • Significant damage such as fire with the other components and subsystems • Electrical and thermal safety hazard • Increased current and power losses • Increase of conductive and differential emissions • User safety hazard and energy exposure	4	4	• Current, voltage, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical open circuit	• Over temperature and breakdown winding • Mechanical failure • Improper assembly and soldering during manufacturing • Improper mechanical design	1	• Damage to the functionality of the filter system, and other components and subsystems • Electrical and thermal safety hazard • Increased high current and power losses • User safety hazard and energy exposure • Damage functionality of PFC circuit	3	3	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Electrical short circuit	• Improper manufacturing and design for electrical or mechanical requirements	1	• Damage to the functionality of the filter system, and other components and subsystems	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• High voltage breakdown of the wire insulation • Improper isolation clearance between the wires		• Dame PFC power module due to very high current demand • Electrical and thermal safety hazard • Increased high current and power losses • User safety hazard and energy exposure			• Safety and quality control during manufacturing	
				High temperature	• High core losses due to improper design • Degraded electrical property of the core material • High conduction losses due to high current and/or conductivity degradation of wire • Improper thermal design	1	• High temperature might break the wire insulation and increase the possibility of short circuit between windings • Damage to the functionality of the filter system, and other components and subsystems • Electrical and thermal safety hazard • Increased high current and power losses • User safety hazard	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Mechanical failure	• Crash-induced mechanical failure • Degradation due to external factors (e.g., temperature, humidity, water, air pressure) • Aging of electrical and mechanical components • Excessive vibration due to transportation and mounting • Improper assembly and soldering during manufacturing	1	• Mechanical damage • Short circuit • Damage PFC functionality and boosting function • Electrical and thermal safety hazard • Increased current and power losses • User safety hazard	4	4	• Voltage, current, and temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.14.	IGBT power module	Insulated gate bipolar transistor	PFC system switching power module	Power module short circuit (lower FET)	• Excessive voltage and current stresses across the power module • Gate driver output pulled high due to	2	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and	4	8	• Short circuit protection in gate driver	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					noise, failure, and so on • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, water flooding, pressure, humidity, and so on • Improper design during manufacturing		damage power module • Inductor saturation due to high current • High power losses in the inductor and switch power module • High temperature in the PFC inductor and switch power module • Damage in front of PFC components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure			• High voltage protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Power module short circuit (upper FET)	• Excessive voltage and current stresses across the power module • Gate driver output pulled high due to noise, failure, and so on • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, water flooding, pressure, humidity, and so on • Improper design during manufacturing	2	• The output voltage across the capacitor will be shorted when the switch power module is conduction, resulting in high currents into the switch power module • High power losses in the switch power module • High temperature in the switch power module • Damage in PFC and components and subsystems • Electrical and thermal safety hazard • User safety hazard and excessive energy exposure	4	8	• DESAT protection in gate driver • High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Power module open circuit (Lower FET)	• Excessive voltage and current stresses across the switch module • Gate driver output pulled low due to noise, failure, and so on	2	• PFC Inductor might be saturated • High temperature in the inductor • Electrical and thermal safety hazard • User safety hazard and energy exposure	3	6	• High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, water flooding, pressure, humidity, and so on • Improper design during manufacturing					• Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Power module open circuit (Upper FET)	• Excessive voltage and current stresses across the switch module • Gate driver output pulled low due to noise, failure, and so on • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors, and so on • Improper design during manufacturing	2	• Open circuit to the output • Zero voltage in the output • The system controllability will be saturated threshing up the PWM control limits. This will cause high current in the lower FET and PFC inductor	3	6	• High voltage and current protections • The input relay contactor in front of PFC turning off with the fault signal • Electrical and mechanical design requirements	
				High temperature	• Excessive voltage and current stresses across the switch module • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, factors, and so on • Improper design during manufacturing • Degradation of thermal performance of the power module due to thermal and power cycling over time	1	• High power losses in the inductor and switch power module • Damage with the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and excessive energy exposure	4	4	• High voltage and current protection • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing • Degradation monitoring of the module on a regular basis	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.15.	Gate driver	Provides an isolation from the microcontroller signal pulse to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the power module switches	Controls turn on and turn off of the power switches in the power module for PFC	Output of gate driver constant high	• Analog/digital circuitry failure • Mechanical assembly failure • PCB circuit failure • Improper circuit design	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module • Inductor saturation due to high current • High power losses in the inductor and power module • High temperature in the inductor and power module • Damage in front of PFC components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• Short circuit protection in gate driver • High voltage protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Output of gate driver constant low	• Analog/digital circuitry failure • Gate driver isolated power supply failure • Mechanical assembly failure • PCB circuit failure • Improper circuit design	1	• Inductor might be saturated • High temperature in the inductor • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure • Mechanical assembly failure • PCB circuit failure • Faulty circuit design	2	• No protection of the switches during short circuit • Excessive currents during short circuit • Damage the power module during short • Inductor saturation due to high current	4	8	• High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• High power losses in the inductor and switch power module • High temperature in the inductor and switch power module • Damage in front of PFC components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure			• Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.16.	Capacitor	Film or electrolytic capacitor	PFC output capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage and current stresses • High power losses and heat dissipation across the capacitor, which may translate in dielectric failure depending on capacitor property • Aging of the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Improper design during manufacturing	1	• The output of rectifier will be shorted, resulting high current in the PFC • Might damage the PFC power module • High power losses in the PFC • High temperature in the PFC • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Capacitor open circuit	• Excessive voltage and current stresses across the capacitor • Excessive heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors, and so on • Improper design during manufacturing	1	• Ripple at the output of the PFC will appear at the input of WPT high-frequency inverter • Might damage the functionality of the WPT system • High power losses and temperature in the WPT system • Damage to the other components and subsystems • Electrical and thermal safety hazard	2	2	• High voltage and current protection in front of PFC • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing • Adequate voltage derating during the design stage	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• User safety hazard and excessive energy exposure				
				High temperature	• Excessive voltage and current stresses across capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Aging, factors, and so on • Improper design during manufacturing	1	• High power losses in the PFC • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• High voltage and current protection • The input relay contactor in front of PFC turning off with the fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.17.	Grid voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for PFC controller and protection	Out of calibration	• Aging, factors, and so on • Water flooding, pressure, humidity, and so on • Excessive heat dissipation due to inaccurate circuit design and component tolerance changes	1	• Might damage the PFC • Break the functionality of PFC • High power losses in the PFC • High temperature in the PFC • Electrical safety hazard • User safety hazard	3	3	• Calibration is conducted or validated periodically • MCU calibration reset in each cycle due to malfunction and so on • High voltage protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to sag, transient, and so on • Analog/digital circuitry failure • Water flooding, pressure, humidity, and so on • Improper design during manufacturing • PCB circuit design failure	1	• Might damage the PFC • Break the functionality of PFC • High power losses in the PFC • High temperature in the PFC • Electrical safety hazard • User safety hazard	4	4	• High voltage protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing						
A.18.	Grid current sensor	Electronic analog to digital circuit	Measures the grid current for PFC controller and protection	Out of calibration	• Aging, factors, and so on • Water flooding, pressure, humidity, and so on • Excessive heat dissipation due to inaccurate circuit design and component tolerance changes	1	• Might damage the PFC • Break the functionality of PFC • High power losses in the PFC • High temperature in the PFC • Damage with the other components and subsystems • Electrical safety hazard • User safety hazard	3	3	• Calibration is conducted or validated periodically • MCU calibration reset in each cycle due to malfunction and so on • High current protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive current at the grid side due to inrush, transient, and so on • Analog/digital circuitry failure • Water flooding, pressure, humidity, and so on • Improper design during manufacturing • PCB circuit design failure • Mechanical failure due to improper assembly or soldering during manufacturing	1	• Might damage the PFC • Break the functionality of PFC • High power losses in the PFC • High temperature in the PFC • Damage to the other components and subsystems • Electrical safety hazard • User safety hazard	4	4	• High current protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
A.19.	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in PFC	Out of calibration	• Aging, factors, and so on • Water flooding, pressure, humidity, and so on • Excessive heat dissipation due to inaccurate circuit	1	• Overheating of critical components in PFC • Electrical safety hazard • User safety hazard	3	3	• Calibration is conducted or validated periodically • MCU calibration reset in each cycle due to malfunction and so on	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					design and component tolerance changes					• High voltage and current protection sensors, • Additional, redundant temperature are used sensors at different locations, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure • Water flooding, pressure, humidity, and so on • Improper soldering, placement, or error during manufacturing • Mechanical failure due to improper assembly or soldering during manufacturing	1	• Might damage with other components and subsystems • Electrical safety hazard • User safety hazard	4	4	• High voltage and current protection sensors • Additional multiple temperature sensors with the different locations • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
B. High-frequency inverter											
A.20.	Semiconductor power module (generally MOSFETs)	Silicon carbide MOSFETs	Converts the DC voltage to high-frequency square or quasi-square AC voltage	One switch in the module shorted	• Excessive voltage, current and power stress across switch. • Gate driver output pulled high • Excessive heat dissipation, • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging, water flooding, pressure, humidity, and so on, • Improper design during manufacturing.	2	• The DC voltage at inverter input is periodically shorted when the complementary switch turns ON resulting in high input currents • High power losses in the inductor and switch power module, • High temperature in the PFC inductor and switch power module, • DC link capacitor is shorted when the complementary switch is turned on	3	6	Short circuit protection in gate driver turns OFF the complementary switch	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Electrical and thermal safety hazard, • User safety hazard and energy exposure.				
				Both switches in the module shorted	• Excessive voltage, current and power stress across the module • Gate driver output pulled high for both switches • Excessive heat dissipation, • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging, water flooding, pressure, humidity, and so on, • Improper design during manufacturing.	2	• The DC voltage at inverter input is permanently shorted resulting in high input currents • DC link capacitor can be damaged due to high inrush current • High temperature in the power module, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.	3	6	• The input relay-contactor turns OFF • Current/voltage sensors communicates fault to upstream PFC • Short circuit protection in gate driver turns OFF the module entirely	
				One module is open circuited	• Excessive heat dissipation • Mechanical failure	1	• No power flow to the GA coil or VA unit	3	3	• Fault communicated by dedicated voltage and current sensors to the battery management system (BMS), gate-driver and upstream PFC • The input relay contactor in front of inverter turning off with the fault signal	
				Both modules are open circuited	• Excessive heat dissipation • Mechanical failure	1	• No power flow to GA coil or VA unit	3	3	Fault communicated by dedicated sensors and also from the BMS	
A.21.	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse	Controls the turn-on and turn-off of the switches in the power modules of the inverter bridge on the GA side assembly	Output of Gate driver constant high	• Analog circuitry failure • Mechanical/pcb failure	2	• The DC voltage at inverter input is shorted resulting in high input currents thereby damaging the MOSFET switches and the module • DC link capacitor can be damaged due to high inrush current	3	6	• The input relay-contactor turns OFF • Current/voltage sensors communicates fault to upstream PFC • Short circuit protection in gate driver turns OFF the module entirely	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
		at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module MOSFETs					• High temperature in the power module, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.				
				Output of gate driver constant low	• Analog circuitry failure • Gate driver isolated power supply failure • Mechanical/pcb failure	2	• No power flow to GA coil or VA unit	2	4	Fault communicated by dedicated sensors and also from the BMS	
				Short circuit protection circuit failure	• Analog circuitry failure • Mechanical/pcb failure	2	• No protection of the switches during short circuit. Excessive currents during short circuit. May damage the MOSFET switches and the module	3	6	• The input relay-contactor turns OFF • Current/voltage sensors communicates fault to upstream PFC	
A.22.	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	3	3	Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the compressor pump	• Electrical failure • Mechanical failure	2	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	8	Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	4	• Periodic maintenance • Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET switches, increase in losses	3	3	Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.23.	High-frequency decoupling capacitor	Film or PLZT ceramic capacitors	Supply switching frequency (or its higher order harmonics) ripple currents	Capacitor failed resulting short circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property	3	• The DC voltage at inverter input is permanently shorted resulting in high input currents	3	9	• The input relay-contactor turns OFF • Current/voltage sensors communicates fault to upstream PFC	
				Capacitor failed resulting open circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property. • Mechanical failure	2	• Switching harmonic ripple supplied from the input resulting in input voltage distortions. • MOSFET switches might be subjected to higher voltage stress	2	4	Proper derating of the capacitor to avoid exceeding recommended operating range. PFC and inverter will trip the system if the current, voltage, and temperature ratings go out of operating range. • High voltage and current protection in front of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing. • Adequate voltage derating during the design stage.	
				Diminishing capacitance value	• Excessive voltage stress over time • Aging of the capacitor	4	• Switching harmonic ripple supplied from the input resulting in input voltage distortions. • MOSFET switches might be subjected to higher voltage stress	1	4	• Proper derating of the capacitor to avoid exceeding recommended operating range. • Lifetime estimation at the design stage to ensure the capacitor will survive expected lifetime.	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Condition monitoring scheme can be implemented for lifetime monitoring of the capacitors.	
C. Compensation networks											
A.24.	Compensation capacitor	Film (metallized or polypropylene film) capacitor	Part of the resonant network to achieve resonance at the desired frequency								
C.1.1.	Compensation series capacitor in GA (referred as C_1 in Figure 2.1–2.4)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Distorted input current, reduced output power as resonance is lost (series-series and series-parallel) • Excessive current on GA side, which can damage the MOSFET switches (LCC-series and LCC-LCC)	2 3	4 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• No power transfer (series–series and series-parallel) • Excessive current on GA, side which can damage the MOSFET switches (LCC-series and LCC-LCC)	2 3	2 3	• Voltage and current protection at the output of the inverter (especially for, LCC-series and LCC-LCC), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing	
C.1.2.	Compensation series capacitor in VA (referred as C_2 in Figure 2.1–2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Excessive current on GA side, which can damage the MOSFET switches (series-series) • Distorted input current (LCC-series and LCC-LCC) • Reduced output power as resonance is lost (LCC-series and LCC-LCC)	3 2 2	6 4 4	• Voltage and current protection at the output of the inverter (especially, series-series), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• Excessive current on GA side, which can damage the MOSFET switches (series-series) • Distorted input current (LCC-series and LCC-LCC) • No power to output (LCC-series and LCC-LCC)	3 2 2	3 2 2	• Voltage and current protection at the output of the inverter (especially for, series-series), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in GA (referred as C_{f1} in Figure 2.2–2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Increased and distorted input current, which may damage the inverter MOSFETs, increased EMI in the inverter (LCC-series and LCC-LCC)	2 2	4 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• No coil current due to the short-circuit at the output of inverter, and subsequently no output power (LCC-series and LCC-LCC)			• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• Input current at the inverter and GA coil current is distorted (LCC-series and LCC-LCC) • Reduced output power, reduced and distorted coil current (LCC-series and LCC-LCC)	2 2	2 2	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in VA (referred as C_{f2} in Figure 2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor • Over temperature, • Aging of capacitor	2	• Input inverter current is distorted • VA coil is shorted (rectifier input is shorted), excess voltage and current stress on the series VA compensation capacitor, • No output power, distorted and increased input current (LCC-LCC)	2 3 2	4 6 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor	1	• Input current is distorted and output power is reduced (LCC-LCC)	2	2	• Voltage and current protection at the output of the inverter,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure • Excessive heat dissipation, • Aging factors,					• The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in VA (referred as C_p in Figure 2.4)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor • Over temperature, • Aging of capacitor	2	• Input current increases, and may damage the inverter MOSFETs • The VA coil is shorted (rectifier input) and subsequently no power transfer to the battery	3 2	6 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• Input current increases, the VA coil current increases, and the output power decreases	3	3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.25.	Compensation series inductor	Inductors with ferrite core, and Litz wire for the winding	Part of the resonant network to achieve resonance at the desired frequency (typically used in higher order networks, example: In LCC series compensation the series inductor helps to maintain a constant coil current at resonance)								
C.2.1	Compensation series inductor in GA (referred as L_{f1} in Figure 2.3)			Inductor failed open circuit	• Mechanical shock or stress or assembly issues (both coil and core) • Over temperature and breakdown winding, • Mechanical failure, • Improper assembly and soldering during manufacturing,	1	No output power (LCC-series and LCC-LCC)	2	2	• Voltage, current, and temperature sensors, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
				Inductor failed short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil • Improper isolation clearance between the wires.	1	• Input current increases and highly distorted (LCC-series and LCC-LCC) • Distorted current and increased current stress across the GA parallel capacitor (LCC-series and LCC-LCC)	3 3	3 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing	
C.2.2	Compensation series inductor in VA (referred as L_{f2} in Figure 2.3)			Inductor failed open circuit	• Mechanical shock or stress or assembly issues (both coil and core) • Over temperature and breakdown winding, • Mechanical failure, • Improper assembly and soldering during manufacturing,	1	• Increases input current and VA coil current • No output power (LCC-LCC) • Increases voltage and current stresses across the compensation capacitor at GA and VA	2 2 3	2 2 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Inductor failed short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil • Improper isolation clearance between the wires.	1	• Distorts input current at GA • Distorted voltage and current across VA the parallel capacitor, which results in distorted currents through the rectifier • Reduced output power or no power based on the load condition	3 2 2	3 2 2	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
D. Rectifier											
A.26.	Diode rectifier on VA	Silicon carbide diodes/fast recovery silicon diodes	Converts the high-frequency AC voltage to DC voltage	One diode in the module shorted	• Excessive voltage, current and power stress across diode	2	• Reduced output power (series-series, series-parallel, LCC-LCC), and distorted inverter current with LCC-LCC tuning • Input inverter current increases (series-parallel)	3 3	6 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Increases the VA coil current, which increases the output power (LCC-series) • Other diodes are subjected to increased current stress (series-parallel, LCC-series)	3 3	6 6	• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
				Both diodes in the module shorted	• Excessive voltage, current and power stress across the module	2	• Output is shorted (series-series, series-parallel, LCC-series, and LCC-LCC) • Distorted and reduced inverter current, no output power (series-series) • Increases inverter current, VA coil voltage increases, no output power, and increased current stress across other rectifier diodes (series-parallel) • Inverter current increases, VA coil current increases, no output power, and increased current stress across other rectifier diodes (LCC-series) • Distorted inverter current, VA coil current reduces, and no output power (LCC-LCC)	3 2 3 3 2	6 4 6 6 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
				One module is open circuited	• Excessive heat dissipation • Mechanical failure	1	• Output power is zero, and increases voltage across coils which may lead to insulation breakdown (series-series) • Reduced output power, and distorted inverter current (series-parallel)	3 2 3	3 2 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Increases voltage stress across complementary diode (due to DC bias), no output power, DC bias across VA coil voltage, which increases the voltage stress, and the inverter current is distorted (LCC-series) • Increases inverter current, increased voltage and current stress across VA coil, series capacitor, and parallel capacitor, no output power (LCC-LCC)	3	3	• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
				Both modules are open circuited	• Excessive heat dissipation • Mechanical failure	1	• Output power is zero • Excessive voltage across coils which may lead to insulation breakdown (series-series) • Distorted and reduced inverter current, no output power (series-parallel) • Increased distortions in inverter current, no output power (LCC-series) • Increases inverter current, increased voltage and current stress across VA coil, series capacitor, and parallel capacitor, no output power (LCC-LCC)	3 2 2 3	3 2 2 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
A.27.	High-frequency decoupling capacitor for the rectifier on VA	Film or PLZT Ceramic Capacitors	Filtering switching frequency (or its higher order harmonics) ripple currents	Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property	3	• Output is shorted. It will repeat the scenario as output capacitor short conditions.	3	9	• Fault communicated by dedicated sensors and also from the BMS	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property. • Mechanical failure	2	• Increased voltage stress across diodes which may cause diodes to fail	2	4	• High voltage and current protection in front of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing. • Adequate voltage derating during the design stage.	
A.28.	Cooling unit (heat sink and chiller) for diode rectifier on VA	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the diode modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit	1	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	3	3	• Temperature sensor communicates to microcontroller for protective action	
				Failure of the compressor pump	• Electrical failure • Mechanical failure	2	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	4	8	• Temperature sensor communicates to microcontroller for protective action	
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	4	4	• Periodic maintenance • Temperature sensor communicates to microcontroller for protective action	
				Failure of the thermal pad between the diode module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the diode rectifier, increase in losses	1	1	• Temperature sensor communicates to microcontroller for protective action	
A.29.	Output diode (referenced as D_5 in Figure 1.2)	Silicon carbide diodes/fast recovery silicon diodes	To block the reverse current flow from the battery to DC link capacitor, C_{out}	Diode open circuit	• Excessive voltage, current and power stress across diode	2	• Output power is zero • Increases input inverter current, VA coil voltage (series-series)	2 3	4 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Reduced and distorted input inverter current (series-parallel) • Distorted inverter current (LCC-series) • Increases inverter current, increased voltage and current stress across VA coil, series capacitor, and parallel capacitor (LCC-LCC)	2 3 3	4 6 6	• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
				Diode short circuit	• Excessive voltage, current and power stress across the module	2	• Reverse battery current may flow in the DC link capacitor	3	6	• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
A.30.	Filter capacitor after rectifier (referenced as C_{out} in Figure 1.2)	Film capacitor	To filter high-frequency ripple current on the output DC bus	Capacitor open circuit	• Mechanical failure	1	• Ripple in output current goes to battery	1	1	• Control action taken by BMS	
				Capacitor short circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property • Aging of the capacitor	2	• Output is shorted • Reduced and distorted inverter current, no output power (series-series) • Increases the inverter current, increased current through the VA rectifier, no output power (series-parallel) • Increased inverter current subsequently increasing the voltage and current stress across input inductor and parallel capacitor, VA coil current increases which results in excess current through VA rectifier, no output power (LCC-series) • Reduced and distorted inverter current, reduced VA coil current, no output power	3 2 3 3 2	6 6 9 9 6	• Fault communicated by dedicated sensors and also from the BMS	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.31.	Filter inductor (sometimes included in the output filter as per the output current ripple requirement)	Ferrite core inductor with Litz wire winding	To filter high-frequency ripple in the voltage output from the rectifier in VA unit	Inductor short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil						
				Inductor open circuit	• Mechanical failure						
E. Wireless charging pads											
A.32.**Couplers**											
A.32.1.	Litz wire–based coil										
A.32.1.a.	Litz wire–based coil of the transmitter pad	Multiturn coil made with high-frequency Litz wire	Carries high-frequency AC current and generates AC magnetic field	Electrical short-circuit	• High voltage breakdown of insulation layers • Insulation breakdown due to the high electric field generated by the inverter • Faulty electrical/mechanical design or installation • Insulation degradation due to the leakage current • Insulation degradation due to Over temperature, increased humidity, over pressure, and so on • High voltage or current due to the fault in the compensation circuits • Runover by extremely heavy vehicle • Exposure to corrosive chemical • Damage of insulating layer of the individual strand and/or whole wire due to sharp bending of the Litz wire • Leaking or damage in the enclosure due to over pressure, Over temperature or other mechanical failure, or due to an accident	2	**Effect on the Ground Pad** • Significant damage in other components and subsystems • Thermal hazard and mechanical damage due to the increased loss in the coil • Increase the EMF emissions due to potential increase in current through the transmitter coil • An interwinding partial short circuit would change the resonance frequency, detune the system, and reduce the power transfer capability • Even a partial short circuit will damage the overall integrity of the Litz wire • An interwinding partial short circuit will change both the self and mutual inductance of the system • A partial short circuit will detune the system and lose the optimal operating condition, such as ZVS	5	10	• Current and temperature sensor • Safety and control requirements • Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions • Adopting the LCC compensation in the ground side, an LCC compensated ground pad is independent of the coil currents in the receiver pad. • Need advanced position and mutual inductance detection method for series compensated ground pad • Need to control and limit the maximum output power for the series compensated receiver pad by the primary side inverter, current sensor, and controller. • Strict Foreign object detection method and temperature monitoring on the surface of the transmitter pad	* For the system with integrated resonance inductor in the charging pad

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							operation of the inverter. • Increase in the current through the inverter for the parallel compensated ground pad • Thermal and fire hazard for the parallel compensated ground pad **Effect on the Vehicle pad** • Partial or complete drop in power transfer capability **Effect on the inverter** • Increase the inverter current for a parallel compensated ground pad under complete short circuit of the coil • Thermal hazard in the inverter under the parallel compensation in the primary side • Increased EMI from the inverter for the parallel compensated inverter **Effect on other system component** • Damage in integrated inductors due to increase temperature in the charging pad*. • Damage in the alignment sensor due to the high temperature caused by the short-circuit			• Product line dielectric strength test • Test on insulating materials considering the extreme worst-case scenario of WCS • Bending test of the coil and limiting maximum bending for the design, and for manufacturing steps of the coil	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.32.1.b.				Electrical open circuit	• Faulty electrical/mechanical design or installation • Electrical open circuit caused by excessively high current through the coils (e.g., caused by a short circuit failure)	1	**Effect on the Ground Pad** • An open circuit in the transmitter pad will stop the power transfer capability **Effect on the Vehicle pad** • Partial or complete drop in power transfer capability	4	4	• Current and temperature sensor • Safety and control requirements • Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions • Adopting the LCC compensation in the ground side, an LCC compensated ground pad is independent of the coil currents in the receiver pad. • Need advanced position and mutual inductance detection method for series compensated ground pad • Need to control and limit the maximum output power • Strict Foreign object detection method and temperature monitoring on the surface of the transmitter pad • Product line dielectric strength test • Test on insulating materials considering the extreme worst case scenario of WCS • Bending test of the coil and limiting maximum bending for the design, and for manufacturing steps of the coil	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.32.1.c.				Mechanical failure	• Heavy vehicle run-over the coil • Crash-induced mechanical failure • Over temperature	1	• Increase in electrical resistivity and loss • Exposed coil may cause electrical open or short circuit • Electrical safety hazard • User exposure to energized component of the charging pad	5	5	• Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions • Safety and control requirements	
A.32.1.d.				High-voltage insulation failure	• Faulty design/manufacturing • Mechanical deformation of the charging pad • Over voltage operation	1	• Electrical open or short circuit • Electrical and thermal safety hazard • Significant damage in other components and subsystems	2	2	• Electrical and mechanical design requirements • Current and temperature sensor • Safety, quality, and control requirements • Safety and quality test for diverse operating conditions	
A.32.1.e.				Conductivity degradation	• Mechanical degradation • Over temperature • Internal insulation failure in Litz wires due to high-temperature or high voltage	2	• Increase in electrical resistivity, • Increase in loss, Over temperature	4	8	• Electrical and mechanical design requirements • Current and temperature sensor • Safety, quality, and control requirements • Safety and quality test for diverse operating conditions	
A.32.2.	Litz wire coil in the receiver pad	Multiturn coil made with high-frequency Litz wire	Carries high-frequency AC current and generates AC magnetic field	Electrical short-circuit	• High voltage breakdown of insulation layers • Insulation breakdown due to the high electric field generated by the inverter • Faulty electrical/mechanical design or installation • Insulation degradation due to the leakage current • Insulation degradation due to Over temperature, increased	1	**Effect on the Receiver pad:** • The current in the receiver coil will reduce • Cause circulating loss current in the receiver pad due to the induced voltage in the generated short-circuit loop • An interwinding partial short circuit will change both the self and mutual	5	5	• Current and temperature sensor • Safety and control requirements • Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions • Adopting the LCC compensation in the ground side, an LCC compensated ground pad is independent of	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					humidity, over pressure, and so on • High voltage or current due to the fault in the compensation circuits • Runover by extremely heavy vehicle • Exposure to corrosive chemical • Damage of insulating layer of the individual strand and/or whole wire due to sharp bending of the Litz wire • Leaking or damage in the enclosure due to over pressure, Over temperature or other mechanical failure, or due to an accident		inductance of the system • Thermal and fire hazard above the transmitter pad due to excessive magnetic field in the accessible area above the transmitter pad. Such high magnetic field will cause high loss in any undetected foreign object. **Effect on the transmitter pad** • An interwinding partial short circuit will change both the self and mutual inductance of the system • Significantly increase in the current of a series compensated ground pad • Increase in EMF emissions for a series compensated ground pad • Thermal hazard in the series compensated ground pad • Increase the reactive power in the transmitter side resonant tank • Increase in the resonant capacitor voltage in a series compensated transmitter pad, in which the capacitor already operates at a significantly high voltage			the coil currents in the receiver pad. • Need advanced position and mutual inductance detection method for series compensated ground pad • Need to control and limit the maximum output power • Strict Foreign object detection method and temperature monitoring on the surface of the transmitter pad • Product line dielectric strength test • Test on insulating materials considering the extreme worst case scenario of WCS • Bending test of the coil and limiting maximum bending for the design, and for manufacturing steps of the coil	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							Effect on the inverter • Increase the inverter current for a series compensated ground pad • Thermal hazard in the inverter • Increased EMI from the inverter **Effect on the overall system** • An interwinding partial short circuit would change the resonance frequency, detune the system, and reduce the power transfer capability • Even a partial short circuit will damage the overall integrity of the Litz wire • Damage in other components and subsystems • Thermal hazard and mechanical damage • A partial short-circuit will reduce the interoperability of one pad wither other types of pads.				
					•					•	
A.32.3.	Ferrite core										
A.32.3.a.	Ferrite core of the transmitter and receiver pad	Made with high-permeability magnetic material, such as ferrite. Ferrite is a highly brittle material	1. Guides the magnetic flux, 2. Increases the self and mutual inductances	High temperature	• Large hysteresis loss • Improper/faulty thermal design • Large current in the coils	2	• Increased resistivity and loss in the coil • Degraded performance of the core • Thermal runaway	4	8	• Electrical and mechanical design requirements • Current and temperature sensor • Safety, quality, and control requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality test for diverse operating conditions	
A.32.3.b.				High loss	• Large hysteresis loss • Large current in the coils • Eddy current loss • Improper/faulty design • Degraded electrical property of ferrites • Increased temperature	1	• Over temperature in the core and coil • Drop in system efficiency • Safety hazard for the users and other components	5	5	• Electrical and mechanical design requirements • Safety, quality, and control requirements	
A.32.3.c.				Mechanical breakdown	• Ferrite is extremely brittle • Excessive vibration from the vehicle • Excessive pressure on the charging pad • Improper mechanical design • Damage from accident or heavy impact	4	Slightly reduced self and mutual inductances	1	4	• Mechanical design requirements of the core as well as surround materials • Safety and quality test for diverse operating conditions	
A.32.4.	Backplate shield										
A.32.4.a.	Backplate shields of the transmitter and receiver pads	Backplate shields are made with aluminum plate, and put behind the ferrite core	1. Gives mechanical support 2. reduces the leakage magnetic field	Excessive loss in the shield	• High eddy current loss in shield • Mechanical breakdown, deformation, or crack in the coil, core, or backplate shield • Increased current in the coils • Increased misalignment between the charging pads • Excessive loss in the coil or core would increase the temperature of the shield degrades its performance	4	• Excessive temperature and thermal hotspot • Increased EMF emissions due to reduced shield current	2	8	• Current and temperature sensor • Safety, quality, and control requirements • Safety and quality test for diverse operating conditions	
A.32.4.b.				Increased EMF emission	• Mechanical breakdown/bending of the shield • Degraded conductivity or the conductive shield	2	• High EMF emission, potentially above the safety limits	5	10	• Strict design requirement for low EMF emission • Safety and quality test for diverse operating conditions	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				• Degraded permeability of the magnetic shield							
A.32.5.	EMF shield										
A.32.5.a.	EMF shield above the receiver pad	Made with large aluminum plate, put on the receiver pad	1. Reduces the leakage magnetic field 2. Protect the vehicle chassis form the magnetic field	Excessive loss in the shield	• High eddy current loss in shield • Mechanical breakdown or deformation in the receiver pad or aluminum shield • Increased current in the coils • Increased misalignment between the charging pads	2	• Excessive high temperature on the shield	4	8	• The misalignment between transmitter and receiver must be low • Monitoring system efficiency to detect potential high loss • Safety and quality test for diverse operating conditions	
A.32.5.b.				Mechanical deformation	• Improper design/installation • Excessive vibration from the vehicle • Extreme pressure/stress on the charging pad • Crash-induced damage	1	• Increased EMF emissions • High temperature on the shield	4	4	The EMF emissions must be monitored to limit it below the safe level	
A.33.**Sensors in the charging pad**											
A.33.1.	Sensor for coil alignment										
A.33.1.a.	Sensors for in the transmitter and receiver pad	Multiple sensors are put around the transmitter and receiver pads for guiding the vehicle for coil alignment. These sensors are consisting of a small coil, and a high permeability core. LF sensor operate at a different frequency than the WPT system.	1. Measures the relative position of the transmitter and receiver pad to guide the driver/auto-parking system for aligning the pads	Breakdown, bending, and other mechanical damage	• Over pressure, Over temperature, • Damage by crash • Mechanical damage in the coil or core of the sensor • Failure due to high temperature	1	• Poor alignment if there is not enough sensor to provide the position information • Potentially high EMF emissions if the misalignment is high • Thermal hazard due to a wrong alignment • Lower mutual inductance and low efficiency due to poor alignment • Large current in the coil of the series-compensated coils due to low mutual inductance caused by the poor or wrong alignment	3	3	• Testing the durability of the sensors for diverse operating conditions • Implementing sensors calibration algorithm to get good accuracy and fault detection capability • Detection of foreign objects near the charging pads using highly sensitive foreign object detector • Using sufficient number of sensors, so that a potentially blocked or distorted sensor can be detected and	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										informed for maintenance	
A.33.1.b.				Blocked or distorted magnetic field	• Proximity of conductive, metallic, materials near the charging pads (e.g., metallic object, water) • Blocked by external objects • Signal gets affected by a small or large foreign object	3	• Poor alignment if there is not enough sensor to provide the position information • Potentially high EMF emissions if the misalignment is high • Thermal hazard due to a wrong alignment • Lower mutual inductance and low efficiency due to poor alignment • Large current in the coil of the series-compensated coils due to low mutual inductance caused by the poor or wrong alignment	3	9	• Detection of foreign objects near the charging pads using highly sensitive foreign object detector • Using sufficient number of sensors, so that a potentially blocked or distorted sensor can be detected and informed for maintenance	
				Electrically damage: open circuit or short circuit in the coil	• Mechanical damage in the sensor • Failure due to high temperature • Failure due to excessive EMF	1	• Poor alignment if there are not enough sensors to provide the correct position information • Potentially high EMF emissions if the misalignment is high • Thermal hazard due to a wrong alignment • Lower mutual inductance and low efficiency due to poor alignment • Large current in the coil of the series-compensated coils due to low mutual inductance caused by the poor or wrong alignment • Electrical safety hazard.	2	2	• Quality and durability test of the system under diverse operating condition	
A.33.2.	Foreign object detection system										

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.33.2.a.	Foreign object detection coil, usually embedded in the transmitter pad	Made with low power coil, put on the transmitter pad	1. Detect small and large conductive and magnetic undesired object near charging pads 2. Detect living object such as animals near the charging pads 3. Essential safety features to shut down the system to protect the system as well as fire and health hazard	Breakdown, mechanical, or damage	• Mechanical breakdown or deformation in the transmitter pad due to Over temperature, over pressure and/or accident	1	• Increases loss due to undetected foreign object • Potential thermal hotspot and fire-hazard	2	2	• Increased testing considering widely diverse operating conditions and samples of foreign objects	
A.33.2.b.				Electrical failure including short or open circuit	• Over temperature, over pressure • Mechanical failure, puncture, crash-induced breakdown	2	• Increases loss due to undetected foreign object • Potential thermal hotspot and fire-hazard	2	4	• Adopting a self-test method to identify if there is any potential fault in the FOD system • Shutting down the power transfer if there is any potential failure	
A.33.2.c.				Failure to detect certain conductive/magnetic object with irregular shape	• Large diversity of size and shape of the foreign objects, and limited testing against such diverse situations	1	• Increases loss due to undetected foreign object • Potential thermal hotspot and fire-hazard	4	4	• Quality and durability test of the system under diverse operating condition	
A.33.3.	Nonmagnetic enclosure										
A.33.3.a.	Nonmagnetic enclosures are put around both the transmitter and receiver pads	• Protect the magnetic component of charging pad • Provide mechanical support and required heat dissipation	1. Provides mechanical support of the charging pad 2. Provides necessary mechanical support for installing the transmitter pads on the ground, or under the ground, and receiver pad under the vehicle undercarriage	Mechanical failure/ breakdown	• Over pressure • Over temperature	1		2	2	• Quality and durability test of the system under diverse operating condition	
A.33.3.b.				Puncture/ intrusion of foreign object	• Crash-induced puncture	2		2	4	• Quality and durability test of the system under diverse operating condition	
A.33.3.c.											
A.33.4.	Nonmagnetic coil holders										
A.33.4.a.	Nonmagnetic coil holders in the transmitter	Nonmagnetic holders are used to keep the coil and ferrite in	• Nonmagnetic holder keeps the coil and	Mechanical damage or breakdown	• Faulty installation, • Over temperature or over pressure	1	• Displacement of the coil and core • Higher loss in the charging pad	2	2	Quality and durability test of the system under diverse operating condition	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
	and receiver pads	desired shape. Commonly the coil holders have the slots to hold the coil at designed winding pattern	ferrite at designed positions • Provide required isolation between the turns of the coil				• Degraded thermal characteristics of the charging pad				
A.33.4.b.											
F. WPT system control and communication subsystem											
A.34.Sensors											
A.34.1.	Input voltage sensor	Isolated voltage sensor	Sense the input DC voltage	Sensor damage	• Short circuit • Aging • Open circuit	1	• Input voltage not communicated to microcontroller. • Controller action is not as desired, output voltage or power might be different from the reference value	2	2	• Microcontroller communicates fault Periodic calibration	
	Output voltage sensor	Isolated voltage sensor	Sense the output voltage	Sensor damage	• Short circuit • Aging • Open circuit	1	• Output voltage not communicated to microcontroller. • Controller might saturate and MOSFETs operate at maximum pulse width for phase shift control. Input current increases. Output voltage is different from the reference value	3	3	• Desat protection in gate driver triggers • Other sensors, microcontroller and BMS communicates fault • Periodic calibration	
	GA coil current sensor	Isolated current sensor	Sense the coil current series	Sensor damage	• Short circuit • Aging • Open circuit	1	• Coil current magnitude not communicated to microcontroller. • Controller might saturate and MOSFETs operate at maximum pulse width for phase shift control. Input current increases. Output voltage is different	3	3	• Desat protection in gate driver triggers • Other sensors, microcontroller and BMS communicates fault • Periodic calibration	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							from the reference value				
	Output current sensor	Isolated current sensor	Sense the output current	Sensor damage	• Short circuit • Aging • Open circuit	1	• Output current magnitude not communicated to microcontroller • Output power control (if being used) is affected	2	2	• Microcontroller communicates fault • Periodic calibration	
	GA side high-frequency inverter temperature sensor	Thermistor based temperature sensor	Sense the GA side MOSFETs' temperature	Sensor damage	• Short circuit • Aging • Open circuit	1	• Temperature monitoring is lost, which may result in increased junction temperature of MOSFETs' under certain operating condition • Efficiency decreases	2	2	• Microcontroller communicates fault • Periodic calibration	
	VA side high-frequency rectifier temperature sensor	Thermistor based temperature sensor	Sense the VA side diode rectifier temperature	Sensor damage	• Short circuit • Aging • Open circuit	1	• Temperature monitoring is lost, which may result in increased junction temperature of diodes in the rectifier under certain operating condition • Efficiency decreases	2	2	• Microcontroller communicates fault • Periodic calibration	
	Ambient and other passives temperature sensor	Thermistor based temperature sensor	Sense the ambient temperature and temperature of selective passives	Sensor damage	• Short circuit • Aging • Open circuit	1	• Thermal stress across passives increases • Efficiency decreases	2	2	• Microcontroller communicates fault • Periodic calibration	
	Microcontroller unit	Off the shelf digital microcontroller	Controlling the overall WPT system	Sensing unit failure	• Analog circuitry failure • Microcontroller ADC unit failure	1	• Signals imperative for the control and fault monitoring not communicated to microcontroller • Controller saturates and MOSFETs operate at maximum pulse width for phase shift control. Input current increases. Output voltage/power	3	3	• Desat protection in gate driver triggers • Periodic calibration	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							is different from the reference value				
				PWM unit failure	• Analog circuitry failure • Microcontroller EPWM unit failure	1	• PWM signals lost to MOSFETs leading to no output power • Constant high PWM signal communicated to one or multiple MOSFETs leading to an increased input current or short circuit	3	3	• Desat protection in gate driver triggers • Periodic calibration	
	Wireless communication network	Off the shelf wireless communication ICs interfaced with LAN or serial port of the microcontroller	Communicating of sensed signals from VA side sensors to GA side microcontroller	Wireless communication network damage	• Analog circuity failure • Open circuit of wireless to microcontroller interface	1	• Communication from VA side is lost or erroneous • Output voltage feedback signal to microcontroller is interrupted. Controller saturates and MOSFETs operate at maximum pulse width for phase shift control. Input current increases. Output voltage/power is different from the reference value	2	2	• Desat protection in gate driver triggers • Microcontroller communicates fault • Periodic calibration	

10.2 Static Wireless XFC (22–120 KW) Concept System, Subsystem, and Components

Table 10.2. FMEA worksheet for heavy-duty static wireless charger (22–120 kW) concept system, subsystem, and components

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A. High-frequency inverter											
A.1.	Semiconductor power module (generally MOSFETs)	Silicon carbide MOSFETs	Converts the DC voltage to high-frequency square or quasi-square AC voltage	One switch in the module shorted	• Excessive voltage, current and power stress across switch. • Gate driver output pulled high • Excessive heat dissipation, • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging, water flooding, pressure, humidity, and so on, • Improper design during manufacturing.	2	• The DC voltage at inverter input is periodically shorted when the complementary switch turns ON resulting in high input currents • High power losses in the inductor and switch power module, • High temperature in the PFC inductor and switch power module, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.	3	6	• Short circuit protection in gate driver turns OFF the complementary switch	
				Both switches in the module shorted	• Excessive voltage, current and power stress across the module • Gate driver output pulled high for both switches • Excessive heat dissipation, • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging, water flooding, pressure, humidity, and so on, • Improper design during manufacturing.	2	• The DC voltage at inverter input is permanently shorted resulting in high input currents • DC link capacitor can be damaged due to high inrush current • High temperature in the power module, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.	3	6	• The input relay-contactor turns OFF • Current/voltage sensors communicates fault to upstream PFC • Short circuit protection in gate driver turns OFF the module entirely	
				One module is open circuited	• Excessive heat dissipation	1	• No power flow to the GA or VA unit	3	3	• Fault communicated by dedicated voltage	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure					and current sensors to the battery management system (BMS), gate-driver and upstream PFC • The input relay contactor in front of inverter turning off with the fault signal	
				Both modules are open circuited	• Excessive heat dissipation • Mechanical failure	1	• No power flow to GA coil or VA unit	3	3	• Fault communicated by dedicated sensors and also from the BMS	
A.2.	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the compressor pump	• Electrical failure • Mechanical failure	2	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	4	• Periodic maintenance • Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Capacitor failed resulting open circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property.	2	• Switching harmonic ripple supplied from the input resulting in input voltage distortions. • MOSFET switches might be subjected	2	4	• Proper derating of the capacitor to avoid exceeding recommended operating range. • PFC and inverter will trip the system if the	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure		to higher voltage stress			current, voltage, and temperature ratings go out of operating range.	
				Diminishing capacitance value	• Excessive voltage stress over time • Aging of the capacitor	4	• Switching harmonic ripple supplied from the input resulting in input voltage distortions. • MOSFET switches might be subjected to higher voltage stress	1	4	• Proper derating of the capacitor to avoid exceeding recommended operating range. • • Lifetime estimation at the design stage to ensure the capacitor will survive expected lifetime. • • Condition monitoring scheme can be implemented for lifetime monitoring of the capacitors.	
B. Compensation networks											
A.3.	Compensation capacitor	Film (metallized or polypropylene film) capacitor	Part of the resonant network to achieve resonance at the desired frequency								
C.1.1.	Compensation series capacitor in GA (referred as C_1 in Figure 2.1–2.4)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Distorted input current, reduced output power as resonance is lost (series-series and series-parallel) • Excessive current on GA side, which can damage the MOSFET switches (LCC-series and LCC-LCC)	2 3	4 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor	1	• No power transfer (series–series and series-parallel)	2	2	• Voltage and current protection at the output of the inverter	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure • Excessive heat dissipation, • Aging factors,		• Excessive current on GA side, which can damage the MOSFET switches (LCC-series and LCC-LCC)	3	3	(especially for, LCC-series and LCC-LCC), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
C.1.2.	Compensation series capacitor in VA (referred as C_2 in Figure 2.1–2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Excessive current on GA side, which can damage the MOSFET switches (series-series) • Distorted input current (LCC-series and LCC-LCC) • Reduced output power as resonance is lost (LCC-series and LCC-LCC)	3 2 2	6 4 4	• Voltage and current protection at the output of the inverter (especially, series-series), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• Excessive current on GA side, which can damage the MOSFET switches (series-series) • Distorted input current (LCC-series and LCC-LCC) • No power to output (LCC-series and LCC-LCC)	3 2 2	3 2 2	• Voltage and current protection at the output of the inverter (especially for, series-series), • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in GA (referred as C_{f1} in Figure 2.2–2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, • Over temperature, • Aging of capacitor	2	• Increased and distorted input current, which may damage the inverter MOSFETs, increased EMI in the inverter (LCC-series and LCC-LCC) • No coil current due to the short-circuit at the output of inverter, and subsequently no output power (LCC-series and LCC-LCC)	2 2	4 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	• 1	• Input current at the inverter and GA coil current is distorted (LCC-series and LCC-LCC) • Reduced output power, reduced and distorted coil current (LCC-series and LCC-LCC)	2 2	2 2	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in VA (referred as C_{f2} in Figure 2.3)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor • Over temperature, • Aging of capacitor	• 2	• Input inverter current is distorted • VA coil is shorted (rectifier input is shorted), excess voltage and current stress on the series VA compensation capacitor,	2 3	4 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• No output power, distorted and increased input current (LCC-LCC)	2	4	• Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure • Excessive heat dissipation, • Aging factors,	1	• Input current is distorted and output power is reduced (LCC-LCC)	2	2	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
	Compensation parallel capacitor in VA (referred as C_p in Figure 2.4)			Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor • Over temperature, • Aging of capacitor	• 2	• Input current increases, and may damage the inverter MOSFETs • The VA coil is shorted (rectifier input) and subsequently no power transfer to the battery	3 2	6 4	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Capacitor failed open circuit	• Excessive voltage, current and power stress across the capacitor • Mechanical failure	1	• Input current increases, the VA coil current increases, and the output power decreases	3	3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excessive heat dissipation, • Aging factors,					inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
A.4.	Compensation series inductor	Inductors with ferrite core, and Litz wire for the winding	Part of the resonant network to achieve resonance at the desired frequency (typically used in higher order networks, example: In LCC series compensation the series inductor helps to maintain a constant coil current at resonance)								
C.2.1	Compensation series inductor in GA (referred as L_{f1} in Figure 2.3)			Inductor failed open circuit	• Mechanical shock or stress or assembly issues (both coil and core) • Over temperature and breakdown winding, • Mechanical failure, • Improper assembly and soldering during manufacturing,	1	No output power (LCC-series and LCC-LCC)	2	2	• Voltage, current, and temperature sensors, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
				Inductor failed short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil	• 1	• Input current increases and highly distorted (LCC-series and LCC-LCC)	3 3	3 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper isolation clearance between the wires.		• Distorted current and increased current stress across the GA parallel capacitor (LCC-series and LCC-LCC)			inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
C.2.2	Compensation series inductor in VA (referred as L_{f2} in Figure 2.3)			Inductor failed open circuit	• Mechanical shock or stress or assembly issues (both coil and core) • Over temperature and breakdown winding, • Mechanical failure, • Improper assembly and soldering during manufacturing,	• 1	• Increases input current and VA coil current • No output power (LCC-LCC) • Increases voltage and current stresses across the compensation capacitor at GA and VA	2 2 3	2 2 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	
				Inductor failed short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil • Improper isolation clearance between the wires.	• 1	• Distorts input current at GA • Distorted voltage and current across VA the parallel capacitor, which results in distorted currents through the rectifier • Reduced output power or no power based on the load condition	3 2 2	3 2 2	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements, • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
C. Rectifier											
A.5.	Diode rectifier on VA	Silicon carbide diodes/fast recovery silicon diodes	Converts the high-frequency AC voltage to DC voltage	One diode in the module shorted	• Excessive voltage, current and power stress across diode	2	• Reduced output power (series-series, series-parallel, LCC-LCC), and distorted inverter current with LCC-LCC tuning • Input inverter current increases (series-parallel) • Increases the VA coil current, which increases the output power (LCC-series) • Other diodes are subjected to increased current stress (series-parallel, LCC-series)	3 3 3 3	6 6 6 6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
				Both diodes in the module shorted	• Excessive voltage, current and power stress across the module	2	• Output is shorted, excessive energy dissipation due to stored energy in the output capacitor.	3	6	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC	
				One module is open circuited	• Excessive heat dissipation • Mechanical failure	1	• Output power is zero, and increases voltage across coils which may lead to insulation breakdown (series-series) • Reduced output power, and distorted inverter current (series-parallel) • Increases voltage stress across complementary diode (due to DC bias), no output power, DC bias across VA coil	3 2 3 3	3 2 3 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							voltage, which increases the voltage stress, and the inverter current is distorted (LCC-series) • Increases inverter current, increased voltage and current stress across VA coil, series capacitor, and parallel capacitor, no output power (LCC-LCC)				
				Both modules are open circuited	• Excessive heat dissipation • Mechanical failure	1	• Output power is zero • Excessive voltage across coils which may lead to insulation breakdown (series-series) • Distorted and reduced inverter current, no output power (series-parallel) • Increased distortions in inverter current, no output power (LCC-series) • Increases inverter current, increased voltage and current stress across VA coil, series capacitor, and parallel capacitor, no output power (LCC-LCC)	3 2 2 3	3 2 2 3	• Voltage and current protection at the output of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Fault communicated to the BMS and upstream PFC • Electrical and mechanical design requirements	
A.6.	High-frequency decoupling capacitors for the rectifier on VA	Film or PLZT Ceramic Capacitors	Filtering switching frequency (or its higher order harmonics) ripple currents	Capacitor failed short circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property	3	• Output is shorted	3	9	• Fault communicated by dedicated sensors and also from the BMS	
				Capacitor failed resulting open circuit	• Excessive voltage, current and power stress across the	2	• Switching harmonic ripple supplied from the input resulting in	2	4	Proper derating of the capacitor to avoid exceeding	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					capacitor, which may translate in dielectric failure depending on capacitor property. • Mechanical failure		input voltage distortions. • MOSFET switches might be subjected to higher voltage stress			recommended operating range. PFC and inverter will trip the system if the current, voltage, and temperature ratings go out of operating range. • High voltage and current protection in front of the inverter, • The input relay contactor in front of inverter turning off with the fault signal, • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing. • Adequate voltage derating during the design stage.	
				Diminishing capacitance value	• Excessive voltage stress over time • Aging of the capacitor	4	• Switching harmonic ripple supplied from the input resulting in input voltage distortions. • MOSFET switches might be subjected to higher voltage stress	1	4	• Proper derating of the capacitor to avoid exceeding recommended operating range. • Lifetime estimation at the design stage to ensure the capacitor will survive expected lifetime. • Condition monitoring scheme can be implemented for lifetime monitoring of the capacitors.	
A.7.	Cooling unit (heat sink and chiller) for diode rectifier on VA	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol	Dissipates heat to keep the junction temperature of the diode modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit	1	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
		and water mix 50-50%)					and damage of the diodes				
				Failure of the compressor pump	• Electrical failure • Mechanical failure	2	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	4	8	• Temperature sensor communicates to microcontroller for protective action	
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	4	4	• Periodic maintenance • Temperature sensor communicates to microcontroller for protective action	
				Failure of the thermal pad between the diode module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the diode rectifier, increase in losses	1	1	• Temperature sensor communicates to microcontroller for protective action	
A.8.	Filter capacitor after rectifier (referenced as C_{out} in Figure 1.2)	Film capacitor	To filter high-frequency ripple current on the output DC bus	Capacitor open circuit	• Mechanical failure	1	• Ripple in output power goes to battery	1	1	• Control action taken by BMS	
				Capacitor short circuit	• Excessive voltage, current and power stress across the capacitor, which may translate in dielectric failure depending on capacitor property • Aging of the capacitor	2	• Output is shorted	3	6	• Fault communicated by dedicated sensors and also from the BMS	
A.9.	Filter inductor (typically required for parallel compensation in secondary)	Ferrite core inductor with Litz wire winding	To filter high-frequency ripple in the voltage output from the rectifier in VA unit	Inductor short circuit	• Excessive current stress causing inductor to saturate • Insulation breakdown of coil						
				Inductor open circuit	• Mechanical failure						
D. Wireless charging pads											
A.10. **Couplers**											
A.10.1.	Litz wire–based coil										
A.10.1.a	Litz wire–based coil of the transmitter and receiver pads	Multiturn coil made with high-frequency Litz wire	Carries high-frequency AC current and	Electrical open/short circuit failures	• Insulation failure due to extremely high current and voltage in the coil	2	• The voltage and current in the coil at high-power are significantly high.	5	10	• Current and temperature sensor • Safety and control requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
			generates AC magnetic field		• High loss in the coil or core.					• Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions	
A.10.1.b				Mechanical failure	• At high-power the coil current and voltages increases significantly. However, the strand-size of the Litz wire remains the same due to the specific high-frequency (~85 kHz) operation. Therefore, the strand-level and the coil-level insulation requirement increases too, making the wire significantly think an and inflexible. It also reduced the maximum bending angle and increase bending induced fault during the manufacturing, installation and operation of the WCS. • Over temperature due to high loss and fault in thermal management system	1	• Increase in electrical resistivity and loss • Exposed coil may cause electrical open or short circuit • Electrical safety hazard • User exposure to energized component of the charging pad	5	5	• Parallel-wire based coil design. • Strict electrical and mechanical design requirements considering bending limitation during manufacturing, installation and operation. • Quality and safety test for diverse operating conditions • Safety and control requirements	
A.10.2.	Ferrite core										
A.10.2.a	Ferrite core of the transmitter and receiver pads	Made with high-permeability magnetic material, such as ferrite. Ferrite is a highly brittle material	1. Guides the magnetic flux, 2. Increases the self and mutual inductances	High loss	• Significantly high hysteresis loss • Fault in thermal management • Ferries will probably cause the largest amount of core loss for fast WCS, which would range up to a few kilowatts.	2	• Degraded performance of the core • Increased resistivity and insulation degradation of the coil • Thermal runaway	4	8	• Temperature sensor in the core • Extremely well thermal management system • Electrical and mechanical design requirements • Safety, quality, and control requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality test for diverse operating conditions	
A.10.3.	EMF shield										
A.10.3.a	EMF shield above the receiver pad	Made with large aluminum plate, put on the receiver pad	1. Reduces the leakage magnetic field 2. Protect the vehicle chassis form the magnetic field	Excessive loss in the shield	• High eddy current loss in shield will be one of the most critical challenge for extremely fast WCS.	3	• Excessive high temperature on the shield	4	12	• Temperature sensor in the shield • The misalignment between transmitter and receiver must be low • Monitoring system efficiency to detect potential high loss • Safety and quality test for diverse operating conditions	
				Increased EMF emissions	• Degradation of conductivity of the aluminum shield.	3	• Exceeding the EMF emission above the ICNIPR limit, causing significant health and safety hazard. • Damage of the EV sensors due to high EMF exposure	4	12	• Monitoring the EMF emissions at the edge of the vehicle using EMF sensors.	
	EMF shield below and around the transmitter pad	Made with aluminum plate, or high-permeability materials, such as ferrite, magment, and so on	Reduce the leakage magnetic field around the vehicle	Excessive loss in the shield	• Mechanical deformation. • The shield of the high power WCS causes high eddy-current and core loss. Any mechanical deformation of the aluminum or ferrite would increase the eddy loss in the aluminum and hysteresis loss in the ferrite.	2	• Thermal hazard • Exceeding the EMF emission above the ICNIPR limit, causing significant health and safety hazard. • Damage of the EV sensors due to high EMF exposure	3	6	• Temperature sensor in the shield • Monitoring the EMF emissions at the edge of the vehicle using EMF sensors	
				Increased EMF emissions	• Degradation of conductivity of the aluminum shield • Degradation of the effective permeability of the magnetic shield layer	2	• Exceeding the EMF emission above the ICNIPR limit, causing significant health and safety hazard.	3	6	• Monitoring the EMF emissions at the edge of the vehicle using EMF sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							Damage of the EV sensors due to high EMF exposure				
E. Rectifier											
A.11.	Cooling unit (heat sink and chiller) for diode rectifier on VA	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the diode modules under tolerable limits.	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack • Leakage or loose contact between the cold plate and the circulating unit	2	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	3	6	• Temperature sensor communicates to microcontroller for protective action	
				Failure of the compressor pump	• Electrical failure • Mechanical failure	2	• Temperature control disrupted. May lead to excessive heating of the diode rectifier, increase in losses and damage of the diodes	4	8	• Temperature sensor communicates to microcontroller for protective action	
				Failure of the thermal pad between the diode module and cold plate	• Mechanical stress and strain	2	• Temperature control disrupted. Increased thermal stress on the diode rectifier, increase in losses	1	2	• Temperature sensor communicates to microcontroller for protective action	

10.3 Static Wireless XFC (120–350 KW) Concept System, Subsystem, and Components

For 120 to 350 kW, the thermal and EMF emissions become the most significant challenges of a WCS. Mitigation of the thermal challenges will be partially similar to a conventional plug-in charging system. Although the charging pad will cause the large share of the power loss, the area of such a high-power WCS will be large, which will increase the heat dissipation rate. Still, a natural convection cooling would not be sufficient for this power range. Either forced air cooling or liquid cooling will be necessary to keep the temperature within desired range.

The EMF emissions at certain distances are approximately proportional to the power level. Therefore, in these high-power applications, the EMF emissions will be significantly high. The large body size of the medium- and heavy-duty vehicles will partially reduce the EMF emissions. However, for the passenger vehicle, the EMF emissions will be a significant challenge to meet under all operating conditions. Proper shield design and extensive testing will be required to keep the EMF emissions under the safe limits.

10.4 Extreme Fast Charging (XFC) Systems

Table 10.3. FMEA for XFC System

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A. Grid Interface											
A.1	Common-mode choke	Multi-turn common-mode inductor (usually made of toroidal core and Litz wire)	Filter inductor for common-mode and differential-mode emissions	High voltage insulation breakdown	• Over voltage operation due to grid voltage swell, voltage transient, and so on, • Mechanical deformation • Improper manufacturing design • Over temperature • Aging of insulation	1	• Insulation breakdown between windings might cause electrical arc • Significant damage (such as fire) to other components and subsystems • Increase of current at the grid and power losses at the Rectifier/PFC • Increase of conductive and differential emissions • User electrical and thermal safety hazard, and excessive energy exposure	4	4	• Current and temperature sensors • Electrical and mechanical design requirements • Safe operating conditions • Enclosure to limit user access	
				Electrical open circuit	• Over temperature and winding breakdown (wire break) • Mechanical failure (e.g., break of winding, disconnect from the circuit board), • Over-tension (stretched) during manufacturing of windings.	1	• Open circuit between live terminals might cause an electrical arc and Over voltage • Significant damage (such as fire) to other components and subsystems • Electrical and thermal safety hazard • User safety hazard	4	4	• Current, temperature, and voltage sensors • Electrical and mechanical design requirements • Safe operating conditions.	
				Electrical short circuit	• Poor electrical or mechanical design, or improper manufacturing • High voltage breakdown of insulation wire	1	• Significant damage (such as fire) to other components and subsystems • Electrical and thermal safety hazard	4	4	• Current, temperature, and voltage sensors • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper isolation clearance between active wires		• Increase of current at the grid and power losses at the Rectifier/PFC			• Safe operating conditions.	
					• Winding high temperature leading to insulation degradation		• Increase of conductive and differential emissions				
							• User safety hazard and energy exposure				
				High temperature	• High core losses due to improper design	1	• High temperature might damage the winding insulation and increase the possibility of short circuit between turns and windings,	4	4	• Current, voltage, and temperature sensors	
					• Degraded electrical property of core material		• Significant damage (such as fire) to other components and subsystems			• Electrical and mechanical design requirements	
					• Conductivity degradation of wire		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• High conduction losses due to high current		• Increase of current at the grid and power losses at the Rectifier/PFC				
					• Improper thermal management and design		• Increase of conductive and differential emission				
					• Excessively high ambient temperature (e.g., operating outside recommended operating range)		• User safety hazard and excessive energy exposure				
				Mechanical failure	• Crash-induced mechanical failure	1	• Mechanical damage	4	4	• Current, voltage, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, air pressure)		• Potential short circuit			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Significant damage (such as fire) to other components and subsystems			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excessive vibration during transportation because of poor mounting		• Electrical and thermal safety hazard				
					• Fragile components subject to mechanical shocks (e.g., crash, vibration, collapse, drop off)		• Increase of current at the grid and power losses at the Rectifier/PFC				
					• Improper assembly and soldering during manufacturing		• Increase of conductive and differential emissions				
					• Improper mechanical design		• User safety hazard and energy exposure				
				Component performance degradation	• High temperature	1	• Conductivity degradation might cause increased power losses	4	4	• Current, voltage, and temperature sensors	
					• Mechanical breakdown		• Core saturation may lead to excessive current at grid			• Electrical and mechanical design requirements	
					• Insulation failure		• Increase of current at the grid and power losses at the Rectifier/PFC			• Quality control during manufacturing	
					• Core saturation		• Significant damage (such as fire) to other components and subsystems			• Lifetime assessment and estimation during the design stage	
					• High voltage breakdown		• Electrical and thermal safety hazard				
					• Reduced current, voltage, and power handling capability		• User safety hazard and excessive energy exposure				
A.2	Y capacitor	Film or ceramic capacitor	Filter capacitor for common-mode emission	High temperature	• High ripple current	1	• High temperature might cause derating, short, open circuit, reduced lifetime, and so on	3	3	• Voltage, current, and temperature sensors	
					• Improper design, placement, and assembly		• Improper functionality and damage to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper capacitor derating during the design stage		• Electrical and thermal safety hazard			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Increased ripple current and power losses				
							• Increase of common-mode and differential-mode emissions				
							• User safety hazard				
				Electrical open circuit	• Over voltage failure due to voltage oscillations between active phases and ground	1	• Improper functionality of the filtering	3	3	Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• High ripple current		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
					• Mechanical failure (e.g., solder crack, disconnect from the board)		• User safety hazard.				
					• Improper soldering and assembly during manufacturing						
					• Improper capacitor derating during the design stage						
				Electrical short circuit	• Over voltage failure due to oscillations between active phases and ground	1	• Improper functionality of the filtering	4	4	• Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Mechanical failure		• Increase ground currents			• Quality control during manufacturing	
					• Improper design due to improper voltage clearance		• Electrical and thermal safety hazard				
					• High ripple current		• Increased ripple current and power losses				
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Increase of common-mode and differential-mode emissions				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper capacitor derating during the design stage		• User safety hazard.				
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure	1	• Mechanical broken of the component,	3	3	• Voltage, current, and temperature sensors,	
					• Degradation due to external factors (e.g., temperature, humidity, water, air pressure)		• Improper functionality of the system,			• Electrical and mechanical design requirements,	
					• Aging of electrical and mechanical components		• Damage to the components and subsystems,			• Quality control during manufacturing	
					• Excessive vibration during transportation due to poor mounting		• Electrical and thermal safety hazard,				
					• Fragile components subject to mechanical shocks (e.g., crash, vibration, collapse, drop off),		• Increased ripple current and power losses,				
					• Improper assembly and soldering during manufacturing,		• Increase of common-mode and differential-mode emissions,				
					• Improper mechanical design.		• User safety hazard.				
A.3	X capacitor	Film capacitor	Filter capacitor for differential mode emission	High temperature	• High voltage	1	• High temperature might cause reduced performance, short, open circuit, and so on,	3	3	• Voltage, current, and temperature sensors,	
					• High ripple current		• Improper functionality and damage to other components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper capacitor derating during the design stage		• Electrical and thermal safety hazard,			• Safety and quality control during manufacturing.	
					• Improper design		• Increased ripple current and power losses,				
							• Increase of common-mode and differential-mode emissions,				
							• User safety hazard.				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Electrical open circuit	• Excessive voltage due to grid voltage surges	1	• Improper functionality of the filtering	3	3	• Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• High ripple current		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
					• Mechanical failure		• User safety hazard.				
					• Improper soldering and assembly during manufacturing,						
					• Improper capacitor derating during the design stage.						
				Electrical short circuit	• Over temperature	1	• Improper functionality of the filtering	4	4	• Voltage, current, and temperature sensors	
					• Mechanical failure		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Improper design due to improper voltage clearance on the board		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
					• High ripple current		• Increased ripple current and power losses				
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Increase of common-mode and differential-mode emissions				
					• Improper capacitor derating during the design stage		• User safety hazard				
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure	1	• Physical damage to the component	3	3	• Voltage, current, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, air pressure)		• Improper functionality of the system			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Damage to the components and subsystems			• Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excessive vibration due to transportation and mounting		• Electrical and thermal safety hazard				
					• Improper assembly and soldering during manufacturing		• Increased ripple current and power losses				
							• Increase of common-mode and differential-mode emissions				
							• User safety hazard.				
A.4	EMI filter	Aluminum or copper cover plate or housing	Absorbs and suppresses high-frequency EMFs for EMI filter circuit	Mechanical aging and deformation	• Extreme temperature	1	• Mechanical deformation	3	3	• Electrical and mechanical design requirements	
					• Mechanical stress		• Electrical malfunctioning of the filter, and increase of common-mode and differential-mode emissions,			• Safety and quality control during manufacturing	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Damage to the other components and subsystems				
					• Improper mechanical design and installation		• Electrical and user safety hazard.				
					• Crash-induced damage						
					• Excessive vibration during transportation and operation, and so on						
				High temperature	• Improper thermal management	1	• Increase the temperature of other components	3	3	• Voltage, current, and temperature sensors	
					• Excessive loss in the EMI filter due to high density eddy currents		• Electrical and thermal safety hazard			• Electrical and mechanical design requirements	
							• Increased power losses			• Safety and quality control during manufacturing	
							• Increase of differential emissions				
							• User safety hazard due to high temperature exposure				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Electrical short circuit	• Contact to electrically live terminals and components	1	• Significant damage (such as fire) to other components and subsystems	4	4	• Voltage, current, and temperature sensors	
					• Crash-induced damage		• Electrical and thermal safety hazard			• Electrical and mechanical design requirements	
					• Mechanical aging and deformation		• Increased current and power losses			• Safety and quality control during manufacturing	
							• Increase of conductive and differential emissions				
							• User safety hazard and excessive energy exposure.				
				Excessive emissions and loss in the shield	• Mechanical breakdown, deformation, or crack in the shield	1	• Malfunctioning of the filter and increase of common-mode and differential-mode EMI	3	3	• Voltage, current, and temperature sensors	
					• Improper design		• Damage to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper mechanical design and installation		• Increased current and power losses			• Safety and quality control during manufacturing	
					• High eddy current loss in shield		• Electrical and user safety hazard				
							• Increased ambient temperature for other components				
							• Electrical and thermal safety hazard				
A.5	Filter inductor	Multi-turn inductor	Filter inductor for high-frequency ripples on the grid side	High voltage insulation breakdown	• Over voltage due to problems in the grid such as voltage swell, surge, transients, and so on	1	• Insulation breakdown between windings might cause electrical arc and short circuit	4	4	• Voltage, current, and temperature sensors	
					• Mechanical deformation (e.g., crash-induced damages)		• Significant damage to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper mechanical design and installation		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
					• Over temperature		• Increased current and power losses				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• Damage to functionality of filtering and not complying with grid requirements				
							• User safety hazard and energy exposure				
				Electrical open circuit	• Over temperature and breakdown of winding wire	1	• Open circuit between grid and XFC	3	3	• Voltage, current, and temperature sensors	
					• Mechanical failure		• Damage to the functionality of the filter system, and other components and subsystems			• Electrical and mechanical design requirements	
					• Improper assembly and soldering during manufacturing		• Electrical safety hazard			• Safety and quality control during manufacturing	
					• Improper mechanical design		• User safety hazard				
				Electrical short circuit	• Improper design for electrical or mechanical requirements	1	• Damage to the functionality of the filter system and other components and subsystems	4	4	• Voltage, current, and temperature sensors	
					• High voltage breakdown of the wire insulation		• Electrical and thermal safety hazard			• Electrical and mechanical design requirements	
					• Improper isolation clearance between the wires		• Increased high current and power losses			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure			• Place input relay contactor in front stage activated (opened) by fault signal	
				High temperature	• High core losses due to improper design	1	• High temperature could damage the wire insulation and increase the possibility of short circuit between windings	4	4	• Voltage, current, and temperature sensors,	
					• Degraded electrical property of the core material		• Damage to the functionality of the filter system, and other components and subsystems			• Electrical and mechanical design requirements,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• High conduction losses due to high current and/or conductivity degradation of wire		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing.	
					• Improper thermal design		• Increased high current and power losses				
							• User safety hazard				
				Mechanical failure	• Crash-induced mechanical failure	1	• Mechanical damage	4	4	Voltage, current, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, air pressure)		• Short circuit			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Damage grid filtering functionality and EMI filtering			• Safety and quality control during manufacturing	
					• Excessive vibration during transportation due to poor mounting		• Electrical and thermal safety hazard				
					• Improper assembly and soldering during manufacturing.		• Increased current and power losses				
							• User safety hazard				
A.6	Filter capacitor	Film capacitor	Filter capacitor for high-frequency ripples on the grid side	Capacitor short circuit	• Excessive voltage and current stresses	1	• Input of Rectifier/PFC will be shorted, resulting in high current in the front stage and EMI filter	4	4	• High voltage and current protection in front of the system,	
					• High power losses and inadequate heat dissipation in the capacitor, which may lead to dielectric failure depending on capacitor properties		• Excessive harmonics may damage the EMI filter leading to damage of other components and subsystems			• The input relay contactor in front stage with the fault signal,	
					• Aging of the capacitor		• High power losses at the front stage			• Temperature sensors,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the components within the short circuit path			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing.	
							• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Capacitor open circuit	• Excessive voltage or current stresses in the capacitor	1	• Inability to meet grid requirements and damage/loss of EMI filter	2	2	• High voltage and current protection	
					• Excessive heat dissipation		• High power losses and temperature due to high ripple current			• Place input relay contactor in front stage activated (opened) by fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage other components and subsystems			• Temperature sensors	
					• Aging factors and lifetime		• Electrical and thermal safety hazard			• Electrical and mechanical design requirements	
					• Improper design		• User safety hazard			• Safety and quality control during manufacturing	
				High temperature	• Excessive voltage and current stresses across the capacitor	1	• High power losses at the front stage	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to other components and subsystems			• The input relay contactor in front of the system for disconnection from the grid,	
					• Aging factors and lifetime		• Electrical and thermal safety hazard			• Temperature sensors,	
					• Improper design; improper manufacturing.		• User safety hazard			• Electrical and mechanical design requirements,	
										• Safety and quality control during manufacturing.	
A.7	Fuse	Low melting lead or zinc	Circuit overcurrent protection for high current conditions	Short circuit	• Does not open during overcurrent condition	1	• Damage to the other components and subsystems	3	3	• Using electronic fuse,	
					• Wrong type fuse selection		• Electrical and thermal safety hazard			• High voltage and current protection,	
					• Manufacturing error		• User safety hazard			• The input relay contactor in front stage with the fault signal,	
					• Mechanical failure due to improper assembly or soldering.					• Temperature sensors,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Electrical and mechanical design requirements, • Safety and quality operating conditions.	
A.8	Contactor	Relay circuit with operating switches	Connects the system to the grid and energizes the subsystem	Short circuit	• Does not function • Manufacturing design error • Mechanical failure due to improper assembly or soldering	1	• Damage other components and subsystems when the failure happens • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection, • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
A.9	Soft start circuit	Electronic circuit charging the DC link capacitor slowly through analog and digital circuits	Ramping the DC link voltage gradually to avoid grid instabilities and transients	Short circuit (not working properly)	• Crash-induced mechanical failure • Improper design during manufacturing • Non-functioning (not able to soft start) • Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure) • Improper assembly and soldering during manufacturing	1	• High voltage and current spikes during startup • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection, • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
A.10	Inrush current limiter circuit	Thermistor	Limit the inrush current	Short circuit	• Does not function • Manufacturing design error • Mechanical failure due to improper assembly or soldering • Crash-induced mechanical failure	1	• High voltage and current inrush during startup • Damage to other components and subsystems • Electrical and thermal safety hazard • User safety hazard	3	3	• High voltage and current protection, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing. • Using electronic fuse,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Open circuit	• Crash-induced mechanical failure	1	• Disconnect from the grid	3	3	• High voltage and current protection,	
					• Improper design		• Startup failure			• Electrical and mechanical design requirements,	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• User safety hazard			• Safety and quality control during manufacturing.	
					• Improper assembly and soldering during manufacturing		• Electrical and thermal safety hazard				
A.11	IGBT/MOSFET power modules	Insulated gate bipolar transistor	Rectifier/PFC system switching power module	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• Input voltage is shorted through the inductor, resulting in high input currents to the power electronic switch (IGBT), which damages the power module	4	8	• Short circuit protection in gate driver	
					• Gate driver output pulled high due to noise, failure, and so on		• Inductor saturation due to high current			• High voltage protection in front of Rectifier/PFC	
					• Inadequate heat dissipation		• High power losses in the inductor and switch power module			• The input relay contactor in front of Rectifier/PFC turning off with the fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the Rectifier/PFC inductor and switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Damage to front end components and subsystems (EMI filter, current limiter, soft-start circuit) before PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Power module open circuit	• Excessive voltage or current stresses in the switch module	2	• Rectifier/PFC might become a diode rectifier (leading to poor power factor, higher input harmonics, higher ripple)	3	6	• High voltage and current protection in front of rectifier/PFC	
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the inductor			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					• Quality control during manufacturing	
					• Improper design						
				High temperature	• Excessive voltage and current stresses across the switch module	1	• High power losses in the inductor and switch power module	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and excessive energy exposure.			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
										• Degradation monitoring of the	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										module on a regular basis	
		Silicon or silicon carbide MOSFETs	Rectifier/PFC system switching power module	One switch in the module shorted	• Excessive voltage, current and power stress across switch	2	• The DC voltage at rectifier output is periodically shorted when the complementary switch turns ON resulting in high shoot-through currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the inductor and switch power module			• Current/voltage sensors communicate fault to rectifier/PFC controller	
					• Inadequate heat dissipation		• High temperature in the rectifier/PFC filter inductor and switch power module				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				Both switches in the module shorted	• Excessive voltage, current and power stress across the module	1	• The DC voltage at rectifier output is permanently shorted resulting in high shoot-through currents	5	5	• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged due to high inrush current			• Current/voltage sensors communicate fault to rectifier/PFC controller	
					• Inadequate heat dissipation		• High temperature in the power module			• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors	
					• Mechanical failure						
A.12	Diode module	Rectifier/PFC circuit formed by semiconductor devices in a discrete package.	Rectifier/PFC system switching power module	Diode short circuit	• Excessive current	2	• Output voltage across the capacitor will be shorted when the switch power module is conducting, resulting in high currents into the switch power module,	4	8	• The input relay contactor in front of rectifier/PFC turns off when receiving fault signal	
					• Poor thermal dissipation		• High power losses in the switch power module			• High voltage and current protection in front of PFC	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage in rectifier/PFC and components and subsystems			• Electrical and mechanical design requirements	
					• Improper design during manufacturing		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure				
				Diode open circuit	• Excessive voltage stresses across the diode module	2	• Open circuit to the output,	3	6	• High voltage and current protection	
					• Inadequate heat dissipation		• XFC system will stop working.			• Input relay contactor in front of rectifier/PFC turns off when it	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing					• Electrical and mechanical design requirements.	
					• Aging factors						
					• Improper design						
				High temperature	• Excessive voltage or current stresses	1	• Damage of other components and subsystems	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard			• Input relay contactor in front of PFC turns off when it receives fault signal	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure.			• Temperature sensors	
					• Improper design					• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time					• Safety and quality control during manufacturing	
A.13	DC link capacitor	Film or electrolytic capacitor	Rectifier/PFC output capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage or current stresses	1	• Output of rectifier/PFC will be shorted, resulting in high current in the rectifier/PFC power modules	4	4	• High voltage and current protection in front of rectifier/PFC	
					• High power losses and heat dissipation across the capacitor, which may translate into dielectric failure depending on capacitor properties		• Power module may be damaged			• Input relay contactor in front of rectifier/PFC turns off when it receives a fault signal	
					• Aging of the capacitor		• High power losses in the rectifier/PFC			• Temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
					• Excessive voltage or current stresses in the capacitor		• Ripple at the output of the rectifier/PFC will appear at the input of the solid-state transformer			• High voltage and current protection in front of rectifier/PFC	
					• Inadequate heat dissipation		• Might damage the functionality of the solid-state transformer			• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal,	
				Capacitor open circuit	• Mechanical failure due to improper assembly or soldering during manufacturing	1	• High power losses and temperature in the solid-state transformer	3	3	• Temperature sensors	
					• Aging factors leading to degradation or failure		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure.			• Adequate voltage margin during the design stage	
					• Excessive voltage and current stresses across capacitor		• High power losses in the rectifier/PFC			• High voltage and current protection	
				High temperature	• Mechanical failure due to improper assembly or soldering during manufacturing	1	• Damage to the other components and subsystems	4	4	• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing.	
A.14	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET/IGBT switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
A.15	Gate driver circuitry	An integrated circuit that provides isolation to the LV and	Controls the turn-on and turn-off of the switches in the power	Output of gate driver constant high	• Analog/digital circuitry failure,	1	• Input voltage is shorted through the inductor, resulting in high input currents to the switch	4	4	• Short circuit protection in gate driver	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
		low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module IGBTs	modules of the rectifier/PFC				and damage power module				
					• Mechanical assembly failure,		• Inductor saturation due to high current			• High voltage protection in front of rectifier/PFC	
					• PCB circuit failure,		• High power losses in the inductor and power module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Improper circuit design		• High temperature in the inductor and power module			• Temperature sensors	
							• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
							• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				Output of gate driver constant low	• Analog/digital circuitry failure	1	• Inductor might be saturated	3	3	• High voltage and current protection in front of rectifier/PFC	
					• Gate driver isolated power supply failure		• High temperature in the inductor			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical assembly failure		• Electrical and thermal safety hazard			• Temperature sensors	
					• PCB circuit failure		• User safety hazard			• Electrical and mechanical design requirements	
					• Improper circuit design					• Safety and quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit	4	8	• High voltage and current protection in front of rectifier/PFC	
					• Mechanical assembly failure		• Excessive currents during short circuit			• Input relay contactor in front of rectifier/PFC	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										turns off when it receives fault signal	
					• PCB circuit failure		• Damage the power module during short			• Temperature sensors	
					• Improper circuit design		• Inductor saturation due to high current			• Electrical and mechanical design requirements	
							• High power losses in the inductor and switch power module			• Safety and quality control during manufacturing	
							• High temperature in the inductor and switch power module				
							• Damage to the other components and subsystems				
							• Electrical and thermal safety hazard				
							• User safety hazard and energy exposure				
A.16	DC voltage sensor	Electronic analog to digital circuit	Measures the DC link voltage for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on	
					• Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• High voltage protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the DC link due to sag, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High voltage protection sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
A.17	Grid voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• High voltage protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Electrical safety hazard,			• Electrical and mechanical design requirements	
							• User safety hazard.			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to sag, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High voltage protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature,		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					humidity, water, mechanical pressure)						
					• Improper design		• High temperature in the rectifier/PFC			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
A.18	Grid current sensor	Electronic analog to digital circuit	Measures the grid current for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes		• High power losses in the rectifier/PFC			• High current protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Damage other components and subsystems,			• Electrical and mechanical design requirements	
							• Electrical safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard				
				Short circuit (not working properly)	• Excessive current at the grid side due to inrush, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High current protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design		• High temperature in the rectifier/PFC			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Damage to other components and subsystems				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical safety hazard				
					•		• User safety hazard				
A.19	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in rectifier/PFC	Out of calibration	• Aging factors	1	• Overheating of critical components in rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• MCU calibration reset in each cycle due to malfunction, and so on	
					• Excess heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard			• Over voltage and overcurrent protection sensors	
										• Additional, redundant temperature sensors are used at different locations	
										• Electrical and mechanical design requirements	
										• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Possibly damage other components and subsystems	4	4	• Over voltage and overcurrent protection sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• Additional multiple temperature sensors at different locations,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard			• Electrical and mechanical design requirements	
										• Safety and quality control during manufacturing	
B. Solid-state transformer											
B.1	IGBT/MOSFET power modules	Insulated gate bipolar transistor	Converts the DC voltage to high-frequency square or quasi-square AC voltage	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• The input voltage is shorted resulting in high input currents to the switch and damage to the power module	4	8	• Short circuit protection in gate driver	
					• Gate driver output pulled high due to noise, failure, and so on		• PFC inductor saturation due to high current			• High voltage protection in front of Rectifier/PFC	
					• Inadequate heat dissipation		• High power losses in the inductor and switch power module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the Rectifier/PFC inductor and switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage PFC components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				Power module open circuit	• Excessive voltage and current stresses in the switch module	2	• High temperature in power module	3	6	• Over voltage and overcurrent protection in front of rectifier/PFC	
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the PFC inductor			• Input relay contactor in front of rectifier/PFC turns off when it	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										receives fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					Safety and quality control during manufacturing	
					• Improper design						
				High temperature	• Excessive voltage and current stresses in the switch module	1	• High power losses in the inductor and switch power module	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and excessive energy exposure			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
										• Degradation monitoring of the module on a regular basis	
		Silicon or silicon carbide MOSFETs	Converts the DC voltage to high-frequency square or quasi-square AC voltage	One switch in the module shorted	• Excessive voltage, current and power stress in switch	2	• The DC voltage at inverter input is periodically shorted when the complementary switch turns ON resulting in high shoot-through currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Gate driver output pulled high		• High power losses in the inductor and switch power module			• Current/voltage sensors communicate fault to upstream rectifier/PFC	
					• Inadequate heat dissipation		• High temperature in the rectifier/PFC filter inductor and switch power module				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				Both switches in the module shorted	• Excessive voltage, current and power stress in the module	1	• The DC voltage at inverter input is permanently shorted resulting in high shoot-through currents	5	5	• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged due to high inrush current			• Current/voltage sensors communicate fault to upstream rectifier/PFC	
					• Inadequate heat dissipation		• High temperature in the power module			• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										solid-state transformer controller	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state transformer controller	
					• Mechanical failure						
B.2	Diode module	Diodes in discrete packages.	Converts the DC voltage to high-frequency square or quasi-square AC voltage (Diodes are anti-parallel with active switches (IGBTs, MOSFETs)	Diode short circuit	• Excessive voltage and current stresses	2	• The input voltage across the capacitor will be shorted when the MOSFET module is conducting, resulting in high shoot-through currents into the switch power module	3	6	• Desaturation (Desat) protection in gate driver	
					• Inadequate heat dissipation,		• High power losses in the switch power module			• Input relay contactor in front of rectifier/PFC turns off after receiving the fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage the inverter components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure				
				Diode open circuit	• Excessive voltage and current stresses across the diode module	2	• Reverse current flows through MOSFET body diode	2	4	• Temperature sensors	
					• Inadequate heat dissipation		• High power losses in the MOSFET module			• Input relay contactor in front of rectifier/PFC	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										turns off when it receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the MOSFET module			• Electrical and mechanical design requirements	
					• Aging factors		• Electrical and thermal safety hazard				
					• Improper design		• User safety hazard and excessive energy exposure				
				High temperature	• Excessive voltage or current stresses	1	• Damage to other components and subsystems	3	3	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure			• Temperature sensors	
					• Improper design					• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
B.3	DC link capacitor	Film or electrolytic capacitor	PFC output capacitor for DC link voltage smoothing	One capacitor short circuit	• Excessive voltage or current stresses	1	• Voltage stress on the other capacitor will increase	4	4	• Over voltage and overcurrent protection in MOSFET modules	
					• High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor properties		• Voltage stress on primary winding will increase			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Aging of the capacitor		• Increase current in MOSFET module and transformer windings			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard			• Electrical and mechanical design requirements	
					• Improper design		• User safety hazard and energy exposure			• Safety and quality control during manufacturing	
							• Damage to the other components and subsystems				
				Both capacitors short circuit	• Excessive voltage or current stresses	1	• The input of the inverter will be shorted, resulting high current in the rectifier/PFC	4	4	• Over voltage and overcurrent protection in front of rectifier/PFC,	
					• High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor properties		• Possible damage to the rectifier/PFC power module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging of the capacitor		• High power losses in the rectifier/PFC			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				One capacitor open circuit	• Excessive voltage or current stresses in the capacitor	1	• Voltage stress on primary winding will increase,	3	3	• Over voltage and overcurrent protection in MOSFET modules	
					• High power losses and heat dissipation across the capacitor, which may translate in dielectric failure depending on capacitor property		• Increase current in MOSFET module and transformer windings,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure.			• Temperature sensors,	
					• Aging factors		• Damage to the other components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard,			• Safety and quality control during manufacturing.	
							• User safety hazard and excessive energy exposure.			• Adequate voltage derating during the design stage.	
				Both capacitors open circuit	• Excessive voltage or current stresses in the capacitor	1	• Inverter is disconnected with the input	2	2	• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• No power flows to vehicle side			• Electrical and mechanical design requirements,	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• User safety hazard and excessive energy exposure.			• Safety and quality control during manufacturing.	
					• Aging factors						
					• Improper design						
				High temperature	• Excessive voltage or current stresses in the capacitor	1	• High power losses in the inverter,	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to the other components and subsystems,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging factors		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• Improper design		• User safety hazard and energy exposure.			• Electrical and mechanical design requirements,	
										• Safety and quality control during manufacturing.	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
B.4	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module MOSFETs	Controls the turn-on and turn-off of the switches in the power modules of the inverter of solid-state transformer	Output of gate driver constant high	• Analog/digital circuitry failure	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module,	4	4	• Short circuit protection in gate driver,	
					• Mechanical assembly failure		• rectifier/PFC output capacitor short circuit			• High voltage protection in front of rectifier/PFC,	
					• PCB circuit failure		• High power losses in the power module,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Improper circuit design		• High temperature in and power module,			• Temperature sensors,	
							• Damage components and subsystems in front of the inverter,			• Electrical and mechanical design requirements,	
							• Electrical and thermal safety hazard,			• Safety and quality control during manufacturing.	
							• User safety hazard and energy exposure.				
				Output of gate driver constant low	• Analog/digital circuitry failure	1	• Unbalanced DC link capacitor	3	3	• High voltage and current protection in the inverter	
					• Gate driver isolated power supply failure		• High voltage stress in one of the DC capacitors			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical assembly failure		• Electrical and thermal safety hazard,				
					• PCB circuit failure		• User safety hazard.			• Electrical and mechanical design requirements	
					• Improper circuit design		• No power delivered to vehicle side			• Safety and quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit,	4	8	• High voltage and current protection in rectifier/PFC stage,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical assembly failure		• Excessive currents during short circuit,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• PCB circuit failure		• Damage the power module during short,			• Temperature sensors	
					• Poor circuit design		• Inductor saturation due to high current,			• Electrical and mechanical design requirements	
							• High power losses in the inductor and switch power module,			• Safety and quality control during manufacturing	
							• High temperature in the inductor and switch power module,				
							• Damage MOSFET modules and subsystems,				
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
B.5	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	3	3	Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
B.6	DC voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excess heat generation or Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the PFC,			• High voltage protection sensors,	
							• High temperature in the PFC,			• Temperature sensors	
							• Electrical safety hazard,			• Electrical and mechanical design requirements	
							• User safety hazard.			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to voltage swell, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High voltage protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the PFC,			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design		• High temperature in the PFC,			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard.				
B.7	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in PFC	Out of calibration	• Aging factors	1	• Overheating of critical components in inverter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excess heat generation or Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard.			• High voltage and current protection sensors,	
										• Additional, redundant temperature are used sensors at different locations,	
										• Electrical and mechanical design requirements,	
										• Safety and quality control during manufacturing.	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Might damage with other components and subsystems,	4	4	• High voltage and current protection sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• Additional multiple temperature sensors with the different locations,	
					• Mechanical failure due to improper		• User safety hazard.			• Electrical and mechanical design requirements,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					assembly or soldering during manufacturing.						
										• Safety and quality control during manufacturing.	
B.8	Litz wire–based coil	Multiturn coil made with Litz wire	Carries high-frequency AC current and generates AC magnetic field	Electrical short-circuit	• High voltage breakdown of insulation layers	1	• Significant damage in other components and subsystems	5	5	• Current and temperature sensor	
					• Improper electrical/mechanical design		• Thermal hazard and mechanical damage			• Safety and control requirements	
							• Significant increase in EMF emissions			• Electrical and mechanical design requirements	
										• Quality and safety test for diverse operating conditions	
				Electrical open circuit	• Mechanical failure	1	• Significant damage in other components and subsystems	4	4	• Current and temperature sensor	
					• Crash-induced open wire		• Thermal hazard and mechanical damage			• Safety and control requirements	
					• Over tensioned (stretched)		• Significant increase in EMF emissions			• Electrical and mechanical design requirements	
					• Over temperature					• Quality and safety test for diverse operating conditions	
				Mechanical failure	• Over tensioned (stretched)	1	• Increase in electrical resistivity and loss	5	5	• Electrical and mechanical design requirements	
					• Crash-induced mechanical failure		• Electrical open or short circuit			• Quality and safety test for diverse operating conditions	
					• Over temperature		• Electrical safety hazard			• Safety and control requirements	
							• User exposure to energized component of the charging pad				
				High temperature	• Excessive high power loss	1	• Significant damage in other components and subsystems	5	5	• Current and temperature sensor	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper thermal design		• Increase in electrical resistivity and loss			• Safety and control requirements	
							• Electrical open or short circuit			• Electrical and mechanical design requirements	
							• Electrical and thermal safety hazard			• Quality and safety test for diverse operating conditions	
				High-voltage insulation failure	• Poor design/manufacturing	1	• Electrical open or short circuit	2	2	• Electrical and mechanical design requirements	
					• Mechanical deformation of the charging pad		• Electrical and thermal safety hazard			• Current and temperature sensor	
					• Over voltage operation		• Significant damage in other components and subsystems			• Safety, quality, and control requirements	
										• Safety and quality test for diverse operating conditions	
				Conductivity degradation	• Mechanical degradation	2	• Increase in electrical resistivity,	4	8	• Electrical and mechanical design requirements	
					• Over temperature		• Increase in loss, Over temperature			• Current and temperature sensor	
					• Internal insulation failure due to high temperature or high voltage					• Safety, quality, and control requirements	
										• Safety and quality test for diverse operating conditions	
B.9	Nanocrystalline core	Made with high-permeability magnetic material, such as nanocrystalline . Nanocrystalline is a highly brittle material	1. Guides the magnetic flux, 2. Increases the self and mutual inductances	High temperature	• Large hysteresis loss	2	• Increased resistivity and loss in the coil	4	8	• Electrical and mechanical design requirements	
					• Poor thermal design		• Degraded performance of the core			• Current and temperature sensor	
					• Large current in the coils		• Thermal runaway			• Safety, quality, and control requirements	
										• Safety and quality test for diverse	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										operating conditions	
				High loss	• Large hysteresis loss • Large current in the coils • Eddy current loss • Poor design • Degraded electrical property of ferrites • Increased temperature	1	• Over temperature in the core and coil • Drop in system efficiency	5	5	• Electrical and mechanical design requirements • Safety, quality, and control requirements	
				Mechanical breakdown	• Nanocrystalline is extremely brittle • Excessive pressure on the charging pad • Improper mechanical design	4	• Slightly reduced self and mutual inductances	1	4	• Mechanical design requirements of the core as well as surround materials • Safety and quality test for diverse operating conditions	
B.10	Metallic enclosure	Metallic enclosure for high-frequency transformer	Protect the magnetic component of high-frequency transformer Provide mechanical support and allow for adequate heat dissipation	Mechanical failure/ breakdown	• Over pressure (mechanical) Over temperature	1	• Damage the transformer coil and core	1	1	• Electrical and mechanical design requirements Safety and quality test for diverse operating conditions	
				Puncture/ intrusion of foreign object	• Crash-induced puncture	1	• Damage the transformer coil and core	1	1	• Electrical and mechanical design requirements Quality control during manufacturing	
B.11	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in PFC	Out of calibration	• Aging factors • Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)	1	• Overheating of transformer • Electrical safety hazard,	3	3	• Calibration is conducted or validated periodically • MCU calibration reset in each cycle due to malfunction and so on,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excessive heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard.			• Additional, redundant temperature are used sensors at different locations,	
										• Electrical and mechanical design requirements,	
										• Safety and quality control during manufacturing.	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Might damage with other components and subsystems,	4	4	• High voltage and current protection sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• Additional multiple temperature sensors with the different locations,	
					• Mechanical failure due to improper assembly or soldering during manufacturing.		• User safety hazard.			• Electrical and mechanical design requirements,	
										• Quality control during manufacturing	
B.12	Resonant capacitor	Film (metallized or polypropylene film) capacitor	Part of the resonant network to achieve resonance at the desired frequency	Capacitor failed short circuit	• Excessive voltage, current and power stress in the capacitor	2	• Distorted input current, reduced output power as resonance is lost	2	4	• Fault communicated by dedicated sensors and also from the controller	
				Capacitor failed open circuit	• Excessive voltage, current and power stress in the capacitor	1	• No power transfer	2	2	• Fault communicated by dedicated sensors and also from the controller	
					• Mechanical failure						
B.13	Compensation inductor	Ferrite inductors with Litz wire used for the winding	Part of the resonant network to achieve resonance at the desired frequency (typically used in higher order networks,	Inductor failed open circuit	• Mechanical shock or stress or assembly issues (both coil and core)	1	• No output power	2	2	• Fault communicated by dedicated sensors and also from the controller	
				Inductor failed short circuit	• Excessive current stress causing inductor to saturate	1	• No output power	2	2	• Fault communicated by dedicated sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
			example: In LCC series compensation the series inductor helps to maintain a constant coil current at resonance)		• Insulation breakdown of coil					and also from the controller	
B.14	Semiconductor power module (generally MOSFETs)	Silicon carbide MOSFETs	Converts the high-frequency square or quasi-square AC voltage to DC voltage	One switch in the module shorted	• Excessive voltage, current and power stress in switch.	2	• The DC voltage at rectifier output is periodically shorted when the complementary switch turns ON resulting in high input currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the MOSFET module,				
					• Inadequate heat dissipation		• High temperature in the MOSFET module,				
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Electrical and thermal safety hazard,				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				Both switches in the module shorted	• Excessive current and power stress in the MOSFET module	1	• The DC voltage at rectifier output is permanently shorted resulting in high input currents	5	5	• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged due to high inrush current			• Current/voltage sensors communicate fault to upstream PFC	
					• Inadequate heat dissipation		• High temperature in the power module,			• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Electrical and thermal safety hazard,				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state transformer controller	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state transformer controller	
					• Mechanical failure						
B.15	Diode module	Diodes in discrete packages.	Converts high-frequency square or quasi-square AC voltage to the DC voltage	Diode short circuit	• Excessive voltage or current stresses	2	• The input voltage across the capacitor will be shorted when the MOSFET module is conducting, resulting in high shoot-through currents into the switch power module,	3	6	• DESAT protection in gate driver,	
					• Inadequate heat dissipation,		• High power losses in the switch power module,			• The input relay contactor in front of rectifier/PFC turning off with the fault signal,	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module,			• Temperature sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage the inverter components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper design during manufacturing		• Electrical and thermal safety hazard,			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• User safety hazard and excessive energy exposure.				
				Diode open circuit	• Excessive voltage and current stresses in the diode module	2	• Reverse current flows through MOSFET body diode	2	4	Temperature sensors,	
					• Inadequate heat dissipation		• High power losses in the MOSFET module			The input relay contactor in front of rectifier/PFC turning off with the fault signal,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the MOSFET module,			Electrical and mechanical design requirements.	
					• Aging factors		• Electrical and thermal safety hazard,				
					• Improper design		• User safety hazard and excessive energy exposure.				
				High temperature	• Excessive voltage or current stresses	1	• Damage with the other components and subsystems,	3	3	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard,			• The input relay contactor in front of rectifier/PFC turning off with the fault signal,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure.			• Temperature sensors,	
					• Improper design					• Electrical and mechanical design requirements,	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time					• Quality control during manufacturing	
B.16	DC link capacitor	Film or electrolytic capacitor	Solid-state transformer output capacitor for DC link	Capacitor short circuit	• Excessive voltage or current stresses	1	• The output of rectifier will be shorted, resulting high current in the rectifier,	4	4	• High voltage and current protection in solid-state transformer stage,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
			voltage smoothing		• High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor properties		• Might damage the rectifier power module,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Aging of the capacitor		• High power losses in the rectifier,			• Temperature sensors,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the rectifier,			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard,			• Safety and quality control during manufacturing.	
							• User safety hazard and energy exposure.				
				Capacitor open circuit	• Excessive voltage and current stresses across the capacitor	1	• Ripple at the output of the solid-state transformer stage will appear at the input of vehicle DC-DC converter stage,	2	2	• High voltage and current protection in solid-state transformer stage,	
					• Inadequate heat dissipation		• Might damage the functionality of the solid-state transformer stage system.			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High power losses and temperature in the solid-state transformer stage system,			• Temperature sensors,	
					• Aging factors		• Damage to the other components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
							• User safety hazard and excessive energy exposure.			• Adequate voltage derating during the design stage.	
				High temperature	• Excessive voltage or current stresses in capacitor	1	• High power losses in the solid-state transformer stage,	4	4	• High voltage and current protection,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Damage to the other components and subsystems,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Aging factors		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• Improper design		• User safety hazard and energy exposure.			• Electrical and mechanical design requirements,	
										• Quality control during manufacturing	
B.17	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module IGBTs	Controls the turn-on and turn-off of the switches in the power modules of the solid-state transformer	Output of gate driver constant high	• Analog/digital circuitry failure	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module,	4	4	• Short circuit protection in gate driver,	
					• Mechanical assembly failure		• Inductor saturation due to high current,				
					• PCB circuit failure		• High power losses in the inductor and power module,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Improper circuit design		• High temperature in the inductor and power module,			• Temperature sensors,	
							• Damage solid-state transformer components and subsystems,			• Electrical and mechanical design requirements,	
							• Electrical and thermal safety hazard,			• Quality control during manufacturing	
							• User safety hazard and energy exposure.				
				Output of gate driver constant low	• Analog/digital circuitry failure	1	• Inductor might be saturated,	3	3	• High voltage and current protection in front of PFC,	
					• Gate driver isolated power supply failure		• High temperature in the inductor,			• The input relay contactor in front of PFC turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical assembly failure		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• PCB circuit failure		• User safety hazard.			• Electrical and mechanical design requirements,	
					• Improper circuit design					• Quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit,	4	8	• High voltage and current protection in front of PFC,	
					• Mechanical assembly failure		• Excessive currents during short circuit,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• PCB circuit failure		• Damage the power module during short,			• Temperature sensors,	
					• Poor circuit design		• Inductor saturation due to high current,			• Electrical and mechanical design requirements,	
							• High power losses in the inductor and switch power module,			• Quality control during manufacturing	
							• High temperature in the inductor and switch power module,				
							• Damage in front of PFC components and subsystems,				
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
B.18	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of	4	8	• Temperature sensor communicates to microcontroller for	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							the MOSFET switches, increase in losses and damage of the switches			protective action, gate driver turns OFF the MOSFETs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
B.19	Output current sensor	Electronic analog to digital circuit	Measure the output current of solid-state transformer for resonant control and protection	Out of calibration	• Aging factors	1	• Might damage the solid-state transformer stage,	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Break the functionality of solid-state transformer stage,			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the solid-state transformer stage,			• High current protection sensors,	
							• High temperature in the solid-state transformer stage,			• Temperature sensors,	
							• Electrical safety hazard,			• Electrical and mechanical design requirements,	
							• User safety hazard.			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Short circuit (not working properly)	• Excessive current due to sag, transient, and so on	1	• Might damage the solid-state transformer stage,	4	4	• High current protection sensors,	
					• Analog/digital circuitry failure		• Break the functionality of solid-state transformer stage,			• Temperature sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the solid-state transformer stage,			• Electrical and mechanical design requirements,	
					• Improper design		• High temperature in the solid-state transformer stage,			• Quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard.				
B.20	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in PFC	Out of calibration	• Aging factors	1	• Overheating of critical components in the rectifier	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• MCU calibration reset in each cycle due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard			• Over voltage and overcurrent protection sensors	
										• Additional, redundant temperature are used sensors at different locations	
										• Electrical and mechanical design requirements	
										• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure) • Mechanical failure due to improper assembly or soldering during manufacturing	1	• Possible damage to other components and subsystems • Electrical safety hazard • User safety hazard	4	4	• Over voltage and over current protection sensors • Additional multiple temperature sensors at different locations • Electrical and mechanical design requirements • Quality control during manufacturing	
C. Vehicle side											
C.1	Input DC capacitor	Film or electrolytic capacitor	DC-DC input capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage or current stresses • High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor property, • Aging of the capacitor • Mechanical failure due to improper assembly or soldering during manufacturing • Improper design	1	• The input of DC-DC converter will be shorted, resulting in high current in the solid-state transformer • Possible damage to the solid-state transformer power module • High power losses in the solid-state transformer • High temperature in the solid-state transformer • Electrical and thermal safety hazard • User safety hazard and energy exposure.	4	4	• Over voltage and overcurrent protection in solid-state transformer stage • Input relay contactor in front of PFC turns off after receives fault signal • Temperature sensors • Electrical and mechanical design requirements • Quality control during manufacturing	
				Capacitor open circuit	• Excessive voltage or current stresses in the capacitor	1	• Possible damage to the DC-DC converter power modules	4	4	• Over voltage and overcurrent protection in DC-DC converter power modules	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Inadequate heat dissipation		• Ripple at the output of the solid-state transformer will appear at the input of DC-DC converter			• Input relay contactor in front of PFC turns off after receives a fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High power losses in DC-DC converter power modules			• Temperature sensors,	
					• Aging factors		• Damage to the other components and subsystems			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard			• Quality control during manufacturing	
							• User safety hazard and excessive energy exposure			• Adequate voltage derating during the design stage.	
				High temperature	• Excessive voltage or current stresses in capacitor	1	• High power losses in the capacitor,	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Damage to the other components and subsystems,			• Input relay contactor in front of PFC turns off after receives a fault signal	
					• Aging factors		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• Improper design		• User safety hazard and energy exposure.			• Electrical and mechanical design requirements,	
										• Quality control during manufacturing	
C.2	IGBT/MOSFET power modules	Insulated gate bipolar transistor	Converts the high DC voltage to low DC voltage suitable for EV charging	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• The input voltage is shorted, resulting in high input currents to the switch and damage power module,	4	8	• Short circuit protection in gate driver,	
					• Gate driver output pulled high due to noise, failure, and so on		• PFC inductor saturation due to high current,			• High voltage protection in front of Rectifier/PFC,	
					• Excess heat generation or Inadequate heat dissipation due to		• High power losses in the inductor and switch power module,			• Input relay contactor in front of rectifier/PFC turns off after	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					inaccurate circuit design and component tolerance changes.					receives a fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the Rectifier/PFC inductor and switch power module,			• Temperature sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage solid-state transformer components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper design		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
							• User safety hazard and energy exposure.				
				Power module open circuit	• Excessive voltage or current stresses in the power module	2	• High temperature in power module,	3	6	• High voltage and current protection in front of rectifier/PFC,	
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the PFC inductor,			• Input relay contactor in front of rectifier/PFC turns off after receives a fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure.			• Electrical and mechanical design requirements,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					• Quality control during manufacturing	
					• Improper design during manufacturing						
				High temperature	• Excessive voltage or current stresses in the power module	1	• High power losses in the inductor and switch power module,	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage solid-state transformer components and subsystems,			• Input relay contactor in front of rectifier/PFC turns off after it	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										receives a fault signal	
					• Aging factors		• Electrical and thermal safety hazard,			• Temperature sensors	
					• Improper design during manufacturing		• User safety hazard and excessive energy exposure.			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Quality control during manufacturing	
										• Degradation monitoring of the module on a continuous or regular basis	
		Silicon or silicon carbide MOSFETs	Converts the high DC voltage to low DC voltage suitable for EV charging	One switch in the module shorted	• Excessive voltage, current and power stress in switch	2	• The DC voltage at inverter input is periodically shorted when the complementary switch turns ON resulting in high input currents	3	6	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the inductor and switch power module,				
					• Excessive heat generation		• High temperature in the DC-DC output inductor and switch power module,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard,				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				Both switches in the module shorted	• Excessive voltage, current and power stress in the module	2	• DC voltage at inverter input is permanently shorted resulting in high input currents	3	6	• The input relay-contactor turns OFF	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Gate driver output pulled high for both switches • Excessive heat generation • Mechanical failure due to improper assembly or soldering during manufacturing • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure) • Improper design		• DC link capacitor can be damaged due to high inrush current • High temperature in the power module, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.			• Current/voltage sensors communicate fault to upstream PFC • Short circuit protection in gate driver turns OFF the module entirely	
				One module is open circuited	• Excessive heat generation • Mechanical failure	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the DC-DC converter control unit	
				Both modules are open circuited	• Excessive heat generation • Mechanical failure	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the DC-DC converter control unit	
C.3	Diode module	Diode in discrete package.	Converts the high DC voltage to low DC voltage suitable for EV charging	Diode short circuit	• Excessive voltage or current stresses • Excessive heat generation	2	• The input voltage across the capacitor will be shorted when the MOSFET module is conducting, resulting in high shoot-through currents into the switch power module, • High power losses in the switch power module,	3	6	• Overcurrent protection in gate driver, • Input relay contactor in front of rectifier/PFC turns off after receives a fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure) • Improper design during manufacturing		• High temperature in the switch power module, • Damage the inverter components and subsystems, • Electrical and thermal safety hazard, • User safety hazard and excessive energy exposure.			• Temperature sensors • Electrical and mechanical design requirements • Quality control during manufacturing	
				Diode open circuit	• Excessive voltage and current stresses in the diode module • Inadequate heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging factors • Improper design	2	• Reverse current flows through MOSFET body diode • High power losses in the MOSFET module • High temperature in the MOSFET module, • Electrical and thermal safety hazard, • User safety hazard and excessive energy exposure.	2	4	• Temperature sensors • Input relay contactor in front of rectifier/PFC turns off after receives a fault signal • Electrical and mechanical design requirements	
				High temperature	• Excessive voltage and current stresses • Mechanical failure due to improper assembly or soldering during manufacturing • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)	1	• Damage with the other components and subsystems, • Electrical and thermal safety hazard, • User safety hazard and excessive energy exposure.	3	3	• High voltage and current protection • Input relay contactor in front of rectifier/PFC turns off after receives a fault signal • Temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design					• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Quality control during manufacturing	
C.4	Filter inductor	Multi-turn inductor	Filter inductor for high-frequency ripples	High voltage insulation breakdown	• Over voltage due to problems in the grid such as voltage swell, surge, transients, and so on	1	• Insulation breakdown between windings might cause electrical arc and short circuit,	4	4	• Voltage, current, and temperature sensors	
					• Mechanical deformation (e.g., crash-induced damage)		• Significant damage to the other components and subsystems,			• Electrical and mechanical design requirements	
					• Improper mechanical design and installation		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
					• Over temperature		• Increased current and power losses,				
							• Damage to functionality of filtering and not complying with grid requirements,				
							• User safety hazard and energy exposure.				
				Electrical open circuit	• Over temperature causing winding breakdown (broken wire)	1	• Open circuit between DC-DC converter and EC battery	3	3	• Voltage, current, and temperature sensors	
					• Mechanical failure		• Damage to the functionality of the filter system, and other components and subsystems,			• Electrical and mechanical design requirements	
					• Improper assembly and soldering during manufacturing		• Electrical safety hazard,			• Quality control during manufacturing	
					• Improper mechanical design		• User safety hazard.				
				Electrical short circuit	• Improper design for electrical or	1	• Damage to the functionality of the filter system, and other	4	4	• Voltage, current, and temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					mechanical requirements		components and subsystems,				
					• High voltage breakdown of the wire insulation		• Electrical and thermal safety hazard,			• Electrical and mechanical design requirements	
					• Improper isolation clearance between the wires		• Increased high current and power losses,			• Quality control during manufacturing	
							• User safety hazard and energy exposure.				
				High temperature	• High core losses due to improper design	1	• High temperature might break the wire insulation and increase the possibility of short circuit between windings,	4	4	• Voltage, current, and temperature sensors	
					• Degraded electrical property of the core material		• Damage to the functionality of the filter system, and other components and subsystems,			• Electrical and mechanical design requirements	
					• High conduction losses due to high current and/or conductivity degradation of wire		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
					• Improper thermal design		• Increased high current and power losses,				
							• User safety hazard.				
				Mechanical failure	• Crash-induced mechanical failure	1	• Mechanical damage,	4	4	• Voltage, current, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Short circuit			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Damage grid filtering functionality and EMI filtering,			• Quality control during manufacturing	
					• Excessive vibration due to transportation and mounting		• Electrical and thermal safety hazard,				
					• Improper assembly and soldering during manufacturing		• Increased current and power losses,				
							• User safety hazard.				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
C.5	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module MOSFETs	Controls the turn-on and turn-off of the switches in the power modules of the DC-DC stage	Output of gate driver constant high	• Analog/digital circuitry failure	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module,	4	4	• Short circuit protection in gate driver	
					• Mechanical assembly failure		• Inductor saturation due to high current,			• Input relay contactor in front of PFC turns off after receives a fault signal	
					• PCB circuit failure		• High power losses in the inductor and power module,			• Temperature sensors	
					• Improper circuit design		• High temperature in the inductor and power module,			• Electrical and mechanical design requirements	
							• Damage MOSFETs and subsystems in DC-DC converter,			• Quality control during manufacturing	
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
				Output of gate driver constant low	• Analog/digital circuitry failure	1	• EV battery is (partially) disconnected	3	3	• Input relay contactor in front of PFC turns off after receives a fault signal	
					• Gate driver isolated power supply failure		• Power delivered to EV battery is reduced			• Electrical and mechanical design requirements	
					• Mechanical assembly failure		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
					• PCB circuit failure		• User safety hazard.				
					• Improper circuit design						
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit,	4	8	• Over voltage and overcurrent protection in DC-DC converter stage	
					• Mechanical assembly failure		• Excessive currents during short circuit,			• Input relay contactor in front of rectifier/PFC turns off after	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										receives a fault signal	
					• PCB circuit failure		• Damage the power module during short,			• Temperature sensors	
					• Improper circuit design		• Inductor saturation due to high current,			• Electrical and mechanical design requirements	
							• High power losses in the inductor and switch power module,			• Quality control during manufacturing	
							• High temperature in the inductor and switch power module,				
							• Damage other components in DC-DC converter and the corresponding subsystems,				
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
C.6	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	
										• Temperature sensor communicates to	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										microcontroller for protective action, gate driver turns OFF the MOSFETs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs	
C.7	Input DC voltage sensor	Electronic analog to digital circuit	Measures the input voltage for DC-DC converter controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the DC-DC converter	3	3	• Calibration is conducted or validated periodically	Back-up capacitor voltage sensor. The input DC voltage sensor for the DC-DC converter is the same measurement as output DC voltage sensor of solid-state transformer
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure),		• DC-DC converter does not function properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Might increase power losses in the DC-DC converter			• High voltage and current protection sensors	
							• High temperature in the DC-DC converter			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to swell, transient, and so on,	1	• Possible damage to the DC-DC converter	4	4	• Overcurrent protection sensors	
					• Analog/digital circuitry failure		• DC-DC converter does not function properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High temperature in the DC-DC converter			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design		• Electrical safety hazard			• Quality control during manufacturing	
					• PCB circuit design failure		• User safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing						
C.8	Output DC voltage sensor	Electronic analog to digital circuit	Measures the output voltage for DC-DC converter controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the DC-DC converter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• DC-DC converter does not function properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Might increase power losses in the DC-DC converter			• High voltage protection sensors	
							• High temperature in the DC-DC converter			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to swell, transient, and so on	1	• Possible damage to the DC-DC converter	4	4	• High voltage protection sensors	
					• Analog/digital circuitry failure		• DC-DC converter does not function properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DC-DC converter			• Electrical and mechanical design requirements	
					• Improper design during manufacturing		• High temperature in the DC-DC converter			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• PCB circuit design failure		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
C.9	Output current sensor	Electronic analog to digital circuit	Measures the input current for DC-DC converter stage controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the DC-DC converter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• DC-DC converter does not function properly			• MCU calibration reset in each cycle due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Possibly increase power losses in the DC-DC converter			• High current protection sensors	
							• High temperature in the DC-DC converter			• Temperature sensors	
							• Damage to other components and subsystems			• Electrical and mechanical design requirements	
							• Electrical safety hazard			• Quality control during manufacturing	
							• User safety hazard				
				Short circuit (not working properly)	• Excessive current at the input side due to inrush, transient, and so on	1	• Possible damage to the DC-DC converter	4	4	• High current protection sensors	
					• Analog/digital circuitry failure		• DC-DC converter does not function properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DC-DC converter			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the DC-DC converter			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• PCB circuit design failure		• Damage to the other components and subsystems				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical safety hazard				
					•		• User safety hazard				
C.10	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in DC-DC converter	Out of calibration	• Aging factors	1	• Overheating of critical components in DC-DC converter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard			• High voltage and current protection sensors	
										• Additional, redundant temperature sensors are used at different locations	
										• Electrical and mechanical design requirements	
										• Quality control during manufacturing	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure,	1	• Possible damage to other components and subsystems	4	4	• Over voltage and overcurrent protection sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• Additional multiple temperature sensors with the different locations	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Quality control during manufacturing	
C.11	Common-mode choke	Multi-turn common-mode inductor made of toroidal core and Litz wire usually	Filter inductor for common-mode and differential-mode EMI,	High voltage insulation breakdown	• Over voltage operation due to output current surge, voltage swell, transient, and so on	1	• Insulation breakdown between windings might cause electrical arc	4	4	• Current and temperature sensors	
					• Mechanical deformation		• Significant damage (such as fire) to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper manufacturing design		• Increase of output current at the EV battery			• Maintain safe operating conditions.	
					• Over temperature		• Increase of common-mode and differential-mode emissions			• Enclosure to limit user access.	
					• Aging of insulation		• User electrical and thermal safety hazard, and excessive energy exposure				
				Electrical open circuit	• Over temperature and breakdown winding	1	• Open circuit between live terminals might cause an electrical arc and Over voltage	4	4	• Current, temperature, and voltage sensors	
					• Mechanical failure (e.g., broken winding, disconnect from the circuit board),		• Significant damage (such as fire) to other components and subsystems			• Electrical and mechanical design requirements	
					• Over pressure (too much tension) during manufacturing of windings		• Electrical and thermal safety hazard			• Maintain safe operating conditions.	
							• User safety hazard				
				Electrical short circuit	• Improper manufacturing electrical or mechanical design	1	• Significant damage (such as fire) to other components and subsystems	4	4	• Current, temperature, and voltage sensors	
					• High voltage breakdown of wire insulation wire		• Electrical and thermal safety hazard			Electrical and mechanical design requirements	
					• Improper isolation clearance between active wires		• Increase of output current at the EV battery			• Maintain safe operating conditions.	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• High temperature across the winding leading to insulation degradation		• Increase of conductive and differential emissions				
							• User safety hazard and energy exposure				
				High temperature	• High core losses due to improper design	1	• High temperature might degrade the winding insulation and increase the possibility of short between turns and windings,	4	4	• Current, voltage, and temperature sensors	
					• Degraded electrical property of core material		• Significant damage (such as fire) to other components and subsystems			• Electrical and mechanical design requirements	
					• Conductivity degradation of wire		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• High conduction losses due to high current		• Increase of output current at the EV battery				
					• Improper thermal management and design		• Increase of common-mode and differential-mode emissions				
					• Excessively high ambient temperature (e.g., operating outside recommended operating range)		• User safety hazard and excessive energy exposure				
				Mechanical failure	• Crash-induced mechanical failure	1	• Mechanical damage	4	4	• Current, voltage, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, air pressure),		• Potential short circuit			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Significant damage (such as fire) to other components and subsystems			• Quality control during manufacturing	
					• Excessive vibration during transportation due to poor mounting		• Electrical and thermal safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Fragile components subject to mechanical shocks (e.g., crash, vibration, drop)		• Increase of output current at the EV battery				
					• Improper assembly and soldering during manufacturing		• Increase of common-mode and differential-mode emissions				
					• Improper mechanical design		• User safety hazard and energy exposure				
				Component performance degradation	• Over temperature	1	• Conductivity degradation might cause increased power losses	4	4	• Current, voltage, and temperature sensors	
					• Mechanical breakdown		• Core saturation may lead to excessive current at grid			• Electrical and mechanical design requirements	
					• Insulation failure		• Increase of output current at the EV battery			• Quality control during manufacturing	
					• Core saturation		• Significant damage (such as fire) to other components and subsystems			• Lifetime assessment and estimation during the design stage	
					• High voltage breakdown		• Electrical and thermal safety hazard				
							• Reduced current, voltage, and power handling capability.				
C.12	Y capacitor	Film or ceramic capacitor	Filter capacitor for common-mode emission	High temperature	• High ripple current	1	• High temperature might cause derating, short, open circuit, reduced lifetime, and so on	3	3	• Voltage, current, and temperature sensors	
					• Improper design, placement, and assembly		• Improper functionality and damage to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper capacitor derating during the design stage		• Electrical and thermal safety hazard			• Quality control during manufacturing	
							• Increased ripple current and power losses				
							• Increase of common-mode and differential-mode emissions				
							• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Electrical open circuit	• Over voltage failure due to oscillations between active phases and ground	1	• Improper functionality of the filtering	3	3	Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• High ripple current		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• Mechanical failure (e.g., solder crack, disconnect from the board)		• User safety hazard				
					• Improper capacitor derating during the design stage						
				Electrical short circuit	• Over voltage failure due to oscillations between active phases and ground	1	• Filter does not function properly	4	4	• Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Mechanical failure		• Increased ground currents			• Quality control during manufacturing	
					• Improper design due to improper voltage clearance		• Electrical and thermal safety hazard				
					• High ripple current		• Increased ripple current and power losses				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Increase of common-mode and differential-mode emissions				
					• Improper capacitor derating during the design stage		• User safety hazard				
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure	1	• Mechanical failure of component	3	3	• Voltage, current, and temperature sensors	
					• Degradation due to external factors (e.g., temperature,		• System does not function properly			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					humidity, water, mechanical pressure)						
					• Aging of electrical and mechanical components,		• Damage to the components and subsystems			• Quality control during manufacturing	
					• Excessive vibration during transportation due to poor mounting		• Electrical and thermal safety hazard				
					• Fragile components subject to mechanical shocks (e.g., crash, vibration, drop)		• Increased ripple current and power losses				
					• Improper assembly and soldering during manufacturing		• Increase of common-mode and differential-mode emissions				
					• Improper mechanical design		• User safety hazard				
C.13	X capacitor	Film capacitor	Filter capacitor for differential mode emission	High temperature	• High voltage	1	• High temperature might cause reduced performance, short, open circuit, and so on	3	3	• Voltage, current, and temperature sensors	
					• High ripple current		• Improper functionality and damage to other components and subsystems			• Electrical and mechanical design requirements	
					• Improper capacitor derating during the design stage		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• Improper design		• Increased ripple current and power losses				
							• Increase of common-mode and differential-mode emissions				
							• User safety hazard				
				Electrical open circuit	• Excessive voltage due to grid voltage sag, surges, and so on	1	• Filtering does not function properly	3	3	• Voltage, current, and temperature sensors	
					• Over temperature		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• High ripple current		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• Mechanical failure		• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper soldering and assembly during manufacturing						
					• Improper capacitor derating during the design stage						
				Electrical short circuit	• Over temperature	1	• Filtering does not function properly	4	4	• Voltage, current, and temperature sensors	
					• Mechanical failure		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Improper design due to improper voltage clearance on the board		• Electrical and thermal safety hazard			• Quality control during manufacturing	
					• High ripple current		• Increased ripple current and power losses				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Increase of common-mode and differential-mode emissions				
					• Improper capacitor derating during the design stage		• User safety hazard				
				Mechanical failure, aging, deformation	• Crash-induced mechanical failure	1	• Physical damage to the component	3	3	• Voltage, current, and temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Improper functionality of the system			• Electrical and mechanical design requirements	
					• Aging of electrical and mechanical components		• Damage to other components and subsystems			• Quality control during manufacturing	
					• Excessive vibration during transportation due to poor mounting		• Electrical and thermal safety hazard				
					• Improper assembly and soldering during manufacturing		• Increased ripple current and power losses				
							• Increase of common-mode and differential-mode emissions				
							• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
D. Charging system control and communication											
D.1	Grid voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Break the functionality of rectifier/PFC			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• Over voltage protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to swell, transient, and so on,	1	• Damage to the rectifier/PFC	4	4	• Over voltage protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not function			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
D.2	Grid current sensor	Electronic analog to digital circuit	Measures the grid current for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not function			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• Overcurrent protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
							• Electrical safety hazard			• Quality control during manufacturing	
							• User safety hazard				
				Short circuit (not working properly)	• Excessive current at the grid side due to inrush, transient, and so on	1	• Possible damage to the rectifier/PFC	4	4	• Overcurrent protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not function			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Quality control during manufacturing	
					• Poor PCB circuit design		• Damage to the other components and subsystems				
					• Mechanical failure due to improper assembly or soldering during manufacturing.		• Electrical safety hazard				
							• User safety hazard				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
D.3	DC voltage sensor	Electronic analog to digital circuit	Measures the DC link voltage for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Possible damage to rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not function			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• High voltage protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the DC link due to sag, transient, and so on	1	• Possible damage to rectifier/PFC	4	4	• Over voltage protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not function			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Quality control during manufacturing	
					• Poor PCB circuit design		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
D.4	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain	Out of calibration	• Aging factors	1	• Overheating of critical components in rectifier/PFC	3	3	• Calibration is conducted or	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
			components in rectifier/PFC							validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard.			• Over voltage and overcurrent protection sensors	
										• Additional, redundant temperature sensors are used at different locations	
										• Electrical and mechanical design requirements	
										• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Possible damage to other components and subsystems	4	4	• Over voltage and overcurrent protection sensors	
					• Water flooding, pressure, humidity, and so on		• Electrical safety hazard			• Additional, redundant temperature sensors are used at different locations	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard			• Electrical and mechanical design requirements	
										• Quality control during manufacturing	
D.5	Output DC voltage sensor	Electronic analog to digital circuit	Measures the output voltage for DC-DC converter controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the dc-dc converter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature,		• DC-DC converter does not function			• MCU calibration reset in each cycle	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					humidity, water, mechanical pressure)					due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Increase power losses in the DC-DC converter			• Over voltage protection sensors	
							• High temperature in the DC-DC converter			• Temperature sensors	
							• Electrical safety hazard			• Electrical and mechanical design requirements	
							• User safety hazard			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to swell, transient, and so on	1	• Possible damage to the DC-DC converter	4	4	• Over voltage protection sensors	
					• Analog/digital circuitry failure		• DC-DC converter does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DC-DC converter			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the DC-DC converter			• Quality control during manufacturing	
					• Poor PCB circuit design		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
D.6	Output current sensor	Electronic analog to digital circuit	Measures the input current for DC-DC converter stage controller and protection	Out of calibration	• Aging factors	1	• Possible damage to the DC-DC converter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• DC-DC converter does not function properly			• MCU calibration reset in each cycle due to malfunction and so on	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Excess heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Increase power losses in the DC-DC converter			• Overcurrent protection sensors	
							• High temperature in the DC-DC converter			• Temperature sensors	
							• Damage other components and subsystems			• Electrical and mechanical design requirements	
							• Electrical safety hazard			• Quality control during manufacturing	
							• User safety hazard				
				Short circuit (not working properly)	• Excessive current at the input side due to inrush, transient, and so on	1	• Possible damage to the PFC	4	4	• Overcurrent protection sensors	
					• Analog/digital circuitry failure		• PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the PFC			Electrical and mechanical design requirements	
					• Improper design		• High temperature in the PFC			Quality control during manufacturing	
					• Poor PCB circuit design		• Damage to the other components and subsystems				
					• Mechanical failure due to improper assembly or soldering during manufacturing.		• Electrical safety hazard				
							• User safety hazard				
D.7	FPGA	Off the shelf Field Programmable Gate Arrays (FPGA)	Controlling the PFC/SST stage of XFC system (optional)	Sensing unit failure	• Analog circuitry failure	1	• Signals needed for the control and fault monitoring not communicated to microcontroller	3	3	• Desat protection in gate driver	
					• Microcontroller ADC unit failure		• Controller saturates and MOFSET/IGBTs operate at maximum PWM duty ratio. Input current increases.			• Periodic maintenance/calibration	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							Output voltage/power is different from the reference value				
				PWM unit failure	• Analog circuitry failure • Microcontroller PWM unit failure	1	• PWM signals lost to IGBT/MOSFETs leading to no output power • Constant high PWM signal communicated to one or multiple MOSFETs leading to an increased input current or short circuit	3	3	• Desat protection in gate driver • Periodic maintenance/ calibration	
D.8	PFC/solid-state transformer controller unit	Off the shelf digital microcontroller	Controlling the solid-state transformer stage of XFC system	Sensing unit failure	• Analog circuitry failure • Microcontroller ADC unit failure	1	• Signals needed for the control and fault monitoring not communicated to microcontroller • Controller saturates and IGBT/MOSFETs operate at maximum PWM duty ratio. Input current increases. Output voltage/power is different from the reference value	3	3	• Desat protection in gate driver • Periodic maintenance/ calibration	
				PWM unit failure	• Analog circuitry failure • Microcontroller PWM unit failure	1	• PWM signals lost to IGBT/MOSFETs leading to no output power • Constant high PWM signal communicated to one or multiple IGBT/MOSFETs leading to an increased input current or short circuit	3	3	• Desat protection in gate driver • Periodic maintenance/ calibration	
D.9	DC-DC converter controller unit	Off the shelf digital microcontroller	Controlling the DC-DC converter stage of XFC system	Sensing unit failure	• Analog circuitry failure	1	• Signals needed for the control and fault monitoring not communicated to microcontroller	3	3	• Desat protection in gate driver	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Microcontroller ADC unit failure		• Controller saturates and IGBT/MOSFETs operate at maximum PWM duty ratio. Input current increases. Output voltage/power is different from the reference value			• Periodic maintenance/ calibration	
				PWM unit failure	• Analog circuitry failure	1	• PWM signals lost to IGBT/MOSFETs leading to no output power	3	3	• Desat protection in gate driver	
					• Microcontroller PWM unit failure		• Constant high PWM signal communicated to one or multiple IGBT/MOSFETs leading to an increased input current or short circuit			• Periodic maintenance/ calibration	
D.10	Communication	Off the shelf communication ICs interfaced with LAN or serial port of the microcontroller	Communicating of sensed signals from different controller units	Communication network damage	• Analog circuity failure	1	• Communication from a certain controller is lost or erroneous	2	2	• Desat protection in gate driver	
					• Open circuit of microcontroller interface		• Output voltage feedback signal to microcontroller is interrupted. Controller saturates and IGBT/MOSFETs operate at maximum PWM duty ratio. Input current increases. Output voltage/power is different from the reference value			• Microcontroller communicates fault	
										• Periodic maintenance/ calibration	
D.11	Heavy duty charging cable	High current cable	Connect XFC to the vehicle battery	Open circuit	• Crash-induced mechanical failure	1	• No power delivered to vehicle battery	1	1	• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Indicating no vehicle connected			• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Aging of electrical and mechanical components						
					• Excessive vibration during transportation due to poor mounting						
					• Improper assembly and soldering during manufacturing						
				High temperature	• Cooling unit failure	1	• High temperature	1	1	• Temperature sensor	
					• Aging of electrical and mechanical components					• Electrical and mechanical design requirements	
										• Quality control during manufacturing	

Table 10.4. Optional PFC-Rec-1

System	Subsystem	ID#	Component	Comments
Grid interface	**Rectifier/PFC**	**A.1**	IGBT/MOSFET power module	Failure modes of IGBT and MOSFET are listed separately in FMEA table
		A.2	Diode module	Diodes may be integrated into IGBT/MOSFET package
		A.3	DC link capacitor	
		A.4	Cooling unit (heat sink and chiller)	
		A.5	Gate driver circuitry	
		A.6	DC voltage sensor	
		A.7	Grid voltage sensor	
		A.8	Grid current sensor	
		A.9	Temperature sensor	

Table 10.5. Optional PFC-Rec-2

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A. Grid interface											
A.1	IGBT/MOSFET power modules	Insulated gate bipolar transistor	Rectifier/PFC system switching power module	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• Input voltage is shorted through the inductor, resulting in high input currents to the power electronic switch (IGBT), which damages the power module	4	8	• Short circuit protection in gate driver	
					• Gate driver output pulled high due to noise, failure, and so on		• Inductor saturation due to high current			• High voltage protection in front of Rectifier/PFC	
					• Inadequate heat dissipation		• High power losses in the inductor and switch power module			• The input relay contactor in front of Rectifier/PFC turning off with the fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the Rectifier/PFC inductor and switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Damage to front end components and subsystems (EMI filter, current limiter, soft-start circuit) before PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				Power module open circuit	• Excessive voltage or current stresses in the switch module	2	• Rectifier/PFC might become a diode rectifier (leading to poor power factor, higher input harmonics, higher ripple)	3	6	• High voltage and current protection in front of rectifier/PFC	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the inductor			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					• Quality control during manufacturing	
					• Improper design						
				High temperature	• Excessive voltage and current stresses across the switch module	1	• High power losses in the inductor and switch power module	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and excessive energy exposure.			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Degradation monitoring of the module on a regular basis	
		Silicon or silicon carbide MOSFETs	Rectifier/PFC system switching power module	One switch in the module shorted	• Excessive voltage, current and power stress across switch	2	• The DC voltage at rectifier output is periodically shorted when the complementary switch turns ON resulting in high shoot-through currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the inductor and switch power module			• Current/voltage sensors communicate fault to rectifier/PFC controller	
					• Inadequate heat dissipation		• High temperature in the rectifier/PFC filter inductor and switch power module				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				Both switches in the module shorted	• Excessive voltage, current and power stress across the module	1	• The DC voltage at rectifier output is permanently shorted resulting in high shoot-through currents	5	5	• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged			• Current/voltage sensors communicate	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							due to high inrush current			fault to rectifier/PFC controller	
					• Inadequate heat dissipation		• High temperature in the power module			• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors	
					• Mechanical failure						
A.2	Diode module	Rectifier/PFC circuit formed by semiconductor devices in a discrete package.	Rectifier/PFC system switching power module	Diode short circuit	• Excessive current	2	• Output voltage across the capacitor will be shorted when the switch power module is conducting, resulting in high currents into the switch power module,	4	8	• The input relay contactor in front of rectifier/PFC turns off when receiving fault signal	
					• Poor thermal dissipation		• High power losses in the switch power module			• High voltage and current protection in front of PFC	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage in rectifier/PFC and components and subsystems			• Electrical and mechanical design requirements	
					• Improper design during manufacturing		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure				
				Diode open circuit	• Excessive voltage stresses across the diode module	2	• Open circuit to the output	3	6	• High voltage and current protection	
					• Inadequate heat dissipation		• MOSFET body diodes play the role of the diode module instead			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the MOSFET module			• Electrical and mechanical design requirements.	
					• Aging factors		• XFC system will stop working for IGBT type rectifier.			• Temperature sensors	
					• Improper design						
				High temperature	• Excessive voltage or current stresses	1	• Damage of other components and subsystems	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure.			• Temperature sensors	
					• Improper design					• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time					• Safety and quality control during manufacturing	
A.3	DC link capacitor	Film or electrolytic capacitor	Rectifier/PFC output capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage or current stresses	1	• Output of rectifier/PFC will be shorted, resulting in high current in the rectifier/PFC power modules	4	4	• High voltage and current protection in front of rectifier/PFC	
					• High power losses and heat dissipation across the capacitor, which may translate into dielectric failure depending on capacitor properties		• Power module may be damaged			• Input relay contactor in front of rectifier/PFC turns off when it receives a fault signal	
					• Aging of the capacitor		• High power losses in the rectifier/PFC			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• User safety hazard and energy exposure				
				Capacitor open circuit	• Excessive voltage or current stresses in the capacitor	1	• Ripple at the output of the rectifier/PFC will appear at the input of the solid-state transformer	3	3	• High voltage and current protection in front of rectifier/PFC	
					• Inadequate heat dissipation		• Might damage the functionality of the solid-state transformer			• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High power losses and temperature in the solid-state transformer			• Temperature sensors	
					• Aging factors leading to degradation or failure		• Damage to the other components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure.			• Adequate voltage margin during the design stage	
				High temperature	• Excessive voltage and current stresses across capacitor	1	• High power losses in the rectifier/PFC	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to the other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives the fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing.	
A.4	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the MOSFET/IGBT switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the MOSFET/IGBT switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
A.5	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module IGBTs/MOSFETs	Controls the turn-on and turn-off of the switches in the power modules of the rectifier/PFC	Output of gate driver constant high	• Analog/digital circuitry failure, • Mechanical assembly failure, • PCB circuit failure, • Improper circuit design	1	• Input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module • Inductor saturation due to high current • High power losses in the inductor and power module • High temperature in the inductor and power module • Damage to the other components and subsystems • Electrical and thermal safety hazard • User safety hazard and energy exposure	4	4	• Short circuit protection in gate driver • High voltage protection in front of rectifier/PFC • Input relay contactor in front of rectifier/PFC turns off when it receives fault signal • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Output of gate driver constant low	• Analog/digital circuitry failure • Gate driver isolated power supply failure	1	• Inductor might be saturated • High temperature in the inductor	3	3	• High voltage and current protection in front of rectifier/PFC • Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical assembly failure		• Electrical and thermal safety hazard			• Temperature sensors	
					• PCB circuit failure		• User safety hazard			• Electrical and mechanical design requirements	
					• Improper circuit design					• Safety and quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit	4	8	• High voltage and current protection in front of rectifier/PFC	
					• Mechanical assembly failure		• Excessive currents during short circuit			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• PCB circuit failure		• Damage the power module during short			• Temperature sensors	
					• Improper circuit design		• Inductor saturation due to high current			• Electrical and mechanical design requirements	
							• High power losses in the inductor and switch power module			• Safety and quality control during manufacturing	
							• High temperature in the inductor and switch power module				
							• Damage to the other components and subsystems				
							• Electrical and thermal safety hazard				
							• User safety hazard and energy exposure				
A.6	DC voltage sensor	Electronic analog to digital circuit	Measures the DC link voltage for	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
			rectifier/PFC controller and protection		• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure) • Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• Rectifier/PFC does not operate properly • High power losses in the rectifier/PFC • High temperature in the rectifier/PFC • Electrical safety hazard • User safety hazard			validated periodically • MCU calibration reset in each cycle due to malfunction and so on • High voltage protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the DC link due to sag, transient, and so on • Analog/digital circuitry failure • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure) • Improper design • PCB circuit design failure • Mechanical failure due to improper assembly or	1	• Damage the rectifier/PFC • Rectifier/PFC does not operate properly • High power losses in the rectifier/PFC • High temperature in the rectifier/PFC • Electrical safety hazard • User safety hazard	4	4	• High voltage protection sensors • Temperature sensors • Electrical and mechanical design requirements • Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					soldering during manufacturing						
A.7	Grid voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the rectifier/PFC			• High voltage protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Electrical safety hazard,			• Electrical and mechanical design requirements	
							• User safety hazard.			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to sag, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High voltage protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Safety and quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• PCB circuit design failure		• Electrical safety hazard				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard				
A.8	Grid current sensor	Electronic analog to digital circuit	Measures the grid current for rectifier/PFC controller and protection	Out of calibration	• Aging factors	1	• Damage the rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Rectifier/PFC does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes		• High power losses in the rectifier/PFC			• High current protection sensors	
							• High temperature in the rectifier/PFC			• Temperature sensors	
							• Damage other components and subsystems,			• Electrical and mechanical design requirements	
							• Electrical safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard				
				Short circuit (not working properly)	• Excessive current at the grid side due to inrush, transient, and so on	1	• Damage the rectifier/PFC	4	4	• High current protection sensors	
					• Analog/digital circuitry failure		• Rectifier/PFC does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging,		• High power losses in the rectifier/PFC			• Electrical and mechanical	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					temperature, humidity, water, mechanical pressure)					design requirements	
					• Improper design		• High temperature in the rectifier/PFC			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Damage to other components and subsystems				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical safety hazard				
							• User safety hazard				
A.9	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in rectifier/PFC	Out of calibration	• Aging factors	1	• Overheating of critical components in rectifier/PFC	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• MCU calibration reset in each cycle due to malfunction, and so on	
					• Excess heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard			• Over voltage and overcurrent protection sensors	
										• Additional, redundant temperature sensors are used at different locations	
										• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Possibly damage other components and subsystems	4	4	• Over voltage and overcurrent protection sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• Additional multiple temperature sensors at different locations,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard			• Electrical and mechanical design requirements	
										• Safety and quality control during manufacturing	

Table 10.6. Optional SST-DAB-1

System	Subsystem	ID#	Component	Comments
Solid-state transformer/ isolated DAB converter	**High-frequency inverter**	**A.1**	Semiconductor power module (generally MOSFETs)	
		A.2	Diode module	Diodes may be integrated into IGBT/MOSFET package
		A.3	DC link capacitor	
		A.4	Gate driver circuitry	
		A.5	Cooling unit (heat sink and chiller)	
		A.6	DC voltage sensor	Input DC voltage sensor
		A.7	Temperature sensor	
	High-frequency transformer	**A.8**	Litz wire coil	
		A.9	Nanocrystalline core	
		A.10	Metallic enclosure	
		A.11	Temperature sensor	
	High-frequency rectifier	**A.12**	Semiconductor power module (generally MOSFETs)	
		A.13	Diode module	
		A.14	DC link capacitor	
		A.15	Gate driver circuitry	
		A.16	Cooling unit (heat sink and chiller)	
		A.17	DC voltage sensor	Output DC voltage sensor
		A.18	Output current sensor	
		A.19	Temperature sensor	

Table 10.7. Optional SST-DAB-2

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A. Solid-state transformer/ isolated DAB converter											
A.1	IGBT/ MOSFET power modules	Insulated gate bipolar transistor	Converts the DC voltage to high-frequency square or quasi-square AC voltage	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• The input voltage is shorted resulting in high input currents to the switch and damage to the power module	4	8	• Short circuit protection in gate driver	
					• Gate driver output pulled high due to noise, failure, and so on		• PFC inductor saturation due to high current			• High voltage protection in front of Rectifier/PFC	
					• Inadequate heat dissipation		• High power losses in the inductor and switch power module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the Rectifier/PFC inductor and switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage PFC components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				Power module open circuit	• Excessive voltage and current stresses in the switch module	2	• High temperature in power module	3	6	• Over voltage and overcurrent protection in front of rectifier/PFC	
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the PFC inductor			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard			• Temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					• Safety and quality control during manufacturing	
					• Improper design						
				High temperature	• Excessive voltage and current stresses in the switch module	1	• High power losses in the inductor and switch power module	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and excessive energy exposure			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
										• Degradation monitoring of the module on a regular basis	
		Silicon or silicon carbide MOSFETs	Converts the DC voltage to high-frequency square or quasi-square AC voltage	One switch in the module shorted	• Excessive voltage, current and power stress in switch	2	• The DC voltage at inverter input is periodically shorted when the complementary switch turns ON resulting in high shoot-through currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the inductor and switch power module			• Current/voltage sensors communicate fault	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										to upstream rectifier/PFC	
					• Inadequate heat dissipation		• High temperature in the rectifier/PFC filter inductor and switch power module				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				Both switches in the module shorted	• Excessive voltage, current and power stress in the module	1	• The DC voltage at inverter input is permanently shorted resulting in high shoot-through currents	5	5	• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged due to high inrush current			• Current/voltage sensors communicate fault to upstream rectifier/PFC	
					• Inadequate heat dissipation		• High temperature in the power module			• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Electrical and thermal safety hazard				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										transformer controller	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state transformer controller	
					• Mechanical failure						
A.2	Diode module	Diodes in discrete packages.	Converts the DC voltage to high-frequency square or quasi-square AC voltage (Diodes are anti-parallel with active switches (IGBTs, MOSFETs))	Diode short circuit	• Excessive voltage and current stresses	2	• The input voltage across the capacitor will be shorted when the power module is conducting, resulting in high shoot-through currents into the switch power module	3	6	• Desaturation (Desat) protection in gate driver	
					• Inadequate heat dissipation,		• High power losses in the switch power module			• Input relay contactor in front of rectifier/PFC turns off after receiving the fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage the inverter components and subsystems			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and excessive energy exposure				
				Diode open circuit	• Excessive voltage and current stresses across the diode module	2	• Partial power can be delivered to the high-frequency transformer through IGBTs. Reverse current flows	2	4	• Temperature sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							through MOSFET body diode.				
					• Inadequate heat dissipation		• High power losses in the MOSFET module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the MOSFET module			• Electrical and mechanical design requirements	
					• Aging factors		• Electrical and thermal safety hazard				
					• Improper design		• User safety hazard and excessive energy exposure				
				High temperature	• Excessive voltage or current stresses	1	• Damage to other components and subsystems	3	3	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure			• Temperature sensors	
					• Improper design					• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
A.3	DC link capacitor	Film or electrolytic capacitor	PFC output capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage or current stresses	1	• The input of the inverter will be shorted, resulting high current in the rectifier/PFC	4	4	• Over voltage and overcurrent protection in front of rectifier/PFC,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor properties		• Possible damage to the rectifier/PFC power module			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging of the capacitor		• High power losses in the rectifier/PFC			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the rectifier/PFC			• Electrical and mechanical design requirements	
					• Improper design		• Electrical and thermal safety hazard			• Safety and quality control during manufacturing	
							• User safety hazard and energy exposure				
				Capacitor open circuit	• Excessive voltage or current stresses in the capacitor	1	• Inverter is disconnected with the input	2	2	• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• No power flows to vehicle side			• Electrical and mechanical design requirements,	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• User safety hazard and excessive energy exposure.			• Safety and quality control during manufacturing.	
					• Aging factors						
					• Improper design						
					•						
				High temperature	• Excessive voltage or current stresses in the capacitor	1	• High power losses in the inverter,	4	4	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to the other components and subsystems,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Aging factors • Improper design		• Electrical and thermal safety hazard, • User safety hazard and energy exposure.			• Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
A.4	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module MOSFETs/IGBTs	Controls the turn-on and turn-off of the switches in the power modules of the inverter of solid-state transformer	Output of gate driver constant high	• Analog/digital circuitry failure • Mechanical assembly failure • PCB circuit failure • Improper circuit design	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module, • rectifier/PFC output capacitor short circuit • High power losses in the power module, • High temperature in and power module, • Damage components and subsystems in front of the inverter, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.	4	4	• Short circuit protection in gate driver, • High voltage protection in front of rectifier/PFC, • Input relay contactor in front of rectifier/PFC turns off when it receives fault signal • Temperature sensors, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
				Output of gate driver constant low	• Analog/digital circuitry failure • Gate driver isolated power supply failure • Mechanical assembly failure • PCB circuit failure	1	• Unbalanced DC link capacitor • High voltage stress in one of the DC capacitors • Electrical and thermal safety hazard, • User safety hazard.	3	3	• High voltage and current protection in the inverter • Input relay contactor in front of rectifier/PFC turns off when it receives fault signal • Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper circuit design		• No power delivered to vehicle side			• Safety and quality control during manufacturing	
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit,	4	8	• High voltage and current protection in rectifier/PFC stage,	
					• Mechanical assembly failure		• Excessive currents during short circuit,			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• PCB circuit failure		• Damage the power module during short circuit,			• Temperature sensors	
					• Poor circuit design		• Inductor saturation due to high current,			• Electrical and mechanical design requirements	
							• High power losses in the inductor and switch power module,			• Safety and quality control during manufacturing	
							• High temperature in the inductor and switch power module,				
							• Damage power modules and subsystems,				
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
A.5	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the power switches, increase in losses and damage of the switches	3	3	Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of the power switches,	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							increase in losses and damage of the switches			OFF the MOSFETs/IGBTs	
					• Mechanical failure						
				Clogging of the cooling fluid circulating unit	• Residue and dirt accumulation in the coolant and the cooling unit	1	• Temperature control disrupted. May lead to excessive heating of the power switches, increase in losses and damage of the switches	4	4	• Periodic maintenance	
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the power switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
A.6	DC voltage sensor	Electronic analog to digital circuit	Measures the grid voltage for DAB controller and protection	Out of calibration	• Aging factors	1	• Damage the DAB	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• DAB does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excess heat generation or Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the DABC,			• High voltage protection sensors,	
							• High temperature in the DAB,			• Temperature sensors	
							• Electrical safety hazard,			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
							• User safety hazard.			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to voltage swell, transient, and so on	1	• Damage the DAB	4	4	• High voltage protection sensors	
					• Analog/digital circuitry failure		• DAB does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DAB,			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the DAB,			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard.				
A.7	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in PFC	Out of calibration	• Aging factors	1	• Overheating of critical components in inverter	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excess heat generation or Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard.			• High voltage and current protection sensors,	
										• Additional, redundant temperature are used sensors at different locations,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										• Electrical and mechanical design requirements, Safety and quality control during manufacturing.	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure • Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure) • Mechanical failure due to improper assembly or soldering during manufacturing.	1	• Might damage with other components and subsystems, • Electrical safety hazard, • User safety hazard.	4	4	• High voltage and current protection sensors, • Additional multiple temperature sensors with the different locations, • Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
A.8	Litz wire–based coil	Multiturn coil made with Litz wire	Carries high-frequency AC current and generates AC magnetic field	Electrical short-circuit	• High voltage breakdown of insulation layers • Improper electrical/mechanical design	1	• Significant damage in other components and subsystems • Thermal hazard and mechanical damage • Significant increase in EMF emissions	5	5	• Current and temperature sensor • Safety and control requirements • Electrical and mechanical design requirements • Quality and safety test for diverse operating conditions	
				Electrical open circuit	• Mechanical failure • Crash-induced open wire • Over tensioned (stretched) • Over temperature	1	• Significant damage in other components and subsystems • Thermal hazard and mechanical damage • Significant increase in EMF emissions	4	4	• Current and temperature sensor • Safety and control requirements • Electrical and mechanical design requirements • Quality and safety test for diverse	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										operating conditions	
				Mechanical failure	• Over tensioned (stretched)	1	• Increase in electrical resistivity and loss	5	5	• Electrical and mechanical design requirements	
					• Crash-induced mechanical failure		• Electrical open or short circuit			• Quality and safety test for diverse operating conditions	
					• Over temperature		• Electrical safety hazard			• Safety and control requirements	
							• User exposure to energized component of the charging pad				
				High temperature	• Excessive high power loss	1	• Significant damage in other components and subsystems	5	5	• Current and temperature sensor	
					• Improper thermal design		• Increase in electrical resistivity and loss			• Safety and control requirements	
							• Electrical open or short circuit			• Electrical and mechanical design requirements	
							• Electrical and thermal safety hazard			• Quality and safety test for diverse operating conditions	
				High-voltage insulation failure	• Poor design/manufacturing	1	• Electrical open or short circuit	2	2	• Electrical and mechanical design requirements	
					• Mechanical deformation of the charging pad		• Electrical and thermal safety hazard			• Current and temperature sensor	
					• Over voltage operation		• Significant damage in other components and subsystems			• Safety, quality, and control requirements	
										• Safety and quality test for diverse operating conditions	
				Conductivity degradation	• Mechanical degradation	2	• Increase in electrical resistivity,	4	8	• Electrical and mechanical design requirements	
					• Over temperature		• Increase in loss, Over temperature			• Current and temperature sensor	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Internal insulation failure due to high temperature or high voltage					• Safety, quality, and control requirements	
										• Safety and quality test for diverse operating conditions	
A.9	Nano-crystalline core	Made with high-permeability magnetic material, such as nanocrystalline . Nanocrystalline is a highly brittle material	1. Guides the magnetic flux, 2. Increases the self and mutual inductances	High temperature	• Large hysteresis loss	2	• Increased resistivity and loss in the coil	4	8	• Electrical and mechanical design requirements	
					• Poor thermal design		• Degraded performance of the core			• Current and temperature sensor	
					• Large current in the coils		• Thermal runaway			• Safety, quality, and control requirements	
										• Safety and quality test for diverse operating conditions	
				High loss	• Large hysteresis loss	1	• Over temperature in the core and coil	5	5	• Electrical and mechanical design requirements	
					• Large current in the coils		• Drop in system efficiency			• Safety, quality, and control requirements	
					• Eddy current loss						
					• Poor design						
					• Degraded electrical property of ferrites						
					• Increased temperature						
				Mechanical breakdown	• Nanocrystalline is extremely brittle	4	• Slightly reduced self and mutual inductances	1	4	• Mechanical design requirements of the core as well as surround materials	
					• Excessive pressure on the charging pad					• Safety and quality test for diverse operating conditions	
					• Improper mechanical design						

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
A.10	Metallic enclosure	Metallic enclosure for high-frequency transformer	Protect the magnetic component of high-frequency transformer Provide mechanical support and allow for adequate heat dissipation	Mechanical failure/ breakdown	• Over pressure (mechanical) Over temperature	1	• Damage the transformer coil and core	1	1	• Electrical and mechanical design requirements Safety and quality test for diverse operating conditions	
				Puncture/ intrusion of foreign object	• Crash-induced puncture	1	• Damage the transformer coil and core	1	1	• Electrical and mechanical design requirements Quality control during manufacturing	
A.11	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in transformer	Out of calibration	• Aging factors	1	• Overheating of transformer	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard.			• Additional, redundant temperature are used sensors at different locations,	
										• Electrical and mechanical design requirements,	
										• Safety and quality control during manufacturing.	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Might damage with other components and subsystems,	4	4	• High voltage and current protection sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard,			• Additional multiple temperature sensors with the different locations,	
					• Mechanical failure due to improper assembly or		• User safety hazard.			• Electrical and mechanical design requirements,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					soldering during manufacturing.						
										• Quality control during manufacturing	
A.12	IGBT/ MOSFET power modules	Insulated gate bipolar transistor	Converts the high-frequency square or quasi-square AC voltage to DC voltage	Power module short circuit	• Excessive voltage or current stresses in the power module	2	• The DC voltage at rectifier output is permanently shorted resulting in high input currents	4	8	• Short circuit protection in gate driver	
					• Gate driver output pulled high due to noise, failure, and so on		• DC link capacitor can be damaged due to high inrush current			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• High temperature in the power module,			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard,			• Electrical and mechanical design requirements	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.			• Safety and quality control during manufacturing	
					• Improper design						
				Power module open circuit	• Excessive voltage and current stresses in the switch module	2	• High temperature in power module	3	6	• Over voltage and overcurrent protection in front of rectifier/PFC	
					• Gate driver output pulled low due to noise, failure, and so on		• High temperature in the PFC inductor			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Inadequate heat dissipation		• Electrical and thermal safety hazard			• Temperature sensors	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard and energy exposure			• Electrical and mechanical design requirements	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)					• Safety and quality control during manufacturing	
					• Improper design						
				High temperature	• Excessive voltage and current stresses in the switch module	1	• High power losses in the inductor and switch power module	4	4	• High voltage and current protection	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Damage to other components and subsystems			• Input relay contactor in front of rectifier/PFC turns off when it receives fault signal	
					• Aging factors		• Electrical and thermal safety hazard			• Temperature sensors	
					• Improper design		• User safety hazard and excessive energy exposure			• Electrical and mechanical design requirements	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time.					• Safety and quality control during manufacturing	
										• Degradation monitoring of the module on a regular basis	
		Silicon or silicon carbide MOSFETs	Converts the high-frequency square or quasi-square AC voltage to DC voltage	One switch in the module shorted	• Excessive voltage, current and power stress in switch.	2	• The DC voltage at DAB output is periodically shorted when the complementary switch turns ON resulting in high input currents	4	8	• Short circuit protection in gate driver turns OFF the complementary switch	
					• Gate driver output pulled high		• High power losses in the MOSFET module,			• Current/voltage sensors communicate fault to upstream rectifier/PFC	
					• Inadequate heat dissipation		• High temperature in the MOSFET module,				
					• Mechanical failure due to improper assembly or		• Electrical and thermal safety hazard,				

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					soldering during manufacturing,						
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
					• Excessive current and power stress in the MOSFET module		• The DC voltage at DAB output is permanently shorted resulting in high input currents			• The input relay-contactor turns OFF	
					• Gate driver output pulled high for both switches		• DC link capacitor can be damaged due to high inrush current			• Current/voltage sensors communicate fault to upstream rectifier/PFC	
				Both switches in the module shorted	• Inadequate heat dissipation	1	• High temperature in the power module,	5	5	• Short circuit protection in gate driver turns OFF the module entirely	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• Electrical and thermal safety hazard,				
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and energy exposure.				
					• Improper design						
				One switch in the module is open circuited	• Inadequate heat dissipation	1	• No/less power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state transformer controller	
					• Mechanical failure						
				Both switches in the module are open circuited	• Inadequate heat dissipation	1	• No power flow to high-frequency transformer or vehicle side	3	3	• Fault communicated by dedicated sensors and also from the solid-state	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
										transformer controller	
					• Mechanical failure						
A.13	Diode module	Diodes in discrete packages.	Converts the DC voltage to high-frequency square or quasi-square AC voltage (Diodes are anti-parallel with active switches (IGBTs, MOSFETs))	Diode short circuit	• Excessive voltage or current stresses	2	• The input voltage across the capacitor will be shorted when the MOSFET/IGBT module is conducting, resulting in high shoot-through currents into the switch power module,	3	6	• DESAT protection in gate driver,	
					• Inadequate heat dissipation,		• High power losses in the switch power module,			• The input relay contactor in front of rectifier/PFC turning off with the fault signal,	
					• Mechanical failure due to improper assembly or soldering during manufacturing,		• High temperature in the switch power module,			• Temperature sensors,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Damage the inverter components and subsystems,			• Electrical and mechanical design requirements,	
					• Improper design during manufacturing		• Electrical and thermal safety hazard,			• Quality control during manufacturing	
					•		• User safety hazard and excessive energy exposure.				
				Diode open circuit	• Excessive voltage and current stresses in the diode module	2	• Partial power can be delivered to the high-frequency transformer through IGBTs. Reverse current flows through MOSFET body diode.	2	4	• Temperature sensors,	
					• Inadequate heat dissipation		• High power losses in the MOSFET/IGBT module			• The input relay contactor in front of rectifier/PFC turning off with the fault signal,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing		• High temperature in the MOSFET/IGBT module,			• Electrical and mechanical design requirements.	
					• Aging factors		• Electrical and thermal safety hazard,				
					• Improper design		• User safety hazard and excessive energy exposure.				
				High temperature	• Excessive voltage or current stresses	1	• Damage with the other components and subsystems,	3	3	• High voltage and current protection,	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• Electrical and thermal safety hazard,			• The input relay contactor in front of rectifier/PFC turning off with the fault signal,	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• User safety hazard and excessive energy exposure.			• Temperature sensors,	
					• Improper design					• Electrical and mechanical design requirements,	
					• Degradation of thermal performance of the power module due to thermal and power cycling over time					• Quality control during manufacturing	
A.14	DC link capacitor	Film or electrolytic capacitor	Solid-state transformer output capacitor for DC link voltage smoothing	Capacitor short circuit	• Excessive voltage or current stresses	1	• The output of rectifier will be shorted, resulting high current in the rectifier,	4	4	• High voltage and current protection in solid-state transformer stage,	
					• High power losses and inadequate heat dissipation in the capacitor, which may translate into dielectric failure depending on capacitor properties		• Might damage the rectifier power module,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Aging of the capacitor		• High power losses in the rectifier,			• Temperature sensors,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Mechanical failure due to improper assembly or soldering during manufacturing • Improper design		• High temperature in the rectifier, • Electrical and thermal safety hazard, • User safety hazard and energy exposure.			• Electrical and mechanical design requirements, • Safety and quality control during manufacturing.	
				Capacitor open circuit	• Excessive voltage and current stresses across the capacitor • Inadequate heat dissipation • Mechanical failure due to improper assembly or soldering during manufacturing • Aging factors • Improper design	1	• Ripple at the output of the solid-state transformer stage will appear at the input of vehicle DC-DC converter stage, • Might damage the functionality of the solid-state transformer stage system. • High power losses and temperature in the solid-state transformer stage system, • Damage to the other components and subsystems, • Electrical and thermal safety hazard, • User safety hazard and excessive energy exposure.	2	2	• High voltage and current protection in solid-state transformer stage, • The input relay contactor in front of PFC turning off with the fault signal, • Temperature sensors, • Electrical and mechanical design requirements, • Quality control during manufacturing • Adequate voltage derating during the design stage.	
				High temperature	• Excessive voltage or current stresses in capacitor • Mechanical failure due to improper assembly or soldering during manufacturing, • Aging factors	1	• High power losses in the solid-state transformer stage, • Damage to the other components and subsystems, • Electrical and thermal safety hazard,	4	4	• High voltage and current protection, • The input relay contactor in front of PFC turning off with the fault signal, • Temperature sensors,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Improper design		• User safety hazard and energy exposure.			• Electrical and mechanical design requirements,	
										• Quality control during manufacturing	
A.15	Gate driver circuitry	An integrated circuit that provides isolation to the LV and low power pulse from the microcontroller and translates the low power signal to an output pulse at appropriate voltage levels capable of sourcing and sinking currents as required by the gate terminal of the Power module IGBTs	Controls the turn-on and turn-off of the switches in the power modules of the solid-state transformer	Output of gate driver constant high	• Analog/digital circuitry failure	1	• The input voltage is shorted through the inductor, resulting in high input currents to the switch and damage power module,	4	4	• Short circuit protection in gate driver,	
					• Mechanical assembly failure		• Inductor saturation due to high current,				
					• PCB circuit failure		• High power losses in the inductor and power module,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Improper circuit design		• High temperature in the inductor and power module,			• Temperature sensors,	
							• Damage solid-state transformer components and subsystems,			• Electrical and mechanical design requirements,	
							• Electrical and thermal safety hazard,			• Quality control during manufacturing	
							• User safety hazard and energy exposure.				
				Output of gate driver constant low	• Analog/digital circuitry failure	1	• Inductor might be saturated,	3	3	• High voltage and current protection in front of PFC,	
					• Gate driver isolated power supply failure		• High temperature in the inductor,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• Mechanical assembly failure		• Electrical and thermal safety hazard,			• Temperature sensors,	
					• PCB circuit failure		• User safety hazard.			• Electrical and mechanical design requirements,	
					• Improper circuit design					• Quality control during manufacturing	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Short circuit protection circuit failure	• Analog/digital circuitry failure	2	• No protection of the switches during short circuit,	4	8	• High voltage and current protection in front of PFC,	
					• Mechanical assembly failure		• Excessive currents during short circuit,			• The input relay contactor in front of PFC turning off with the fault signal,	
					• PCB circuit failure		• Damage the power module during short,			• Temperature sensors,	
					• Poor circuit design		• Inductor saturation due to high current,			• Electrical and mechanical design requirements,	
							• High power losses in the inductor and switch power module,			• Quality control during manufacturing	
							• High temperature in the inductor and switch power module,				
							• Damage in front of PFC components and subsystems,				
							• Electrical and thermal safety hazard,				
							• User safety hazard and energy exposure.				
A.16	Cooling unit (heat sink and chiller)	Cold plate with a compressor pump and ethylene glycol storage tank (with Ethylene glycol and water mix 50-50%)	Dissipates heat to keep the junction temperature of the power modules under tolerable limits	Mechanical failure of cold plate and coolant circulating unit	• Mechanical shock or crack	1	• Temperature control disrupted. May lead to excessive heating of the power switches, increase in losses and damage of the switches	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Leakage or loose contact between the cold plate and the circulating unit						
				Failure of the compressor pump	• Electrical failure	2	• Temperature control disrupted. May lead to excessive heating of the power switches, increase in losses and damage of the switches	4	8	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
					• Mechanical failure						
					• Residue and dirt accumulation in the	1	• Temperature control disrupted. May lead to	4	4	• Periodic maintenance	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
				Clogging of the cooling fluid circulating unit	coolant and the cooling unit		excessive heating of the power switches, increase in losses and damage of the switches				
										• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
				Failure of the thermal pad between the power module and cold plate	• Mechanical stress and strain	1	• Temperature control disrupted. Increased thermal stress on the power switches, increase in losses	3	3	• Temperature sensor communicates to microcontroller for protective action, gate driver turns OFF the MOSFETs/IGBTs	
A.17	DC voltage sensor	Electronic analog to digital circuit	Measures the output DC voltage for DAB controller and protection	Out of calibration	• Aging factors	1	• Damage the DAB	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• DAB does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excess heat generation or Inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the DAB,			• High voltage protection sensors,	
							• High temperature in the DAB,			• Temperature sensors	
							• Electrical safety hazard,			• Electrical and mechanical design requirements	
							• User safety hazard.			• Safety and quality control during manufacturing	
				Short circuit (not working properly)	• Excessive voltage at the grid side due to voltage swell, transient, and so on	1	• Damage the DAB	4	4	• High voltage protection sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Analog/digital circuitry failure		• DAB does not operate properly			• Temperature sensors	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DAB,			• Electrical and mechanical design requirements	
					• Improper design		• High temperature in the DAB,			• Safety and quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard.				
A.18	Output current sensor	Electronic analog to digital circuit	Measure the output current of solid-state transformer for DAB control and protection	Out of calibration	• Aging factors	1	• Damage the DAB	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• DAB does not operate properly			• MCU calibration reset in each cycle due to malfunction and so on,	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• High power losses in the DAB,			• High current protection sensors,	
							• High temperature in the DAB,			• Temperature sensors,	
							• Electrical safety hazard,			• Electrical and mechanical design requirements,	
							• User safety hazard.			• Quality control during manufacturing	
				Short circuit (not working properly)	• Excessive current due to sag, transient, and so on	1	• Damage the DAB	4	4	• High current protection sensors,	
					• Analog/digital circuitry failure		• DAB does not operate properly			• Temperature sensors,	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• High power losses in the DAB,			• Electrical and mechanical design requirements,	
					• Improper design		• High temperature in the DAB,			• Quality control during manufacturing	
					• PCB circuit design failure		• Electrical safety hazard,				
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard.				
A.19	Temperature sensor	Electronic analog to digital circuit	Measures the temperature of certain components in DAB rectifier	Out of calibration	• Aging factors	1	• Overheating of critical components in the rectifier	3	3	• Calibration is conducted or validated periodically	
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• MCU calibration reset in each cycle due to malfunction and so on	
					• Excessive heat generation or inadequate heat dissipation due to inaccurate circuit design and component tolerance changes.		• User safety hazard			• Over voltage and overcurrent protection sensors	
										• Additional, redundant temperature are used sensors at different locations	
										• Electrical and mechanical design requirements	
										• Quality control during manufacturing	
				Short circuit (not working properly)	• Analog/digital circuitry or sensor failure	1	• Possible damage to other components and subsystems	4	4	• Over voltage and over current protection sensors	

No.	Component	Component description	Component function	Potential failure mode	Cause of failure modes	Likelihood score	Failure mode consequences	Consequence score	Risk score	Controls	Comments
					• Degradation due to external factors (e.g., aging, temperature, humidity, water, mechanical pressure)		• Electrical safety hazard			• Additional multiple temperature sensors at different locations	
					• Mechanical failure due to improper assembly or soldering during manufacturing		• User safety hazard			• Electrical and mechanical design requirements	
										• Quality control during manufacturing	

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