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DC and AC Charging Safety Evaluation Procedure Development, Validation, and Assessment

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16. Abstract

Charging a plug-in electric vehicle exposes new hazards and risks different from internal combustion engine vehicles. These hazards and risks must be defined and mitigated through proper system design and verified via functional system performance testing. DC charging represents additional challenges. Unlike AC charging where the on-board charger and battery system are under direct control of a vehicle, DC charging uses an external charger and requires the vehicle, high-voltage system controls, and battery management systems to interact with an external device directly connected to the vehicle's high-voltage battery. This report focuses on system-level safety verification procedures to test if a connected vehicle/charging system can safely handle failure modes and hazards commonly associated with charging. This project developed a DC fast-charging safety test procedure, a holistic collection of tests based on 24 FMEAs conducted by the battery system developer for real-world applications and clients reflecting a broad range of in-field scenarios. This project report presents validation and refinementof the test procedures maintaining the holistic approach initially used by SAE. This report also addresses a broader range of vehicle charging technologies to include AC charging technology presently available for electric vehicles. This report documents these efforts to independently evaluate, refine, and validate test procedures that can be applied to a range of vehicles, charger technologies, and battery configurations.

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Table of Contents

Acronyms

NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers, known formally since 2006 as SAE International
CCS	combined charging cystem
EMI	electromagnetic interference
EMC	electromagnetic compatibility
HV	high voltage
BMS	battery management system
PEV	plug-in electric vehicle
ICE	internal combustion engine
RESS	rechargeable energy storage system
DFMEA	design failure mode and effects analysis
EVSE	electric vehicle supply equipment
OBCM	on-board charge module
BECM	battery energy control module
NRTL	Nationally Recognized Testing Laboratory, designation of independent laboratory recognized by the Occupational Safety and Health Administration to test products to applicable product safety standards
PWM	pulse width modulated
PLC	power line communication
HPGP	HomePlug Green PHY
OFDM	orthogonal frequency division multiplexing
CAN	controller area network
JARI	Japan Automobile Research Institute
DIN	Deutsches Institut für Normung e.V. (German Institute for Standardization)
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
FMVSS	Federal Motor Vehicle Safety Standards
GND	ground
ECU	electronic control unit
OEM	original equipment manufacturer
SOC	state-of-charge

1 Introduction

The process of charging a plug-in electric vehicle exposes new hazards and risks that differ from internal combustion engine vehicles. These new hazards and risks must be defined and mitigated through proper system design and verified via functional system performance testing. If not properly protected and controlled, vehicle charging using either alternating current or direct current can introduce a range of possible hazards ranging from high-voltage exposure to vehicle or battery damage. Regardless of charging method, actions including establishing and monitoring an equipment grounding path, exchanging control information between the vehicle and the electrical supply equipment, monitoring the system for isolation issues and shorting, avoiding vehicle movement while connected, and returning the vehicle to a safe state following any unexpected behavior or faults are of critical importance to ensure safe charging of a PEV. DC charging represents additional challenges since the DC charger is external to the vehicle. Unlike AC charging where the on-board charger (converter) and battery management system/controls are under direct control of a vehicle, DC charging uses an external charger and thus requires the vehicle, high-voltage system controls, and battery management systems to interact with an external device that is directly connected to the vehicle's high-voltage battery. While a range of documents describe the interoperability requirements required to have chargers that can function reliably across a range of vehicles and situations, this document focuses on system-level safety verification procedures to test if a connected vehicle/charging system can safely handle failure modes and hazards commonly associated with charging.

This project scope was based upon research conducted by the Society of Automotive Engineers[1] and a selected set of collaborative industry partners under contract with the National Highway Traffic Safety Administration. In that body of work, one of the collaboration partners, an industry expert battery system developer working together with an electric vehicle supply equipment (EVSE) manufacturer, developed a DC fast-charging safety test procedure. This procedure was a holistic collection of tests based on 24 failure mode and effects analyses) conducted by the battery system developer for real-world applications and clients reflecting a broad range of in-field actual scenarios. In addition to this foundation of applied expertise, the resultant test procedures were also reflective on a large range of industry best-practices, strongly using information from the SAE combined charging system Recommended Practice documents (SAE J1772) (see Appendix B for additional background) and *Institute of Electrical and Electronics Engineers Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles– Annex A CHAdeMO Specifications* (IEEE Std 2030.1.1-2015) interoperability documents (see Appendix C for applicable document references. These baseline references were used as a starting point to further identify failure modes associated with DC charging and system-level protections and behaviors to detect and prohibit these issues from creating an unsafe situation. This validation report refines the existing set of required tests as well as validates the developed test procedures using a DC-Fast charge equipped vehicle and charger.

This project report, which is based on the initial DC charging test procedures provided by NHTSA, presents validation and refinement, where possible, of the provided test procedures maintaining the holistic approach initially used by SAE. This report also addresses a broader range of vehicle charging technologies to include AC charging technology that is presently available to electric vehicle users. Thus, following similar safety analysis and test development processes, allowing for certain adjustments for specific issues related to AC charging, a holistic set of AC charging performance test procedures were developed and included in draft status as complete validation is presently underway. Together with the DC procedures, the tests detailed in this report provide a coordinated core of safety evaluation procedures

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[1] In 2006 the Society of Automotive Engineers changed its name to SAE International. SAE remains the initialsm, hower, for reference purposes.

built from shared hazard analysis, while also providing charging-method-specific procedures that comprehend the differences between AC and DC charging.

This report documents the results of these efforts to independently evaluate, refine, and validate these test procedures for use within a set of tests that can be applied to a wide range of vehicles, charger technologies, and battery configurations.

For this report, Argonne National Laboratory acted as an independent evaluator of the procedures and best practices across manufacturers and varying interoperability and charging standards. The end-product of this report is to create a holistic collection of procedures to be used to assess the safety performance of a vehicle-charger system. Without any additional data or prior evaluations for the hazards described later in this document, the entire suite of tests must be run for a particular vehicle as opposed to simply selecting highlighted tests from the collective whole. If a test operator, supplier, or OEM can justify that the hazard protections are enabled and functional with prior testing or analysis, certain tests can be omitted, but significant engineering judgement must be applied to ensure the discussed hazards are truly addressed at the vehicle-charger integrated system level.

1.1 Scope

The scope of this test procedure will focus on the interactions between a vehicle's high-voltage control system (contactors, sensors, etc.), battery management system, and the charging system. The test procedures will document the steps required to create or simulate the selected failure modes and how to observe and measure the system response. When possible, the test procedure will identify the test limits (ex. temperatures, battery SOC levels) and boundary conditions. Pass/fail criteria for the system response, system limit conditions, measurement criteria and metrics are also identified as part of the test procedure. The validation portion of this work highlights insights gained and validation examples of the individual tests for a DC-charging-equipped vehicle.

1.2 Highlighted DC-Fast-Charging References and Applicable Insights for System-level Procedure Development

At the highest level, this report focuses on identifying hazards related to PEV charging. These hazards can then be decomposed into failure modes and fault conditions that can be used to develop safety evaluation procedures that seek to determine system responses to an unexpected or failure condition. The following table outlines the primary safety hazards involved with PEV charging and the potential risk each hazard poses:

Table 1: Safety Hazards and Potential Risks of PEV DC Charging

Safety Hazard	Potential Risk
Over Current	Melted Wires, Fire, Burns, etc.
Over Charge	RESS Thermal Runaway Leading to Fire or Explosion
Exposed HV and Isolation Loss	Shock/Electrocution, Short Leading to Thermal Runaway
Increased Resistance	Fire, Burns, etc.

From hazards discussed above, failure modes leading to these hazards were identified. Using these identified failure modes, scenarios leading to these hazards can be developed for use in a test procedure.

Fortunately, a large volume of related work exists in this area related to interoperability, defined in this context as a set of standardized hardware and software specifications to enable consistent operation and communication between "interoperable" chargers and vehicles. While a broad range of applicable documents are presented in "Appendix C-Applicable Publications," this section seeks to highlight some specific requirements discussed in IEEE Std 2030.1.1-2015 [2] that are foundational to the failure modes and hazard exposure associated with this report. Specifically, Section 5.2 of the IEEE document dictates requirements that are common between Annex A (CHAdeMO) and Annex B (SAE CCS and other combination chargers) and provides a good starting point into failures that lead to hazard exposure. It should be noted, while most of the general requirements highlight a related safety need, some of these requirements and those in subsequent sub-sections of the IEEE document pertain only to communications interoperability and the range of operable ambient conditions. Particularly relevant sections have been underlined within the excerpt.

5.2 Requirements

a) General

1) Device shall be able to indicate to the user the status of the charging process and take corrective actions if required.

2) Both the charger and the vehicle shall be equipped with <u>a means to confirm they stay physically and/or electrically connected with each other during charging</u>.

3) The charger shall be equipped with a <u>means to stop charging in the case that communication between the vehicle and the charger (via the communications interface) is interrupted</u>.

4) <u>When the protective conductor between the charger and the vehicle is disconnected, the charger shall stop charging</u> within 10 s.

5) The charger shall be able to <u>detect loss of isolation, short circuit, and earth faults</u>.

6) The charger shall be equipped with an <u>overvoltage protection function</u>.

7) The system shall be designed so that <u>a level of voltage that is dangerous to the human body shall not be applied on the charging connector when the connector is not connected to the vehicle</u>.

8) The system shall be designed to <u>prevent users from touching electrically energized parts on the vehicle and the charger</u>.

9) The charger shall be equipped with <u>a means of earth leakage current detection and automatic disconnection to help prevent electric shock</u>.

10) The charger or charging connector shall be equipped with measures (e.g., plastic cap on connector power terminals) to <u>reduce the risk of contact with exposed live parts</u> as a measure against remaining electric charge on the charging connector.

11) The charger shall be equipped with a means of protection against overload and short circuit in the ac main circuit or internal circuit of the charger.

12) The charging system shall be designed so that the <u>voltage level between any accessible conductive parts, including charging cable and charging connector, and any grounding parts decreases to less than 60 V within 1 s or less, after connector removal from station or vehicle</u>.

These requirements create the foundation for the AC and DC system-level safety tests discussed in this report by highlighting the need to assess a vehicle's HV system and battery management system's response to issues related to a variety of relevant conditions. Supplementing the above material with additional reference documents, standards, and a range of rechargeable energy storage system design failure mode and effects analyses, five primary failure conditions/risk areas were identified that can occur before, during, and after charging.

1. System Grounding
2. 12 V_{DC} Network Control, communications, and BMS functionality
3. High Voltage Exposure
4. Environmental Effects
5. Operational Disturbances

A DC charging-enabled PEV should always end a charge session in a safe manner. A "safe state of the system" (1.3.2) is defined as a condition of the PEV and DC charger system that contains the high voltage within the system boundaries and protects the operator from getting harmed under any operating conditions. Exposure to PEV's RESS high voltage could lead to potential shock or electrocution of the operator. In addition to the risks of harming the operator, exposure of high voltage may lead to an RESS short circuit possibly causing a thermal event. The RESS itself should also be protected from damaging or detrimental usage.

1.2.1 Safety Rationale for Specific Tests

From these five risk areas, specific test procedures were developed to evaluate a PEV's ability to mitigate the hazards associated with specific failure modes associated with DC and AC charging. The following paragraphs provide the safety rationale for each specific test detailed within this report. The tests included in the discussion below should be considered holistically in that each test is tailored to identify a specific response to a particular hazard. Selecting individual tests or skipping tests without confidence of suffiecient protection could lead to missing certain safety-relevant behaviors given the integrated nature of the test procedure development.

Ground Fault Test (DC Only)- Ground faults can lead to unintended discharge of the PEV battery and possibly a thermal event.

Chassis Ground Offset Test (DC and AC) - If a PEV or charger determines a charging session should not start, or if charging is halted, then it must do so in a safe manner. Possible safety hazards include exposed high voltage if the system is not brought to a safe state.

DC or AC Bus Short Test (DC and AC) - If the (+) and (–) busses are shorted an over-current safety hazard is possible. This over-current hazard could lead to melted wires, fire, or battery damage.

DC Bus Held High Test (DC Only) – To avoid user/operator contact with elevated voltage, a vehicle should not unlock the charge connector from the inlet until the bus voltage has dropped below 60V DC

12V System Over-Voltage Test (DC and AC) - If a PEV ECU faults due to a 12V system over-voltage the resulting possible safety hazards include over-current, over-charge, and exposed HV due to possibly uncontrolled operation.

12V System Under-Voltage Test (DC and AC) - When the PEV's 12V system source voltage reaches a certain point at which individual ECUs begin to not operate, unsafe conditions may occur depending on the order of ECU depowering. The resulting possible safety hazards include over-current, over-charge, and exposed HV.

12V System Disturbance Test (DC and AC) – An unexpected disturbance to a vehicle's 12V bus could result in an unsafe condition if a PEV ECU is adversely affected. Resulting possible safety hazards include over-current, over-charge, and exposed HV.

12V System EMI/EMC Test (DC and AC) - Unexpected EMI during a charge session could possibly result in an unsafe condition due to loss of individual ECUs or unexpected, uncontrolled behavior. Resulting possible safety hazards include over-current, over-charge, and exposed HV.

Vehicle Movement Test (DC and AC) – A PEV allowed to drive away while connected to a charger creates a possible safety hazard. In addition to damaging the infrastructure and the PEV itself, high voltage may be exposed leading to the risk of shock or fire.

Vehicle Crash or Bump Test (DC Only) - If a collision exposes energized components or ends the charge session in an unsafe state, a possible safety hazard is created. Safety hazards include over-current, over-charge, exposed HV and stranding the PEV driver.

Charge Operation Disturbance Test (DC only) – Unexpected actions by an operation (premature removal of the connector, trying to start the vehicle, movement of the charging handle, etc.) could lead to an unexpected end of charging session or fault condition. Possible safety hazards include over-current, over-charge, increased resistance, exposed HV or stranding a driver.

Charge Connector Control Signal Disturbance Test (DC and AC) - If the control pilot and/or the proximity circuit is shorted, opened, or changed to a significant degree, the PEV and charger must perform an emergency shutdown and end the charge session in safe manner.

Charge Connector Field Ground Connection Disturbance Test (DC and AC) - If the field ground is shorted, opened, or changed to a significant degree, the PEV and charger must perform an emergency shutdown and end the charge session in safe manner.

Charge Connector HV Connection Disturbance (DC Only)- Contamination of the terminals increases resistance that in turn can heat up the coupler leading to the potential for fire or burns.

Failed Battery Cooling/Heating System Test (DC Only) – Charging performed at low cell temperatures could lead to battery damage and shorter life. Charging performed at high cell temperatures could lead to cell degradation and, more significantly, thermal runaway if not properly mitigated.

BMS Internal Fault Detection Test (DC Only) - Faults in the RESS as detected and mitigated by the PEV's BMS may require an emergency stoppage and thus must end in a safe condition.

Over-Charge Test (DC only) - Over-charging of the RESS could lead to cell degradation and possibly thermal runaway resulting in a fire and bodily harm.

Over-Current Test (DC Only) - An overcurrent condition could lead to battery degradation or even thermal runaway if not properly mitigated.

Reverse Power Flow (Under-Voltage) Test (DC Only) - Unintended discharge of the RESS (i.e., not V2G functionality) could possibly degrade/damage the RESS.

PEV Inlet Temperature Test (AC or DC When Applicable) - Contamination, degradation, or improper fit of the CCS connector or inlet could result in increased resistance at the connection point between the charger and the DC charging port. A potential safety hazard may occur if the coupler begins to significantly heat up. The risk of fire and possibly burning the PEV driver are potential risks.

It is worth noting that a significantly smaller subset of tests is provided for AC charging versus DC charging. This is due to the lack of direct connection between the vehicle RESS and off-board charging equipment for AC charging. For AC charging, an on-board charger acts as the interface between the offiline EVSE equipment and the vehicle RESS, allowing for much tighter coordination and thus fewer hazards. Relatedly, since, at the time of publication, the vast majorty of AC on-board chargers are not capable of feeding power back to the grid, several additional hazards related to HV exposure at the vehicle charging inlet are not applicable. If a vehicle is AC V2G capable, an evalatuion procedure might need to be added to ensure protection against AC high-votlage exposure, but this is outside the scope of the procedures developed in this document.

1.3 System-level Charging Safety Evaluation Testing Concepts

1.3.1 Interoperability versus Safety

While interoperability and safety are very closely related, it is important to differentiate between the two concepts within the context of this report's focus on system-level safety performance verification. Interoperability specifically dictates the means or range allowable for a specific hardware or communications component, whereas the system-level safety test procedures contained in this document only assess a vehicle's safety response to a particular situation. These safety focused procedures consider not starting a charge sessions and/or ending a charge session in a safe state to be a successful outcome for a specific test, whereas interoperability sometimes focuses on a successful charging session taking place. For example, an "interoperable" system may need to continue operating despite external EMI, whereas it is acceptable to stop charging from a safety perspective. Interoperability (and the associated standards documents) often include many connector interface and communications synchronization requirements that are not exclusively safety related and therefore do not need to be specified within this document. While the loss of communication between the vehicle BMS and charger is of a specific safety interest in order to avoid uncontrolled operation, the specific protocols (or even connection methods) used are not specified or investigated in this report.

It is noteworthy to explain that while existing interoperability standards often dictate what should be done in specific scenarios, they typically do not provide a robust evaluation procedure to confirm that the requirement has been fulfilled. For example, IEEE Std 2030.1.1-2015 states that: "The charger shall have a mechanism to lock the charging connector in place during charging….," but does not specify a test procedure to confirm that this functionality has been implemented for a specific vehicle/charger combination. While most OEMs have the capability to perform these tests internally on a case-by-case basis (if so desired), it is helpful to have an established set of common procedures that can be consistently referenced by anyone interested in confirming the safety behavior of a particular vehicle's high voltage system and battery management system during charging.

1.3.2 Safe State of the System

Given this document's focus on safety as opposed to interoperability, a general criterion has been developed and deemed "safe state of the system" to represent the desired outcome to a highlighted failure mode or fault condition. As used in this document, a "safe state of the system" is defined as:

1) High voltage is contained within the system boundaries,

2) Operator is protected under any operating condition (faulty or not faulty) from getting harmed, and

3) Hazardous battery conditions leading to deterioration or thermal runaway are avoided.

In addition to these three requirements, it is desired (but not required) that some sort of fault indication be provided to the operator so that possible system degradation can be addressed quickly and not allowed to expand into a larger issue.

It should again be noted that continued charging or an abrupt halt to charging are both acceptable from a safety standpoint as long as all three criteria are met. For certain tests within this document, the criteria for a successful test differ from the allowance for continued safe operation or a halt to charging in that a halt to testing is the desired option due to the desired intent to avoid a cacade of possible hazards associated with an accident during DC charging.

Specific to the case of an impact during DC charging, the vehicle must monitor for a vehicle collision ("bump") while actively charging. If a collision is detected at a relative velocity of greater than 5 mph, the charging operation must be halted. Charging may be resumed only after system safety self-assessment has been completed followed by an operator restart of the charging session.

1.3.3 The Connected Vehicle-Charger System

When connected, it is important to consider the vehicle and charger as a "connected vehicle-charger system." This comprehends the fact that once connected, a vehicle and charger are effectively one entity. In the case of DC charging, the charger is off-board the vehicle, yet the charger is directly connected to the battery. Due to this external connection, the vehicle (and thus BMS) must both communicate with and control the charger to facilitate safe charging, fault detection, and safe system shutdown. In the IEEE document, this connection is succinctly described as "collaborative actions between electric vehicles (or PEVs] and quick chargers." Prior to connection a vehicle will certainly not know the isolation state of a charging station, but once the two systems are electrically connected an isolation fault in the charging system should be detected by the vehicle's isolation detection system, since they are effectively operating on a single high-voltage bus. A vehicle should also be capable of detecting issues related to unexpected, uncontrolled charger operation and provide a mitigation response, regardless of which component is at "fault." For example, if a charger is providing too much current, the vehicle should detect this abnormality and respond appropriately to mitigate any hazardous conditions due to the unexpected operation.

The second important consideration of the vehicle-charger system concept is that all three criterion related to a "safe" system state must be met. While a vehicle's BMS may respond to a faulty condition in a way that protects the battery, containment of high voltage and operator protection must be considered as well. For example, a BMS could de-rate or limit charging due to a fault condition, but high-voltage exposure at the terminals must also be considered. Thus, battery protection alone is not sufficient to meet the "safe" system criteria. Ultimately, the intent of the connected vehicle-charger concept is to ensure that vehicles and their battery management systems can properly facilitate a safe response to a range of hazards and fault conditions.

1.4 Definitions

- *PEV* - Plug-in electric vehicle is a term that includes plug-in hybrid electric vehicles, PHEVs, extended-range electric vehicles, EREVs, and battery electric vehicles BEVs.
- *Active protection device* - Safety device that consists of a sensor and actuator and is intended for protection from or mitigation of abusive, out of range conditions experienced by the device under test (DUT).
- *Ambient temperature* - The ambient temperature for any test defined in this document shall be within the range of 25°C ±10°C.

- *Safe state of the system* - For the purposes of this test procedure, safe state of the system shall be defined as a condition of the vehicle and charger system that shall contain the high voltage within the system boundaries and protect the operator under any operating condition (faulty or not faulty) from getting harmed.

- *Breakout box* - A breakout box is a device that allows the test technician to introduce certain conditions between the vehicle charge coupler and the DC charger for the purposes of performing the test procedures in this document. It is further described in section 2.2.

- *BMS* - The BMS is the battery management system that is typically part of the high voltage battery pack. Its purpose is to monitor both the pack and the individual battery cells, calculate and communicate battery status and state of function to other modules in the vehicle in order for the vehicle system to manage the energy flow into and out of the battery. In the event of a system failure, the BMS can also open contactors, which isolate the battery from the rest of the Hybrid system.

- *DUT* - The DUT is the "device under test" that in the context of this procedure is the PEV's DC combined charging system that includes electronic control units (ECU) and hardware devices necessary to charge the PEV.

2 Developed Test Procedures

2.1 Precautions and Safety Considerations

When working on or around high voltage systems, always follow the appropriate safety precautions. Read and follow the recommended service procedures for high voltage systems and high voltage parts for the vehicle/system under test.

Be sure to wear the appropriate personal protective equipment, which includes Class 0 insulated rubber gloves with leather outer gloves. Always inspect the insulated gloves for any defects that might prevent the insulating properties, and do not wear them if they are damaged.

Always observe high voltage warning labels (see examples below):

Examples of high voltage warning labels (Source: GM First Responder Guide)

2.1.1 Test-Specific Precautions

While working on a vehicle system, always ensure that the parking brake is actuated. Additionally, block the drive wheels to prevent unintended vehicle movement.

2.1.2 Safety Requirements

Portions of this test procedure call for the manipulation of high voltage connections and the introduction of ground faults that can be dangerous to the test technician. Personal protection equipment to isolate the operator of the test from high voltage contact is required at all times when contacting high voltage components.

The work shall be performed in a well-ventilated area to allow the safe removal of any smoke or toxic gases. Fire extinguishing equipment shall be available and easily accessible at all times during the test execution.

2.2 Test Facility and Equipment Requirements

The following equipment is required to conduct the tests defined in this test procedure. The test equipment shall fulfill the general requirements outlined below.

<u>**DC Charging Equipment Requirements**</u>

- DC charger with a voltage range of 0 VDC to 600 VDC or a battery test system (e.g., BTS-320)
- DC fast charger breakout box with toggle switches to create controlled faults and internal fuses for protection (see Figure 2 for example schematic). Breakout should match required connections for DUT (i.e., CCS, CHAdeMO).
- High voltage meter to measure DC voltage from 0V to 600V with a minimum safety classification of CAT III according to IEC 61010 (e.g., Fluke 189)

- High voltage insulation tester with a minimum safety classification of CAT III according to IEC 61010, to measure the insulation between high voltage circuits and chassis/earth ground (e.g., Fluke 1503)
- Vehicle specific Scan tool to read and clear diagnostic trouble codes (OEM specific)
- Short circuit protected high voltage power supply (diode protected against back feeding) (e.g., Magna-Power SL600-2.5)
- Short-circuit-protected low voltage power supply with voltage regulation from 24V down to 0V with a minimum power of 1,200W (e.g., Sorensen XFR 33-85).
- 12V switchable load with a minimum current draw of 20A @12V (e.g., automotive fan or pump)

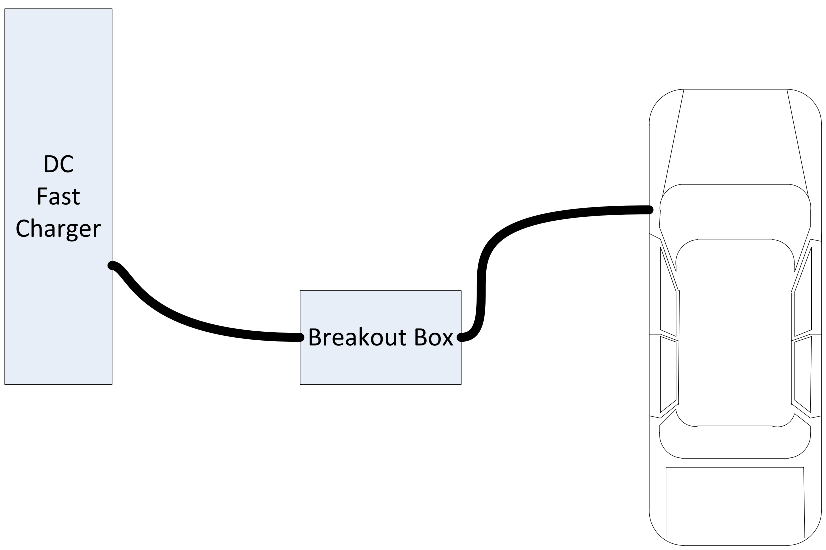

Figure 1: DC Fast Charge Breakout Box Connection

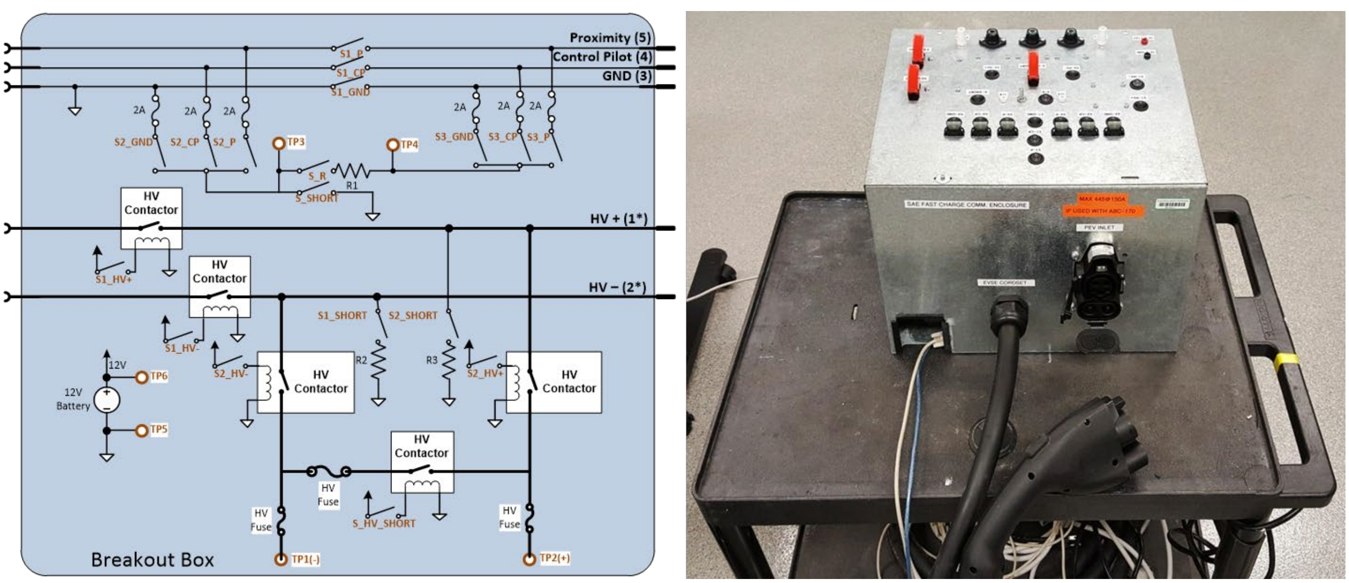

Figure 2: DC Fast Charge Breakout Box Schematic (CCS version shown) and Prototype Breakout Box

NOTE: Test resistance R1 should be a 20k Ω potentiometer.

2.2.1 Discussion Regarding Break-Out Box Configurations for Other DC Charging Protocols and Connectors

As mentioned in the introduction, the requirements and considerations used to create these test procedures were drawn from a range of DC charging protocols and documents. Specifically, a significant portion of the core of this work as well as the earlier draft research project documentation build off a set of common requirements summarized in IEEE Std 2030.1.1-2015, which discusses both SAE J1772 CCS and CHadeMO standards. While these two charging standards as well as many others (i.e., Tesla) are functionally very similar, the connectors themselves do differ in terms of pin layout and sometimes number and functionality of individual pins. At a minimum, any DC charging protocol/hardware compatible with these procedures is expected to include the following.

1) + and – HV lines sized appropriately to the required current/power
2) Proximity pin capable of detecting vehicle-charger connection
3) Control pilot connection for exchange of basic information and coordination of more complex communication methods (i.e., CAN or PLC depending on protocol in use)
4) Shared ground connection between vehicle ground and EVSE ground

This functionality is reflected in the schematic above for the J1772 CCS system, requiring 5 pins. While retaining these basic pins, other protocols may have additional pins or provide some additional functionality above the capabilities of the 5 basic pins above. For example, a CHadeMO compliant inlet will contain the above 5 pins as well as 2 additional pins for CAN communication versus PLC for CCS that requires no additional pins) as well as 3 additional pins related to system control and, in some cases, actuation. Certain CHadeMO applications can directly actuate a vehicle's HV charging contactors if desired. Additional validation with a CHAdeMO equipped vehicle and break-out box is currently under-way, but was not available at the time of report publication. Aside from the additional pins mentioned above, the schematics and associated breakout box between these two charging protocols will be functionally very similar and the validation of the test procedures for clarity and ease of implementation is equally applicable for any type of DC charging protocol. While some specific implementations of certain protocols offer additional functionality (i.e., direct charger-side contactor control) it is suggested these additional functionalities be evaluated on a case-by-case basis since they are not applicable across different charging protocols or different vehicles using the same protocol.

<u>AC Charging Equipment Requirements</u>

- AC Level 2 EVSE that is rated for at least 20 amps continuous. EVSE must be NRTL listed (to UL 2594).
- AC J1772 connector that has a modified proximity connection within. The proximity circuit within the off-the shelf connector must be modified to pass through to the breakout fixture directly with <0.2 ohms of added resistance. **NOTE:** The latch button on the modified connector will not function. The point of disconnect at the end of all tests will be with the EVSE connector first.
- AC breakout box with toggle switches and internal fuse for protection to enable faults
- High voltage meter to measure AC voltage from 0V to 240VRMS with a minimum safety classification of CAT III according to IEC 61010 (e.g., Fluke 189)
- High voltage insulation tester with a minimum safety classification of CAT III according to IEC 61010, to measure the insulation between high voltage circuits and chassis/earth ground (e.g., Fluke 1503)
- Vehicle specific Scan tool to read and clear diagnostic trouble codes (OEM specific)

- Short circuit protected low voltage power supply with voltage regulation from 24V down to 0V with a minimum power of 1,200W (e.g., Sorensen XFR 33-85).

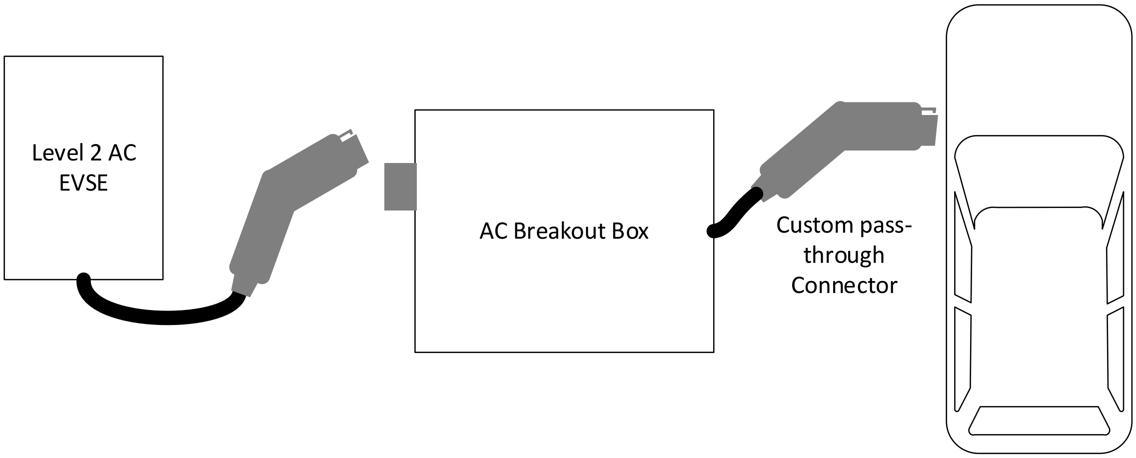

Figure 3: AC Charge Breakout Box Connection

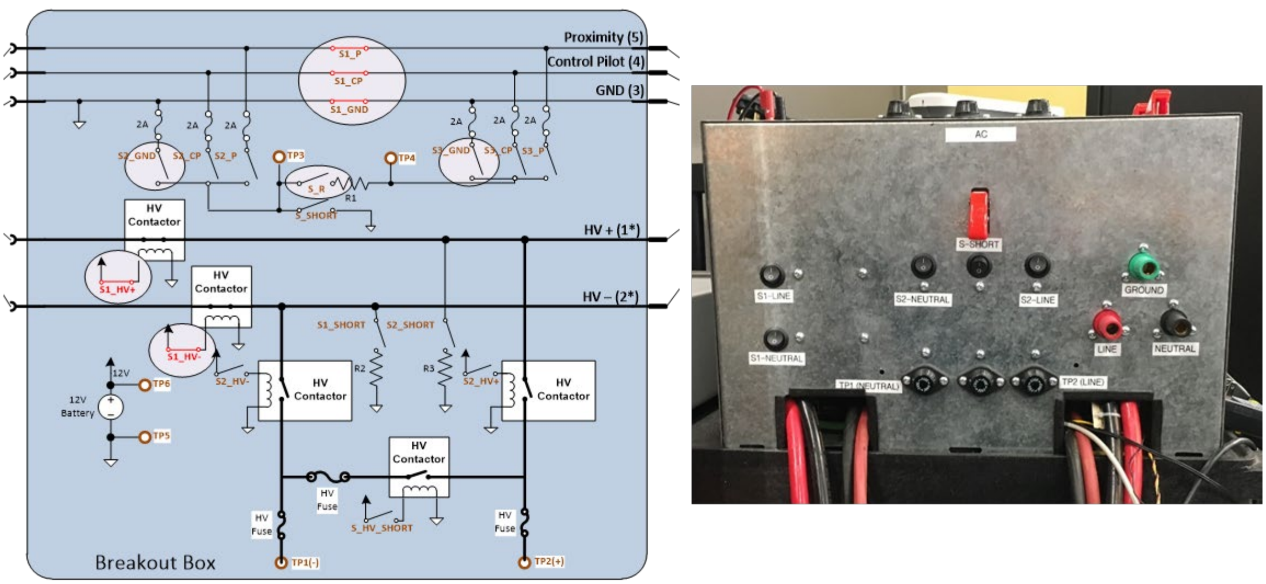

Figure 4: AC Charge Breakout Box Schematic and Prototype Breakout Box

NOTE: Test resistance R1 should be a 20k Ω potentiometer.

2.2.2 Test Equipment Calibration

All test equipment shall be maintained and calibrated according to the manufacturer's specific recommendations to ensure valid results conducting the measurements. The calibration certificate shall identify the type of equipment, manufacturer and model number of test equipment along with the measurement range and the accuracy that can be obtained with the test equipment. The test equipment shall clearly identify when the next calibration is due.

2.2.3 Device Under Test

The device under test for these test procedures is the complete PEV and charger system. Tests defined in this procedure can also be conducted using simulation hardware/software to simulate the charge station operation as long at the behavior can be shown comparable to an actual charging system.

2.2.4 Visual Inspection of Charge Port

The purpose of this inspection is to detect any incompatibility between the charge plug and the vehicle receptacle (or breakout box connectors when applicable). It is possible that low quality adapters or unsupported charging type may cause damage to the connector. This inspection may determine if any damage has occurred due to incompatible or substandard connections.

Visual inspection of charge coupler:

1. Look for debris in the connector
2. Look for mechanical damage due to poor fitting connections
3. Look for abrasions that may indicate poor fitting connections
4. Look for distortions or discoloration due to excess heat
5. Look for discoloration on terminals and contacts

Record any observations of abnormal conditions detected during the visual inspection. It may be necessary to compare the connector and coupler to new and unused parts to determine what is normal and what is abnormal or indicating wear or damage.

2.3 DC Charging Test Procedures

Note on fault detection time: Since fault detection timing and confirmation allowances vary from vehicle to vehicle and technology to technology, these procedures do not specify a "wait" time between when a fault is initialized to an acceptable time to end testing (remove the fault condition). This is done intentionally to ensure appropriate test flexibility. Engineering judgement or manufacturer provided information should be used for a specific vehicle application to allow for sufficient time for a fault to be detected, yet not overly burden testing waiting for a fault that will not be detected. From the validation testing and other in-field experiences, unless otherwise noted in the specific procedure, 5 to 10 seconds is a reasonable starting point for a "wait" time to allow for the vehicle to detect a fault and end the test condition.

2.3.1 Ground Fault Test

2.3.1.1 Purpose

This test will verify that the DUT reacts appropriately to a loss of or a fault on the ground connection between the vehicle charge port and the charger.

2.3.1.2 Rationale and Description

A ground fault is a condition where one pole of the DC bus has continuity with ground. This type of fault represents a dangerous condition that can be hazardous to a test technician if not detected and the proper precautions taken.

A ground fault can happen due to contamination (moisture, dust, etc.), an internal failure of insulation or breakdown of insulation of cabling due to excess temperature or abrasion.

A loss of the ability to detect a ground isolation fault can be caused by the DUT or charger being in the wrong operating mode, a loss of or impaired connection of the DC CCS connection to reference ground, or an internal malfunction of the DC CCS.

This test is designed to determine the effects and the reaction of the DUT to a fault on the ground connection between the vehicle charge port and the charger. The test conditions shall be applied both before a charge session is initiated and during an active charge session to test the effects during different charging modes.

NOTE: Vehicle isolation requirements of 100 ohm/volt (DC) or 500 ohm/volt (AC or AC/DC) are stated in multiple documents including ECE R100, ISO 6469-3 and SAE J2344. Charger DC output isolation requirements are stated in IEC 61851-23 and UL2231, FMVSS 305. This documents states that the EVSE shall terminate charge when the isolation of the output falls below 500 ohm/volt in order to be consistent with the guidelines provided in FMVSS 305.

The ground fault will be established through a pre-calculated resistance with proper wattage to provide a minimum of 500Ω/V isolation ground fault.

2.3.1.3 Sample Preparation

Install the DC charge breakout box between the DC fast charger and the vehicle charging port.

2.3.1.4 Equipment Setup

Configure the DC charge breakout box to perform the ground fault test with the initial switch setting (Table 2). Connect the DC charger to the DC charge breakout box (Figure 5). Connect the DC charge breakout box to the vehicle charge port.

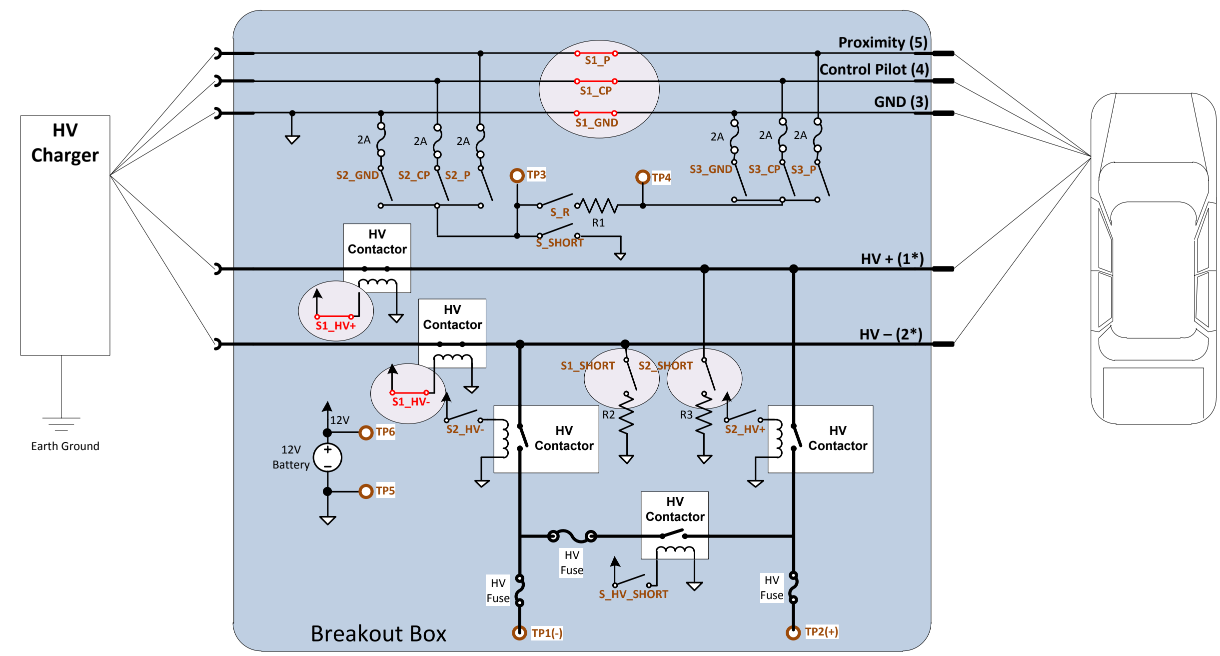

Figure 5: Ground Fault Test - DC Fast Charge Breakout Box Configuration

Table 2: Ground Fault Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.3.1.5 Test Method and Procedure

2.3.1.5.1 Determining Resistance and Power Rating of R2 and R3:

1. Connect the DC charger to the DC charge breakout box
2. Connect the DC charge breakout box to the vehicle charge port
3. Start a charge session and allow the charge current to stabilize for 20 seconds.
4. Close switches **S2_HV+** and **S2_HV-**.
5. With a Digital Multi-Meter (DMM) measure and record the DC voltage between TP2 (+) and TP5 (DC voltage with respect to DC+ and Ground (GND)).
6. With a DMM measure and record the DC voltage between TP1 (-) and TP5 (DC voltage with respect to DC- and GND).
7. Open switches **S2_HV+** and **S2_HV-**.
8. Stop the charge session.
9. Calculate the necessary resistances of R3 to induce 500 Ω/volt fault using the following equation: $R3 = 500\ \Omega/\text{volt} * V_{DC} - R_{tolerance}$, where V_{DC} was the DC voltage with respect to DC+ and Ground (GND) and $R_{tolerance}$ is a small resistance offset to bring the system slightly under the detection threshold
10. Calculate the power rating of R3 using the following equation: $P3 = V_{DC}^2/R3$, where VDC was the DC voltage with respect to DC+ and Ground (GND).
11. Calculate the necessary resistances of R2 to induce 500 Ω/volt fault using the following equation: $R2 = 500\ \Omega/\text{volt} * VDC - R_{tolerance}$, where VDC was the DC voltage with respect to DC- and Ground (GND).
12. Calculate the power rating of R2 using the following equation: $P2 = V_{DC}^2/R2$, where V_{DC} was the DC voltage with respect to DC- and Ground (GND).

2.3.1.5.2 Faults Introduced <u>Before</u> Charge Session Initiation

<u>Fault to ground – DC Positive</u>

1 Introduce a short between the DC positive and the ground connection at the breakout box by **closing** switch **S2_Short**.
2 Connect the DC charger to the DC charge breakout box.
3 Connect the DC charge breakout box to the vehicle charge port.
4 Attempt to start a charge session.
5 Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
6 Remove the short between the DC positive and the ground connection by **opening** switch **S2_Short**. Although unlikely, if charging begins once the ground fault is removed, end charging manually.
7 Clear all faults on the vehicle and key cycle the vehicle.
8 Disconnect the DC charger and vehicle charge port from the breakout box.
9 Reset the faults on the charge station as needed.

Fault to ground – DC Negative

1 Introduce a short between the DC negative and the ground connection at the breakout box by **closing** switch **S1_Short**.
2 Connect the DC charger to the DC charge breakout box.
3 Connect the DC charge breakout box to the vehicle charge port.
4 Attempt to start a charge session.
5 Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
6 Remove the short between the DC negative and the ground connection by **opening** switch **S1_Short**. Although unlikely, if charging begins once the ground fault is removed, end charging manually.
7 Clear all faults on the vehicle and key cycle the vehicle.
8 Disconnect the DC charger and vehicle charge port from the breakout box.
9 Reset the faults on the charge station as needed.

2.3.1.6 Faults Introduced <u>During</u> Fast Charging

Fault to ground – DC Positive

1 Start a charge session and allow the charge current to stabilize for 20 seconds.
2 Introduce a short between the DC positive and the ground connection at the breakout box by **closing** switch **S2_Short**.
3 Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
4 Stop the charge session if closing switch **S2_Short** did not initiate a shutdown.
5 Remove the short between the DC positive and the ground connection by **opening** switch **S2_Short**.
6 Clear all faults on the vehicle and key cycle the vehicle.
7 Reset the faults on the charge station as needed.

Fault to ground – DC Negative

1 Start a charge session and allow the charge current to stabilize for 20 seconds.
2 Introduce a short between the DC negative and the ground connection at the breakout box by **closing** switch **S1_Short**.
3 Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
4 Stop the charge session if closing switch **S1_Short** did not initiate a shutdown.
5 Remove the short between the DC negative and the ground connection by **opening** switch **S1_Short**.
6 Clear all faults on the vehicle and key cycle the vehicle.
7 Reset the faults on the charge station as needed.

2.3.1.6.1 End of Test Procedure

1 Clear all faults on the vehicle and key cycle the vehicle.
2 Reset the faults on the charge station as needed.
3 Disconnect the vehicle from the DC charge breakout box.
4 Disconnect the charger from the DC charge breakout box.

2.3.1.7 Pass Fail Criteria

Pass Criteria:

For tests that introduce the fault before the charge has started:

The system shall not start the charge session and the system shall remain in a safe state.

For tests that introduce the fault during the charge:
The system shall stop or abort the charge session and bring the system to a safe state.

Fail Criteria:
The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.2 Chassis Ground Offset Test

2.3.2.1 Purpose
This test will verify that the vehicle and charger system reacts appropriately to an offset on the ground connection between the vehicle charge port and the charger. The test conditions shall be applied both before a charge session is initiated and during an active charge session.

2.3.2.2 Rationale and Description
The ground connection between the charge station and the vehicle can become degraded due to increased resistance related to poor connections or failure of a conductor. This condition can result in communication stress (signal offset) causing partial or complete loss of analog and digital communications. Control pilot and proximity signals and/or power line communication can become impaired. This test will introduce a ground offset in the ground connection to determine the reaction of the system.

2.3.2.3 Sample Preparation
Install the DC charge breakout box between the DC fast charger and the vehicle.

2.3.2.4 Equipment Setup
Configure the DC charge breakout box to perform the chassis ground offset test with the initial switch setting (Table 3). Connect the DC charger to the DC charge breakout box (Figure 6). Connect the DC charge breakout box to the vehicle charge port.

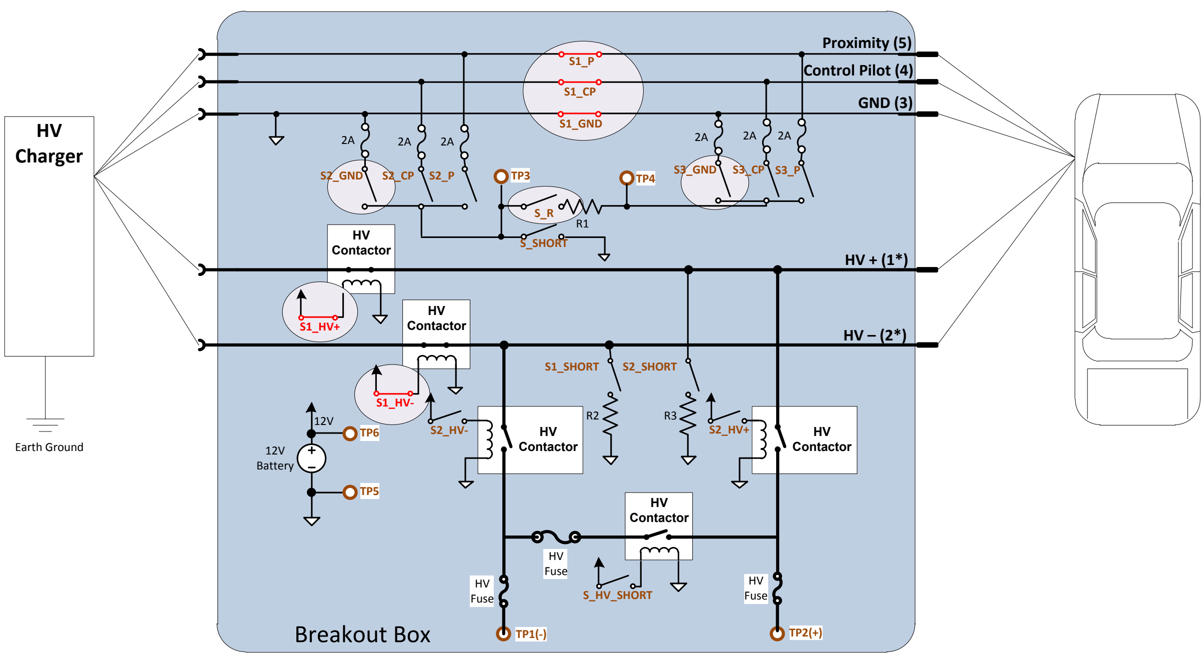

Figure 6: Chassis Ground Offset Test - DC Fast Charge Breakout Box Configuration

Table 3: Chassis Ground Offset Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this pre-test value.

2.3.2.5 Test Method and Procedure

Chassis Ground Offset introduced before a fast charge session

1. Introduce several resistances R1 (for example-1kΩ, 100Ω, 47Ω, 24Ω) between the vehicle and charger ground connections at the breakout box by **closing** switch **S2_GND, S3_GND** and **S_R**. Resistances should be chosen to represent levels ranging from "minimal" resistance increase relative to the detection threshold for a specific vehicle to a resistance well above the expected detection threshold.
2. Open the shorting bar connection on the breakout box between the vehicle ground and the charger ground by **opening** switch **S1_GND** leaving only the resistance connected in the above step.
3. Attempt to start a charge session.
4. Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
5. Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this value.
6. Remove the resistance installed in step 2 by **opening** switch **S2_GND,S3_GND** and **S_R**.
7. Replace the shorting bar removed in step 3 ground by **closing** switch **S1_GND**.
8. Clear all faults on the vehicle and key cycle the vehicle.
9. Reset the faults on the charge station as needed.
10. Perform test for all resistance values

Chassis Ground Offset introduced during a fast charge session

1. Start a normal charge session.
2. Introduce several resistances (1kΩ, 100Ω, 47Ω, 24Ω) between the vehicle and charger ground connections at the breakout box by **closing** switch **S2_GND, S3_GND** and **S_R**.
3. Open the shorting bar connection on the breakout box between the vehicle ground and the charger ground by **opening** switch **S1_GND** leaving only the resistance connected in the above step.
4. Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
5. Measure the voltage between chassis ground and earth (station) ground (**TP4-TP5**). Record this value.
6. Remove the resistance installed in step 2 by **opening** switch **S2_GND,S3_GND** and **S_R**.
7. Replace the shorting bar removed in step 3 ground by **closing** switch **S1_GND**.
8. Clear all faults on the vehicle and key cycle the vehicle.
9. Reset the faults on the charge station as needed.
10. Perform test for all resistance values

2.3.2.6 End of Test Procedure

1. Using the breakout box, measure the voltage between the vehicle ground and the earth (station) ground (**TP4-TP5**). Record this value.

2 Clear all faults on the vehicle and key cycle the vehicle.
3 Reset the faults on the charge station as needed.

2.3.2.7 Pass Fail Criteria

NOTE: Per J1772-2012-10, the voltage measured between the vehicle's chassis ground and the charger's earth ground (**TP4-TP5**) should not exceed 0.7V for proper function of the control pilot signal.

Pass Criteria:
For tests that introduce the fault before the charge has started:
If the additional ground resistance affects the charge session, the DUT shall not start the charge session and remain in a safe state. If the additional ground resistance does not affect the DUT, a charge session may begin but must maintain a safe state while charging and when the charge session ends.

For tests that introduce the fault during the charge:
If the additional ground resistance affects the charge session, the DUT shall maintain a safe state. If the additional ground resistance does not affect the DUT, a charge session may continue but must maintain a safe state while charging and when the charge session ends.

Fail Criteria:
The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.3 DC Bus Short Test

2.3.3.1 Purpose

This test procedure will determine if a DC bus short in the vehicle charge coupler can be detected and handled or communicated by the DUT. The test conditions are applied before a charge session is initiated.

2.3.3.2 Rationale and Description

It is possible for the vehicle coupler to have a short circuit due to tampering with the charge coupler, frayed insulation, etc. This test procedure will introduce a short circuit on the charge coupler prior to a charge session initiation to determine if the DUT can safely detect the short on the coupler before the main charge session is initiated. It should be noted that a compliant CCS charger should detect the short before initiating a charge session.

2.3.3.3 Sample Preparation

Install the DC charge breakout box between the DC fast charger and the vehicle.

2.3.3.4 Equipment Setup

Configure the DC charge breakout box (Figure 7) to perform the DC bus short test with the initial switch setting (Table 4). Test the fuses with an ohmmeter before the test to ensure they have not blown (**TP1-TP2**). Replace as necessary. Record the resistance value of the intact fuses.

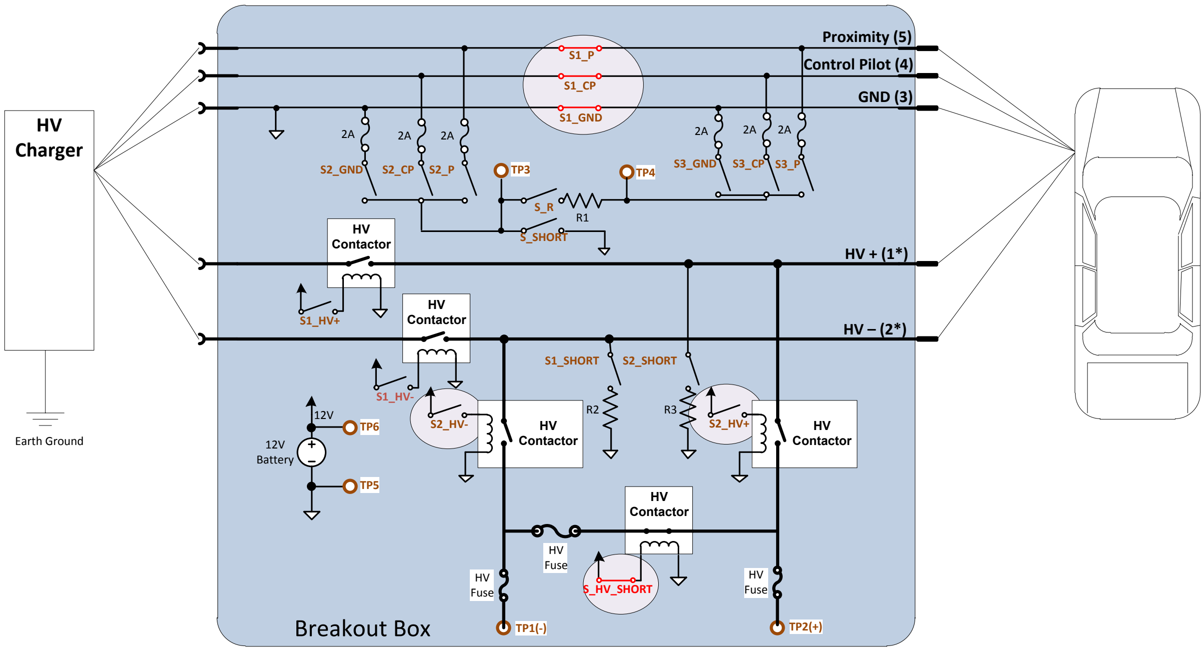

Figure 7: DC Bus Short Test - DC Fast Charge Breakout Box Configuration

Table 4: DC Bus Short Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED															CLOSED

2.3.3.5 Test Method and Procedure

DC Bus Short in Charge Coupler

1. Introduce a fused short between the HV + and HV - in the breakout box by **closing** switch **S2_HV-** and **S2_HV+**.
   (Note: Table 4 shows switch S2_HV short as "closed" at the start of testing, but this step is included to remind the user to activate the short condition prior to pluggin in the connector]
2. Plug in the CCS charger to the breakout box and breakout box's connector into the DUT to initiate the start of a charge session.
3. Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
4. Remove the short installed in Step 2 box by **opening** switch **S2_HV-** and **S2_HV+**.
5. Measure the fuses with an ohmmeter to determine if they have blown (**TP1-TP2**). Record the resistance values.
6. Clear all faults on the vehicle and key cycle the vehicle.
7. Reset the faults on the charge station as needed.

2.3.3.6 End of Test Procedure

Disconnect the vehicle and charger from the DC charge breakout box.

Measure the resistances of the fuses after they are removed from the test equipment to determine if they have blown (**TP1-TP2**). Record the condition of the fuses.

2.3.3.7 Pass Fail Criteria

Pass Criteria:
The charge session shall not start if the fault is present.
If the fuses are rated for the maximum current of the charger, the fuses shall not be blown.

Fail Criteria:
The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.4 DC Bus Held High Test

2.3.4.1 Purpose
The purpose of this test procedure is to determine the reaction of the vehicle and DC charging system to a vehicle DC bus being held high during disconnect, which means that a potential high voltage is still present at the two extended DC charge connector pins. The presence of high-voltage during disconnection could result in a high voltage exposure risk to the operator.

2.3.4.2 Rationale and Description
It is possible that the DC bus is held high after disconnect. This can occur if the DC bus discharge that should occur after the charger disconnects from the vehicle is interrupted or the bus voltage measurement does not match the actual bus voltage during the initial connection. DC bus voltage can also be held high if a faulty DC/DC converter is back feeding to the high voltage DC bus. This test will emulate this condition to determine how the system will react to this type of fault.

2.3.4.3 Sample Preparation
Install the DC charge breakout box between the vehicle and the DC charger.

2.3.4.4 Equipment Setup
Configure the DC charge breakout box to perform the DC Bus Held High test with the initial switch setting (Table 5). Connect the DC charger to the DC charge breakout box (Figure 8). Connect the DC charge breakout box to the vehicle charge port. Configure a high voltage power supply with diode protection to prevent negative current flow. Attach the power supply's leads to the breakout box test points: negative connection to TP1(-) and positive connection to TP2(+). Please refer to the test procedure schematic, below.

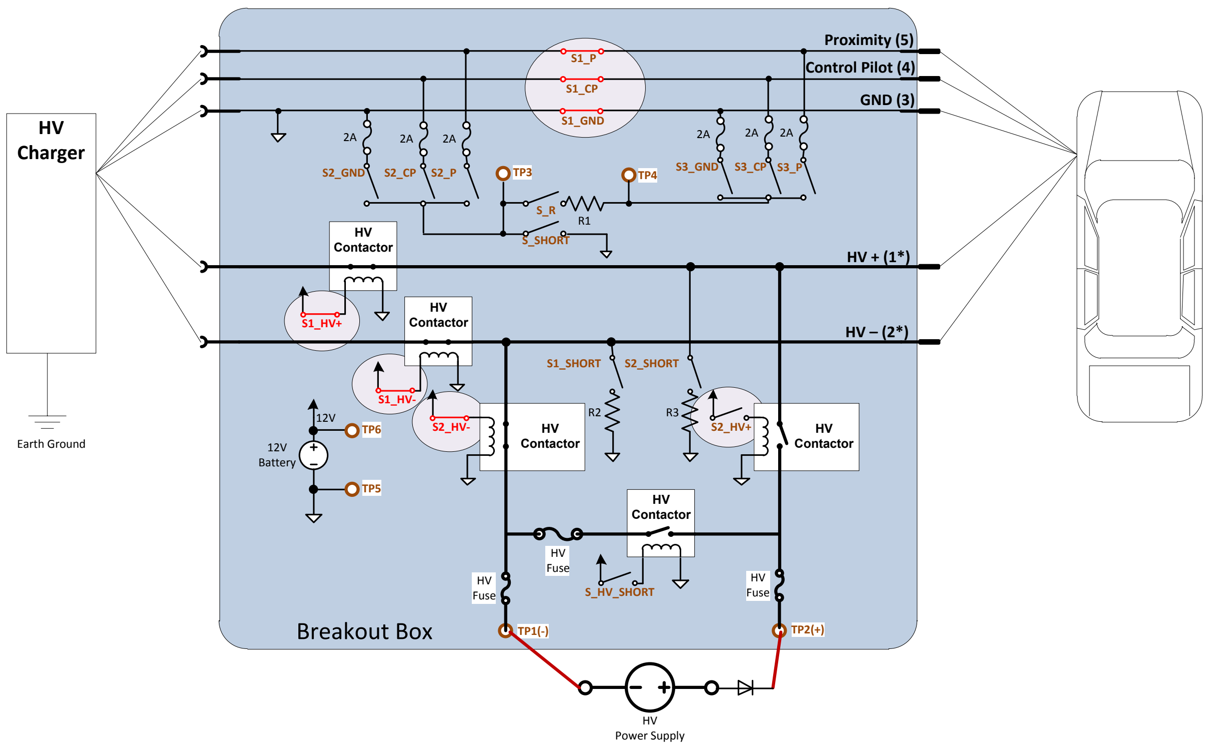

Figure 8: DC Bus Held High Test - DC Fast Charge Breakout Box Configuration

Table 5: DC Bus Held High - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED		CLOSED	

2.3.4.5 Test Method and Procedure

DC bus held high before charging session is started:

1. Using the breakout box, connect the DC bus of the charge coupler to a high voltage power supply (Diode protected to prevent negative current flow) by **closing** the switch **S2_HV+**.
2. Set the power supply to voltage control mode with a current limit.
3. Set the voltage to 60 V_{DC} and the maximum current to 1A.
4. Start a charge session.
5. Observe the system behavior.
6. Record any faults on the DUT and the DC fast charge station.
7. Remove the connection to the power supply by **opening** the switch **S2_HV+**.

DC bus held high after charging session is ended:

1. Start a normal charge session through the breakout box.
2. Measure the high voltage of the REES (at **TP1-TP2**) and record.
3. Set the power supply to voltage control mode with a current limit.
4. Set the voltage to the RESS voltage measure in step 2. (+5/-0 VDC) and the maximum current to 1A.

5. Using the breakout box, connect the DC bus of the charge coupler to a high voltage power supply (Diode protected to prevent negative current flow) by **closing** the switch **S2_HV+**.
6. End the charge session.
7. Observe the system behavior and determined if the connector is still locked to the DUT's inlet.
8. If the connector is still locked, begin to reduce the voltage of the high voltage power supply until the inlet is unlocked. Record this voltage value.
9. Record any faults on the DUT and the DC fast charge station.
10. Remove the connection to the power supply by **opening** the switch **S2_HV+**.

2.3.4.5.1 End of Test Procedure

Remove the connection to the power supply by **opening** the switch **S2_HV+**. Remove the breakout box from the system

2.3.4.6 Pass Fail Criteria

Pass Criteria:

The charge session shall not start if high voltage is present at the beginning of the charge session.

The DUT shall not allow the CCS connector to be removed from the inlet if the DC voltage is greater than 60 VDC.

Fail Criteria:

If the CCS connector is allowed to be removed from the DUT's inlet with a voltage greater than 60 VDC the DUT fails this test.

The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.5 12V System Overvoltage

2.3.5.1 Purpose

The purpose of this test procedure is to simulate an overvoltage on the 12V net during a DC charge session to determine the reaction of the vehicle and charger system to this condition.

2.3.5.2 Rationale and Description

It is possible for the 12V system on the vehicle to experience an overvoltage due to faulty DC/DC converter or external jump starting or external charging of the 12V battery during a DC fast charge. This test shall introduce this condition to determine how the vehicle and charger system reacts.

2.3.5.3 Sample Preparation

Install a high power DC power supply in place of the 12V lead acid battery in the vehicle. Ensure that the 12V power to the vehicle is never interrupted during the installation.

2.3.5.4 Equipment Setup

Configure the DC power supply to provide 12V power to the vehicle to enable a 12V System Overvoltage Test.

Connect the DC charger to the vehicle charge port (without break out box installed).

Refer to the schematic of the test procedure, below. In vehicle systems where there is a DC/DC converter connected to the 12V battery and is activated during charging, it has to be ensured that this DC/DC converter does not interfere with the reduction of the 12V system voltage. It is therefore necessary to either disconnect the DC/DC converter output from the vehicle system (if it is determined that it will not interfere with the charging operation) or alternatively it is possible to install a resistor of proper resistance and wattage at the output of the DC/DC converter. This resistor will limit the current the DC/DC converter can provide to the 12V board net and allow the test to be conducted.

Figure 9: 12V System Overvoltage Test - 12V Power Supply Connection

2.3.5.5 Test Method and Procedure

<u>12V system overvoltage:</u>

1. Conduct an over voltage test according to ISO 16750-2 for overvoltage conditions.
2. Attempt to start a charge session while applying the conditions outlined in ISO 16750-2 for overvoltage (**18V** for **60 minutes** or until the charge session is complete).
3. Observe the system behavior.
4. Record any faults on the DUT and the DC fast charge station.
5. Return the vehicle's 12V system to normal (set DC power supply to 12V).

2.3.5.6 End of Test Procedure

Return the vehicle 12V system to the original configuration.

2.3.5.7 Pass Fail Criteria

Pass Criteria:

It is unknown how the DUT will react to these procedures. A charge session may or may not be initiated and maintained, however the DUT must maintain a safe state of the system.

Fail Criteria:

The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.6 12V System Under voltage Test

2.3.6.1 Purpose

The purpose of this test is to simulate the gradual discharge of the 12V battery during a fast charge.

2.3.6.2 Rationale and Description

It is possible for the vehicle's 12V system to experience an under voltage condition during a DC fast charge. This can be due to a faulty DC/DC converter, a loss of connection between the DC/DC converter and the 12V battery, a faulty 12V battery or the operator leaving on a high current draw accessory during a DC fast charge. This test will introduce this condition to determine how the vehicle and charger system will react to this condition.

2.3.6.3 Sample Preparation

Install a high power DC power supply in place of the 12V battery in the vehicle. Ensure that the 12V power to the vehicle is never interrupted during the installation. Alternatively to the DC power supply, a low capacity battery (4Ah-8Ah) can be used in combination with a low power supply to provide a slowly dropping 12V system voltage.

2.3.6.4 Equipment Setup

Prepare the power supply according to ISO 16750-2 test "Slow decrease and increase of supply voltage" by setting the starting voltage to 13.2V (or use a fully charged low capacity battery).

Connect the DC charger to the vehicle charge port (without break out box installed).

Refer to the schematic of the test procedure, below. In vehicle systems where there is a DC/DC converter connected to the 12V battery and is activated during charging, it has to be ensured that this DC/DC converter does not interfere with the reduction of the 12V system voltage. It is therefore necessary to either disconnect the DC/DC converter output from the vehicle system (if it is determined that it will not interfere with the charging operation) or alternatively it is possible to install a resistor of proper resistance and wattage at the output of the DC/DC converter. This resistor will limit the current the DC/DC converter can provide to the 12V board net and allow the test to be conducted.

Figure 10: 12V System Under Voltage Test – 12V Power Supply Connection

2.3.6.5 Test Method and Procedure

<u>12V system under voltage due to battery discharge</u>

1. Verify that the DC power is set to **13.2V**.
2. Start a charge session.
3. Apply the conditions outlined in ISO 16750-2 for "Slow decrease of supply voltage": Simulate a gradual discharge of the 12V battery with the DC power by supplying the vehicle board with a regulated voltage from a **<u>starting value</u>** of **13.2V** at the beginning of the DC fast charge, **<u>down to</u>** **0V** **<u>at a rate</u>** of **0.5V/min**.
   Note: If possible adjust the DC fast charge rate to be active during the entire duration of the board net voltage slew (26 minutes)
4. Observe the system behavior during the entire charge cycle until the board net voltage of 0V is reached or the charger/vehicle systems enters a permanent fault state.
5. Record any faults on the DUT and the DC fast charge station.
6. Return the vehicle 12V system to normal by reinstalling the 12V battery.

2.3.6.5.1 End of Test Procedure
Return the vehicle 12V system to normal by reinstalling the 12V battery. Clear any codes set in the vehicle or charger.

2.3.6.6 Pass Fail Criteria

Pass Criteria: It is unknown how the DUT will react to this procedure. A charge session should be initiated but it is unclear how the DUT will react to an emulated discharge of the 12V bus. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.7 12V System Disturbance Test

2.3.7.1 Purpose

The purpose of this test is to simulate a switching 12V load application that can disturb the stability of the 12V bus.

2.3.7.2 Rationale and Description

It is possible that a large 12V load turning on and off, such as a pump, fan, aftermarket system, or jump starting a second car, can cause disturbances in the 12V system in the vehicle. These fluctuations, if severe enough, may cause different modules on the vehicle to malfunction during a DC fast charge. This test shall introduce this condition to determine what the reaction of the vehicle and charger system will be.

2.3.7.3 Sample Preparation

Connect the vehicle to the DC charging system normally, without the breakout box.

2.3.7.4 Equipment Setup

Prepare the power supply according to ISO 16750-2 test “Slow decrease and increase of supply voltage” by setting the starting voltage to 13.2V.

Connect the DC charger to the vehicle charge port (without break out box installed).

Refer to the schematic of the test procedure, below. In vehicle systems where there is a DC/DC converter connected to the 12V battery and is activated during charging, it has to be ensured that this DC/DC converter does not interfere with the reduction of the 12V system voltage. It is therefore necessary to either disconnect the DC/DC converter output from the vehicle system (if it is determined that it will not interfere with the charging operation) or alternatively it is possible to install a resistor of proper resistance and wattage at the output of the DC/DC converter. This resistor will limit the current the DC/DC converter can provide to the 12V board net and allow the test to be conducted.

Figure 11: 12V System Disturbance Test – 12V Load Connection

2.3.7.5 Test Method and Procedure

Alternating load applied to 12V bus while charging:

1. Connect a 20A load to the 12V bus of the DUT. (pump, fan, heater etc.)
2. Toggle the load at a **1 Hz** rate on/off.
3. Start a charge session
4. Observe the system behavior
5. Record any faults on the DUT and the DC fast charge station.
6. Remove the load from the vehicle 12V bus.

2.3.7.5.1 End of Test Procedure

Remove the load from the vehicle 12V system.

2.3.7.6 Pass Fail Criteria

Pass Criteria: It is unknown how the DUT will react to this procedure. A charge session should be initiated but it is unclear how the DUT will react to a 20A toggled load on the 12V bus. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.8 12V System EMI/EMC Test

2.3.8.1 Purpose

The purpose of this test procedure is to determine if electromagnetic disturbances can affect the DC charging system.

2.3.8.2 Rationale and Description

It is possible that large electromagnetic disturbances during a DC fast charge can affect the low voltage power system and disturb communication between vehicle components. This test shall introduce this type of condition during a DC fast charge and determine the reaction of the vehicle/charger system.

2.3.8.3 Sample Preparation

Prepare the vehicle and charger system to perform a normal DC fast charge.

2.3.8.4 Equipment Setup
Prepare the EMI/EMC equipment per SAE test procedures J1113-3, -4, -21, and -24.

2.3.8.5 Test Method and Procedure

Electromagnetic Disturbance During DC Fast Charge:

1. Conduct the EMI/EMC vehicle level SAE test procedures according to SAE J1113-3,-4,-21,-24 to the extent to which it is feasible.
2. Start a charge session.
3. Observe the behavior of the system.
4. Record any faults on the DUT and the DC fast charge station.

2.3.8.5.1 End of Test Procedure
Remove the test equipment. Record and then clear any codes that may have set in the vehicle or the charger.

2.3.8.6 Pass Fail Criteria
Pass Criteria: It is unknown how the DUT will react to electromagnetic disturbance. A charge session may or may not be initiated and maintained, however the DUT must maintain a safe state of the system.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.9 Vehicle Movement Tests

2.3.9.1 Purpose
The first purpose of this set of tests is to determine if the drive away interlocks of the vehicle system are effective while the connector is mated the vehicle's inlet. The second is to confirm that a charge session cannot be initiated for a vehicle with a failed parking brake/pawl system, thus enabling the vehicle to roll during a charge session if not prohibited from charging.

2.3.9.2 Rationale and Description
It is possible that the operator of the vehicle will inadvertently try to drive off while the charger is still connected. It is also possible that the vehicle could roll away during a DC fast charge due to faulty parking pawl mechanism or parking brake mechanism. This test shall introduce this condition during the DC fast charge to determine what the reaction of the vehicle/charger system will be.

2.3.9.3 Sample Preparation
For the vehicle movement during DC fast charge test the vehicle's parking pawl/brake mechanism should be disabled. Connect the vehicle to the DC charger.

Note: Although through the open differential individual or counter wheel rotation is possible, however rotation in the same direction should not be allowed in park mode.

2.3.9.4 Equipment Setup
There are no specific equipment setup instructions for this test.

2.3.9.5 Test Method and Procedure

<u>Vehicle Drive Away Attempt before DC Fast Charge:</u>

1. Plug in the DC charger connector to the vehicle inlet but do not start a charge session.
2. **Release** the parking brake.
3. Observe system behavior.
4. Get inside the vehicle and attempt to **turn on** the vehicle
5. Observe system behavior.
6. **Move the PRND** gear shift lever to the Drive position.
7. Observe system behavior.
8. **Move the PRND** gear shift lever to the Neutral position.
9. **Move the PRND** gear shift lever to the Reverse position.
10. Observe the system behavior.
11. Record any faults on the DUT and the DC fast charge station.
12. Clear all faults on the vehicle and key cycle the vehicle.
13. Reset the faults on the charge station as needed.

<u>Vehicle Drive Away Attempt During DC Fast Charge</u>

1. Start a normal charge session.
2. **Release** the parking brake.
3. Observe system behavior.
4. Get inside the vehicle and attempt to **turn on** the vehicle
5. Observe system behavior.
6. **Move the PRND** gear shift lever to the Drive position.
7. Observe system behavior.
8. **Move the PRND** gear shift lever to the Neutral position.
9. **Move the PRND** gear shift lever to the Reverse position.
10. Observe the system behavior.
11. Record any faults on the DUT and the DC fast charge station.
12. Clear all faults on the vehicle and key cycle the vehicle.
13. Reset the faults on the charge station as needed.

<u>Protection from unexpected vehicle movement during DC fast charge:</u>
Discussed in greater detail within the Validation Section of this report, this test remains a requirement for safe DC charging, but a common procedure cannot be provided without dictating a specific technology. The intent of this requirement is that a vehicle must not begin a charge session if there is an increased likelihood of unexpected, non-propulsion based movement due to a failure in the vehicle motion prevention system (parking brake, parking pawl, etc.). Thus an individual vehicle's parking system must be evaluated and a specific procedure developed to assess its behavior to this condition. An example procedure can be found in Section 4.9.2.4.

2.3.9.5.1 End of Test Procedure

Lower the vehicle from the jack/lift.

2.3.9.6 Pass Fail Criteria

Pass Criteria: The DUT should not enable its drive train and allow the vehicle to move while the connector is mated to the vehicle inlet. The DUT should also inhibit and protect against unexpected vehicle movement during charging due to a failed parking brake/pawl or similar system. The DUT must maintain a safe state of the system.

Fail Criteria: The DUT fails this test if the drive train is enabled and vehicle movement of 150mm or greater can occur while the connector is mated to the vehicle inlet (before, during or after a charge session).

The DUT fails if a charge session can be initiated in which the vehicle can be rolled due to a failed parking pawl/brake mechanism.

The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.10 Vehicle Crash or Bump Test

2.3.10.1 Purpose

The purpose of this test is to determine the reaction of a RESS safety protection system when subjected to a vehicle collision during a DC fast charge. If an incident is severe enough to damage a vehicle's RESS and charging system during a charge event, this incident should be detected and charging halted in a safe manner resulting in a fail-safe condition of the vehicle.

2.3.10.2 Rationale and Description

The typical DC fast charger is located in a public parking area where the vehicle may be exposed to other vehicle traffic. Inevitably, a collision will occur to an actively charging vehicle during a DC fast charge causing vehicle damage that may result in RESS safety failure, particularly to unique to battery and electrical failure modes including arcing and HV exposure if damage occurs during a high-rate charging event. Given the voltage and current levels observed in DC charging, an additional issue realted to an undetected crash situation could be from an arc flash related to the rapid separation (via damage) of the connectors, cabling, or other vehicle-charging interface. Depending on the type and response time of a vehicle's RESS protection system, the arc flash may be difficult or not possible to observe via the RESS sensing, whereas a collision detection ststem woul typically be more likely to detect the collision allowing for charging to be halted. To these ends, the vehicle must monitor for a vehicle collision (bump) while actively charging. If a collision is detected at a relative velocity of greater than 5 mph, the charging operation must be halted. The charging may be resumed only after system safety self-assessment has been completed followed by an operator restart of the charging session.

A starting point for this test is the low speed impact test input is that as defined in CFR 49 Part 581 (Bumper Standard), but if that is insufficient to induce the desired vehicle protection actions, a more severe test or other crash emulation strategy is allowable, but should be in-line with ehe 5mph detection requitement.

2.3.10.3 Sample Preparation

Ensure that the vehicle high voltage system has no isolation fault that will endanger the test personnel. Perform an isolation test according to SAE J1766 at the HV terminals of the charge connector prior to performing this test procedure.

Prepare the vehicle and test fixture for an impact equivalent to FMVSS Test Procedure TP-581, pendulum impact test. It is not necessary to duplicate the full TP-581 instrumentation and data recording. It is only necessary to subject the vehicle to an equivalent impact during the charge session.

In deviation from TP-581, the vehicle shall be parked normally with the parking brake engaged. Do not place the vehicle in neutral as specified in TP-581 as this is not the typical condition during a fast charge session.

2.3.10.4 Equipment Setup

Set up the pendulum test device according to FMVSS Test Procedure TP-581.

2.3.10.5 Test Method and Procedure

<u>Simulated vehicle Crash or Bump During DC Fast Charge (front impact):</u>

1. Plug the vehicle in to the DC fast charger
2. Start a charge session
3. Wait for 1 minute for the charger and vehicle to connect and stabilize.
4. Impact the vehicle in the front with the pendulum test device (PTD) at 2.3 +/- 0.1 MPH using the bumper impact block test device as defined in TP-581.
5. Observe the state of the charger and vehicle system.
6. Record any faults on the DUT and the DC fast charge station.
7. Record any damage of the charger coupler or cable.
8. Clear all faults on the vehicle and key cycle the vehicle.
9. Reset the faults on the charge station as needed.

<u>Simulated vehicle Crash or Bump During DC Fast Charge (rear impact)</u>

1. Plug the vehicle in to the DC fast charger
2. Start a charge session
3. Wait for 1 minute for the charger and vehicle to connect and stabilize.
4. Impact the vehicle in the rear with the pendulum test device (PTD) at 2.3 +/- 0.1 MPH.
5. Observe the state of the charger and vehicle system.
6. Record any faults on the DUT and the DC fast charge station.
7. Record any damage of the charger coupler or cable.
8. Clear all faults on the vehicle and key cycle the vehicle.
9. Reset the faults on the charge station as needed.

2.3.10.5.1 **End of Test Procedure**

Perform a post test safety inspection to ensure that no high voltage safety violation is present (e.g., disconnected or damaged HV connectors/wires, debris or sharp edges). Inspect all cables and connectors between fast charger and vehicle.

2.3.10.6 Pass Fail Criteria

Pass Criteria: For a collision above the 5 mph relative velocity threshold, the charging operation must be halted. The charging may be resumed only after system safety self-assessment has been completed followed by an operator restart of the charging session. During and following this emergency shut-down, the DUT must maintain a safe state of the system.

Fail Criteria: The DUT fails this test if the vehicle does not detect the impact event, or does not halt charging, or if at any point during or after this test a safe state of the system is not maintained.

2.3.11 Charge Operation Disturbance Test

2.3.11.1 Purpose

The purpose of this test is to determine if abnormal actions by the operator can cause an unsafe condition during a DC fast charge.

2.3.11.2 Rationale and Description

It is possible that unintended conditions for either the vehicle or the charger can be realized by unexpected inputs to either the vehicle or charger during a DC fast charge. This test is designed to test the reaction of the vehicle/charger system to a series of unexpected inputs during a DC fast charge.

2.3.11.3 Sample Preparation
Connect the vehicle to the DC charging system normally, without the breakout box.

2.3.11.4 Equipment Setup
There are no specific equipment setup instructions for this test.

2.3.11.5 Test Method and Procedure

Premature disconnect attempt:
1. Begin a normal charge session
2. After the charge has begun successfully, attempt to disconnect the charge coupler from the vehicle without pressing the stop button on the charger.
3. Record the results

Operator interference at the charger:
1. Begin a normal charge session
2. After the charge has begun successfully, press all the available operator accessible buttons on the DC fast charger
3. Record the results.

Wiggle the connector
1. Begin a normal charge session
2. After the charge has begun successfully, wiggle the charger connector while it is plugged in to the vehicle.
3. Record the results.

Operator interference on the vehicle:
1. Begin a normal charge session
2. After the charge has begun successfully, turn on the vehicle ignition
3. Record the results

Operator interference with the vehicle key fob:
1. Begin a normal charge session
2. After the charge has begun successfully, press all key fob functions on the vehicle transmitter/key
3. Record the result

Operator interference with a remote telematics command:
1. Begin a normal charge session
2. After the charge has begun successfully, exercise all Telematics functions (unlock doors, turn on HVAC remotely during a charge, etc.)
3. Record the result

2.3.11.5.1 **End of Test Procedure**
Disconnect the vehicle from the DC charging system. Record and then clear any codes that may have set in the vehicle or the charger.

2.3.11.6 Pass Fail Criteria
Pass Criteria: In all the procedures of this test, the DUT and charger shall result in either no reaction, a vehicle initiated shutdown, or a charger initiated shutdown and the DUT shall remain in a safe state of the system.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.12 Charge Connector Control Signal Disturbance Test

2.3.12.1 Purpose

The purpose of this test procedure is to determine the reaction to control signal disturbances between the vehicle and the fast charger.

2.3.12.2 Rationale and Description

It is possible that disturbances in the control signals in the charge coupler connector can cause loss of control of the charge session and potentially hazardous situations. These control signals can include earth/chassis ground, control pilot (including PLC over pilot), and proximity signals. PLC signals can degrade due to disturbances induced from the grid (e.g., arc welder, compressor, etc.) or incompatible devices on the network. The physical connection can degrade or break due to contamination in the charge coupler or connector terminals. The connector can even forcefully "break-away" during a charge session if any vehicle movement or a minor collision is experienced. This test will subject the vehicle/charger system to these types of conditions to determine the reaction of the vehicle/charger system.

2.3.12.3 Sample Preparation

Install the DC charge breakout box between the vehicle and the DC charger.

2.3.12.4 Equipment Setup

Configure the DC charge breakout box to perform the Charge Connector Control Signal Disturbance test with the initial switch setting shown in Table 6.

Connect the DC charger to the DC charge breakout box (Figure 14).

Connect the DC charge breakout box to the vehicle charge port.

Please refer to the test procedure schematic, below.

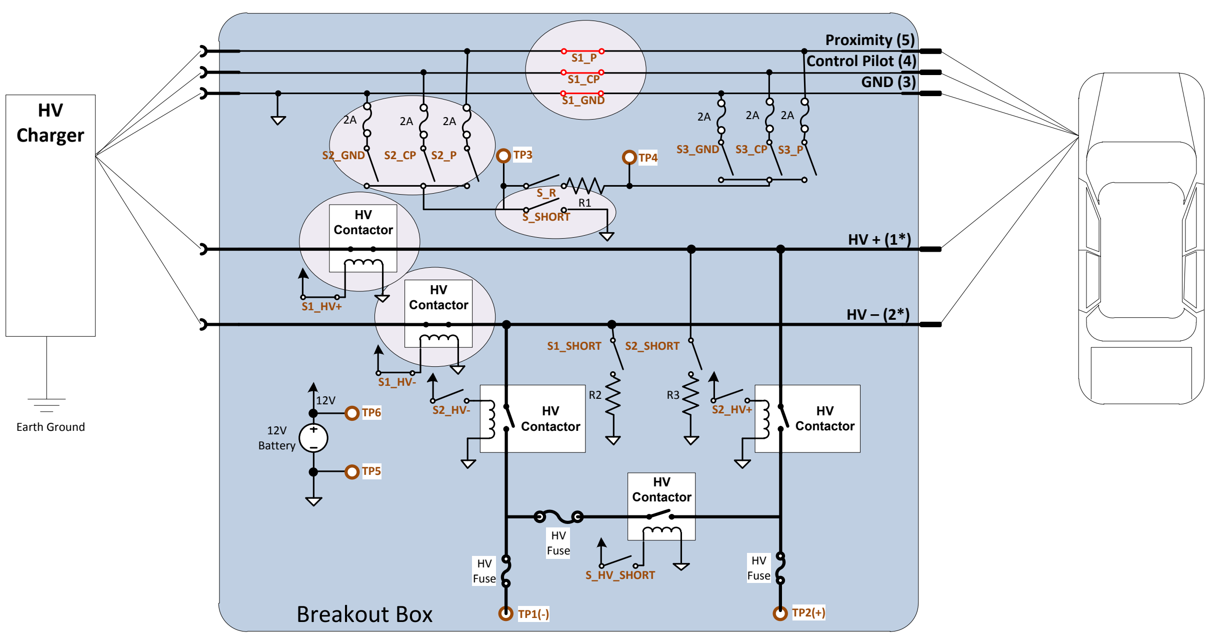

Figure 12: Control Signal Disturbance Test - Breakout Box Configuration

Table 6: Charge Connector Control Signal Disturbance Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.3.12.5 Test Method and Procedure

Communication connection interrupted in breakout box during charge session -
Control pilot interruption through breakout box:

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Break the control pilot connection in the breakout box by **opening** **S1_CP** switch.
4. Observe the system behavior
5. Record any faults from the DUT and the DC charge station.
6. Return the breakout box switches to the initial state.

Communication connection interrupted in breakout box during charge session -
Control pilot short to ground through breakout box:

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Short the control pilot connection in the breakout box to ground by **closing** the **S2_CP** and **S_SHORT** switches.
4. Observe the system behavior
5. Record any faults from the DUT and the DC charge station.
6. Return the breakout box switches to the initial state.

Communication connection interrupted in breakout box during charge session
(Proximity interruption through breakout box):

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Break the proximity signal connection in the breakout box by **opening** the **S1_P** switch.
4. Observe the system behavior
5. Record any faults from the DUT and the DC charge station.
6. Return the breakout box switches to the initial state.

Communication connection interrupted in breakout box during charge session
(Proximity short to ground through breakout box):

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Short the proximity signal connection in the breakout box to ground by **closing** the **S2_P** and **S_SHORT** switches
4. Observe the system behavior
5. Record any faults from the DUT and the DC charge station.
6. Return the breakout box switches to the initial state.

2.3.12.5.1 End of Test Procedure
Remove the breakout box from the system.

2.3.12.6 Pass Fail Criteria
Pass Criteria: In all the procedures of this test, the DUT and charger shall initiate either a vehicle initiated shutdown, or a charger initiated shutdown and the DUT shall remain in a safe state of the system.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.13 Charge Connector Ground Connection Disturbance

2.3.13.1 Purpose
The purpose of this test procedure is to determine the reaction to a disturbance between the vehicle chassis ground and the charger earth ground connection.

2.3.13.2 Rationale and Description
It is possible that the chassis/earth ground connection between the charger and the vehicle can experience a disturbance during a DC fast charge. This can be due to increased resistance on the connection, mechanical damage such as a broken wire or worn contact. This test shall introduce this condition and determine the reaction of the vehicle/charger system.

2.3.13.3 Sample Preparation
Install the DC charge breakout box between the vehicle and the DC charger.

2.3.13.4 Equipment Setup
Configure the DC charge breakout box to perform the Charge Connector Ground Connection Disturbance Test with the initial switch setting shown in Table 7.

Connect the DC charger to the DC charge breakout box (Figure 13).

Connect the DC charge breakout box to the vehicle charge port.

Please refer to the test procedure schematic, below.

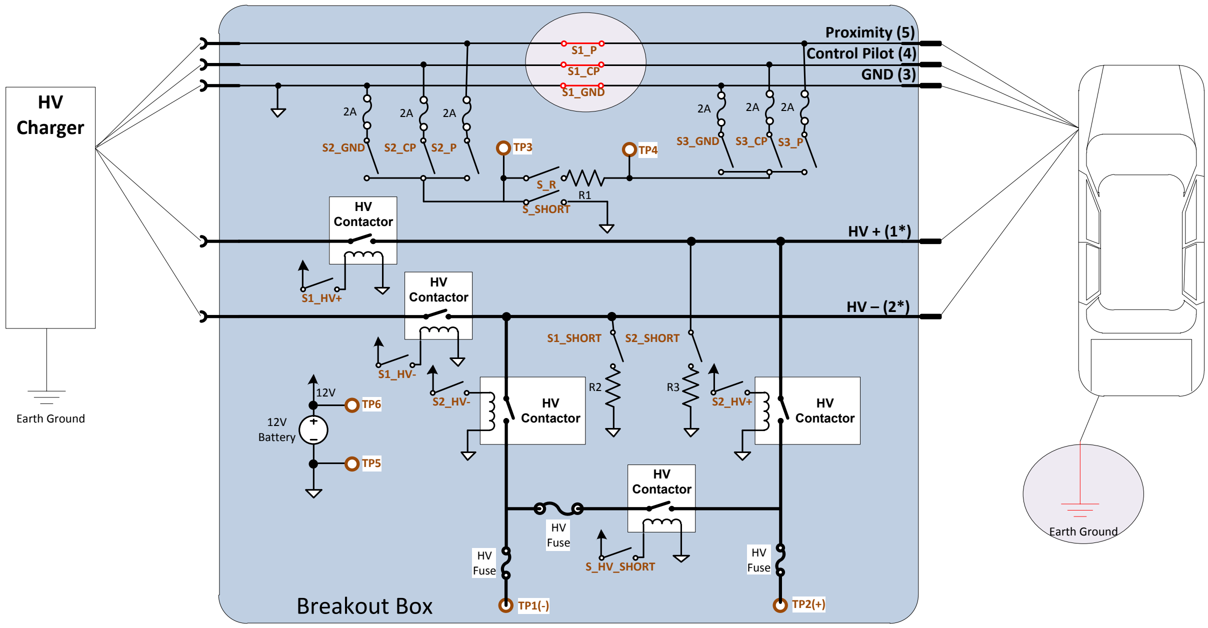

Figure 13: Ground Connection Disturbance Test - Breakout Box Configuration

Table 7: Charge Ground Connection Disturbance Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.3.13.5 Test Method and Procedure

Remove chassis/earth ground connection during a fast charge session using the breakout box:

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Disconnect the chassis/earth ground connection in the breakout box by opening switch **S1_GND**.
4. Observe the system behavior
5. Record any faults from the DUT and the DC charge station.

2.3.13.5.1 End of Test Procedure

Remove the breakout box from the system.

2.3.13.6 Pass Fail Criteria

Pass Criteria: For this procedure the charge session will shutdown upon removal of the chassis/earth ground connection and the DUT shall remain in a safe state of the system.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.14 Charge Connector HV Connection Disturbance

2.3.14.1 Purpose

The purpose of this test is to determine the vehicle/system reaction to poor HV connection between the vehicle and the DC fast charger.

2.3.14.2 Rationale and Description

It is possible that the HV connection between the vehicle and the charger has become degraded or interrupted during a charge. This can be due to contamination of the terminals resulting in increased resistance of the receptacle/plug interface, worn high voltage contacts, over-temperature of the cable or terminals, or a degraded cable due to inadequate strain relief.

2.3.14.3 Sample Preparation

Install the DC charge breakout box between the vehicle and the DC charger.

2.3.14.4 Equipment Setup

Configure the DC charge breakout box to perform the Charge Connector HV Connection Disturbance Test with the initial switch setting shown in Table 8.

Connect the DC charger to the DC charge breakout box (Figure 14)

Connect the DC charge breakout box to the vehicle charge port.

Please refer to the test procedure schematic, below.

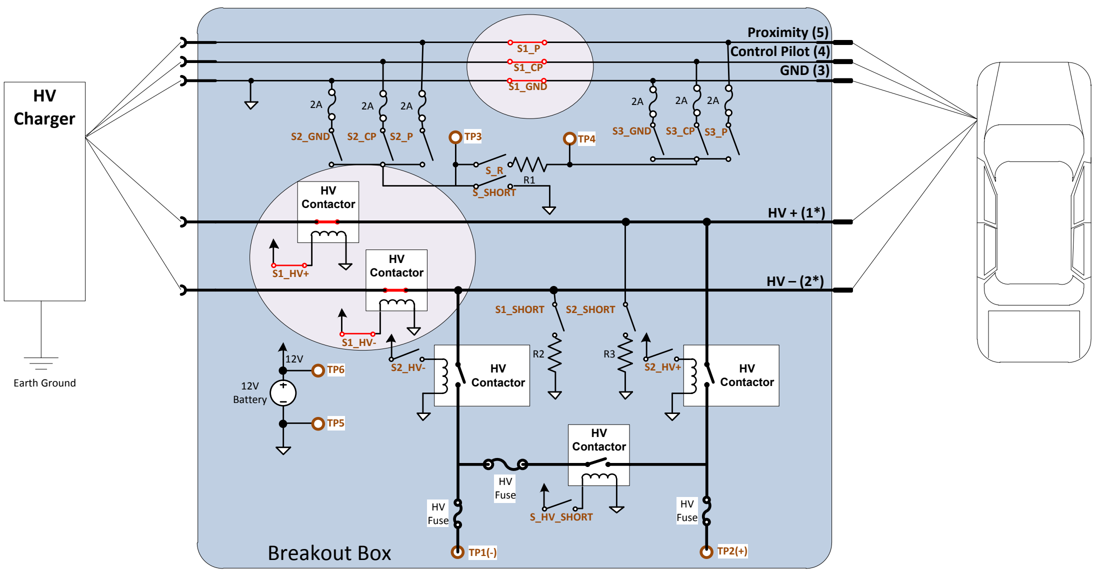

Figure 14: Charge Connector HV Connection Disturbance Test - Breakout Box Configuration

Table 8: Charge Connector HV Connection Disturbance Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.3.14.5 Test Method and Procedure

<u>Disconnect HV+ During Charge Session:</u>

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Allow the charging current to stabilize.
4. Disconnect the HV+ DC bus by **opening** switch **S1_HV+** using the breakout box.
5. Observe the system behavior
6. Record any faults from the DUT and the DC charge station.

Disconnect HV- During Charge Session:

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Allow the charging current to stabilize.
4. Disconnect the HV- DC bus by **opening** switch **S1_HV-** using the breakout box.
5. Observe the system behavior
6. Record any faults from the DUT and the DC charge station.

Disconnect HV- and HV+ During Charge Session:

1. Connect the vehicle to the DC charge station through the breakout box
2. Start a normal charge session.
3. Allow the charging current to stabilize.
4. Disconnect the HV- and HV+ DC buses by **opening** switch **S1_HV-** & **S1_HV+** simultaneously using the breakout box.
5. Observe the system behavior
6. Record any faults from the DUT and the DC charge station.

***2.3.14.5.1* End of Test Procedure**

Remove the breakout box from the system.

2.3.14.6 Pass Fail Criteria

Pass Criteria: It is unknown how the DUT will react to a sudden loss of high voltage. A charge session should not continue and the DUT must maintain a safe state of the system.

Fail Criteria: The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.15 Failed Battery Cooling/Heating System Test

2.3.15.1 Purpose

The purpose of this test is to determine the reaction of degraded or failed thermal management system in the vehicle/charger system.

2.3.15.2 Rationale and Description

Current, high powered off-board DC fast charging can charge up to 200A continuous. This would typically require cooling in the energy storage system being charged. It is possible that the vehicle's RESS cooling system is in a degraded state due to loss of refrigerant, failed actuator (pump, fan, etc.), or other condition that causes the RESS to overheat during a fast charge. This test is designed to determine the reaction of the vehicle/charger system to this condition.

2.3.15.3 Sample Preparation

This test requires specific knowledge of the cooling and heating system design details for the RESS on each vehicle tested in order to be able to modify the vehicle system to subject the DUT to the conditions described below.

High Ambient Temperature Test Preparation:

For the high ambient temperature test, the vehicle or RESS must be placed in an environmental chamber capable of increasing the temperature of the sample to 40 DegC (+5/-0). Allow the sample to soak at this temperature for 24 hours prior to the test. Restrict the flow of coolant medium used on vehicles that use active cooling for the RESS (e.g., water cooling loop through battery). The method of restricting the cooling capability of the RESS cooling system may differ significantly from vehicle to vehicle.

Low Ambient Temperature Test Preparation:

For the low ambient temperature test, the vehicle or the RESS must be placed in an environmental chamber capable of decreasing the temperature of the sample to -20 DegC (+0/-5). Allow the sample to soak at this temperature for 24 hours prior to the test. Bypass the battery heater by modifying the coolant hoses coming from the battery heater creating a bypass. Make sure the heater element is still full of glycol even though it is bypassed to prevent damage to the unit. The method of restricting the heating capability of the RESS heating system may differ significantly from vehicle to vehicle.

2.3.15.4 Equipment Setup
There is not specific equipment setup required for this test procedure.

2.3.15.5 Test Method and Procedure

Restricted RESS cooling system before and during charging, at high ambient temperature:

1. Place the vehicle or RESS in the environmental chamber for 24 hours at 40 Deg C. Connect the vehicle to the DC fast charge station
2. Start a normal charge session.
3. Observe the system behavior during charge
4. Record any faults from the DUT and the DC charge station.

Restricted RESS heating system before and during charging, at low ambient temperature:

1. Place the vehicle or RESS in the environmental chamber for 24 hours at -20 Deg C.
2. Connect the vehicle to the DC charge station
3. Start a normal charge session.
4. Observe the system behavior during charge
5. Record any faults from the DUT and the DC charge station.

2.3.15.5.1 End of Test Procedure
Remove the restrictions and restore the RESS cooling and heating components back to normal.

2.3.15.6 Pass Fail Criteria
Pass Criteria: It is unknown how the DUT will react to this procedure. The DUT may record an over-temperature or under-temperature fault, limit the charge current, or stop the charge session prematurely. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT shall not allow the RESS to enter into thermal runaway conditions at high or low ambient temperatures. The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.16 Over-Charge Test

2.3.16.1 Purpose
This purpose of this test is to determine the reaction of the system to an overcharge condition.

2.3.16.2 Rationale and Description
It is possible that the DC charger applies more current than is requested by the DUT. This could lead to the RESS being overcharged (i.e., SOC > 100%). This can be due to a failure in communication between

the vehicle and the charger or a defective DC power supply in the charger. This test will try to overcharge the battery by applying excess current towards the end of a charge session.

This test should be conducted by connecting to an equivalent battery tester with emulation hardware/software to emulate the charge station operation. Alternately, if engineering access to the charge station software debugging interface is available, the test conditions can be achieved by modifying the signals using overrides that may be available in the charger software debugging interface.

2.3.16.3 Sample Preparation
There are no specific sample preparation requirements for this test.

2.3.16.4 Equipment Setup
Configure the battery tester with emulation hardware/software to allow the override of the current request signal coming from the vehicle.

2.3.16.5 Test Method and Procedure

Override of current request using DC charger control overrides:

1. Start a charge session.
2. Wait for the charge current to initialize and stabilize.
3. Continue to charge to approximately 90% SOC and the charge current requested by the vehicle is observed to reduce at least 10% from the maximum charge current observed during the start of the test.
4. Substitute a current request signal to the DC charger that is 10% higher than the current actually requested by the vehicle.
5. Continue applying 10% higher current that actually requested while monitoring the DUT's SOC. If the DUT does not end the charge session once the DUT's RESS reaches 100% SOC a user initiated shutdown may be necessary.
6. Observe the system behavior. Record any faults on the DUT and the DC fast charge station.

2.3.16.5.1 **End of Test Procedure**
The DUT could end the charge session once the 10% higher than requested current is supplied, it may also continue to charge until 100% SOC then end the session. If the DUT does not end the charge session at 100% SOC, store the vehicle in an open space area and monitor any heat generation (using thermal imaging camera) for a duration of at least 72 hours. Then reduce the battery charge to 50% SOC and continue monitoring the thermal signature for 48 hours. Perform a battery system check according to the manufacturer recommended practice to ensure that no long term failures are present.

2.3.16.6 Pass Fail Criteria
Pass Criteria: It is unknown how the DUT will react to this procedure. The DUT may end the session once a 10% higher current is applied or continue the charge session. The DUT must end the charge session once 100% SOC is reached. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT shall stop the charge session if 100% SOC is reached. The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.17 Over-Current Test

2.3.17.1 Purpose
The purpose of this test is to determine the reaction of the PEV charging system to an over-current condition where the DC charger is supplying more current than requested. Actual charging current that is

above a particular threshold relative to a vehicle's requested current should be idetifed as a fault and charging should behalted in a safe manner. Note: this test is not similar to an over-current condition that would be resolved by fuses or similar stratiegies as the threshold at which a supplied current is deemed "over" is much lower that something that would be considered a over-current in the battery capability sense. That said, the vehicle's reponse to this condition should be assessed since it is an established condition and response in many DC charging procedures and documents.

2.3.17.2 Rationale and Description

This test will explore the DUT's ability to detect an over-current condition. The DUT should monitor the actual charge current and compare it to the requested charge current. Each OEM will have a tolerance and if that tolerance is exceeded the DUT should end the charge session. This tolerance is not specified in the SAE J1772 standard so it will be unknown for each DUT tested. This procedure will determine this tolerance to over-current and asses the safety of the DUT's reaction.

This test should be conducted by connecting to an equivalent battery tester with emulation hardware/software to emulate the charge station operation. Alternately, if engineering access to the charge station software debugging interface is available, the test conditions can be achieved by modifying the signals using overrides that may be available in the charger software debugging interface.

2.3.17.3 Sample Preparation

There are no specific sample preparation requirements for this test.

2.3.17.4 Equipment Setup

Configure the battery tester with emulation hardware/software to apply an over-current condition once the charge current reaches 100 ADC. The 100 ADC set point is only suggested and may need to be altered dependent upon the capabilities of the battery tester hardware and DUT.

2.3.17.5 Test Method and Procedure

1. Configure the battery tester simulation hardware/software to apply a 10A over-current once a requested current of 100 A is received from the DUT.
2. Start a charge session.
3. Wait for the charge current to reach 100A and the over-current fault to occur.
4. Observe the system behavior. Record any faults on the DUT and the DC fast charge station.
5. If the charge session continues, perform a user initiated shutdown and reconfigure the setup to apply a 15A over-current fault. Keep performing this test, increasing the over-current fault each time until the DUT initiates an emergency shutdown once the fault occurs.

2.3.17.5.1 **End of Test Procedure**

Disconnect the DUT from the DC charging system.

2.3.17.6 Pass Fail Criteria

Pass Criteria: It is unknown how the DUT will react to this procedure. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT shall fail this test if no over-current fault initiates an emergency shutdown. The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.18 Reverse Power Flow Test

2.3.18.1 Purpose
The purpose of this test is to determine the reaction of the DUT to a situation in which the output voltage of the DC charger drops below the RESS voltage resulting in unintended reverse-power flow or discharging of the RESS.

2.3.18.2 Rationale and Description
Also known as Vehicle to Grid (V2G), the concept of discharging the battery and using off-board inversion to provide power to the grid is intriguing. However, unintended discharge of the RESS could possibly strand the driver or degrade the RESS. This test will assess the reaction of the PEV's CCS to an under-voltage situation during a charge session to determine if the PEV's RESS could be discharged.

This test should be conducted by connecting to an equivalent battery tester with emulation hardware/software to emulate the charge station operation. Alternately, if engineering access to the charge station software debugging interface is available, the test conditions can be achieved by modifying the signals using overrides that may be available in the charger software debugging interface.

2.3.18.3 Sample Preparation
There are no specific sample preparation requirements for this test.

2.3.18.4 Equipment Setup
Configure the battery tester with emulation hardware/software to sink the requested current from the DUT instead of sourcing the requested current.

2.3.18.5 Test Method and Procedure
1. Start a charge session with the configured emulation charge station.
2. Observe the system behavior. If the charge session continues, perform a user initiated shutdown. Record any faults on the DUT and the DC fast charge station.

2.3.18.5.1 **End of Test Procedure**
Disconnect the DUT from the DC charging system.

2.3.18.6 Pass Fail Criteria
Pass Criteria: It is unknown how the DUT will react to this procedure. The DUT most likely will quickly end the charge session. The DUT must maintain a safe state of the system during and after the test.

Fail Criteria: The DUT shall fail this test if reverse power flow is allowed to occur, but was never intended as a feature of the DUT. The DUT fails this test if at any point during or after this test a safe state of the system is not maintained.

2.3.19 Elevated PEV Inlet Temperature Test

2.3.19.1 Purpose
The purpose of this test is to determine the reaction of the PEV charging system to an increase in temperature at the PEV inlet. This test is only applicable if a vehicle has a PEV-side inlet temperature sensor (currently optional in a SAE-J1772 CCS PEV inlet), since it is seeking to investigate the vehicle's behavior to an over-temperature detection at the PEV inlet.

2.3.19.2 Rationale and Description
Similar to the rationale described in the Charge Connector HV Connection Disturbance Test outlined in the original research project documentation, contamination, degradation, or improper fit of the CCS connector or inlet could result in an increased resistance at this connection point. As outlined in Section

4.14.1, an SAE J1772 CCS compliant connector is required to have an internal temperature sensor, while it is optional in the PEV CCS inlet. This procedure will use heat tape wrapped around the charger inlet from inside the PEV's body to emulate an increase in inlet temperature to determine the response from the PEV. A potential safety hazard may occur if the coupler begins to heat up. The risk of fire and possibly burning the PEV driver are potential risks.

2.3.19.3 Sample Preparation
120 V_{AC} heater tape should be wrapped around the exterior of the charger handle and a thermocouple should be wrapped between the heater tape in order to measure temperature within the tape. Once this is completed, connect the vehicle to the DC charging system normally.

Figure 15: Example Heater Tape Installation

2.3.19.4 Equipment Setup
Configure charging system such that charging session can be manually activated following sufficient warm-up.

2.3.19.5 Test Method and Procedure

<u>Elevated PEV Inlet Temperature Test:</u>

1. Connect heat tape wrapped connector to vehicle charging inlet, but do not initiate charge session

2. Start a normal charge session.
3. Observe the system behavior
4. Record any faults from the DUT and the DC charge station.

2.3.19.5.1 **End of Test Procedure**
Remove the test equipment. Record and then clear any codes that may have set in the vehicle or the charger.

2.3.19.6 Pass Fail Criteria
Pass Criteria: If the DUT is known to have a PEV inlet temperature sensor, the system must maintain a safe state of the system during and after the test following the stopping of a charging session due to excessive inlet temperature.

2.4 AC Charging Test Procedures

These procedures have been created using the hazards and failure modes discussed in the introductory section, providing modifications and deletions related to the fundamental differences between AC and DC charging.

2.4.1 Chassis Ground Offset Test

2.4.1.1 Purpose

This test will verify that the PEV and EVSE react appropriately to an offset on the ground connection between the vehicle charge port and the charger. The test conditions shall be applied both before a charge session is initiated and during an active charge session.

2.4.1.2 Rationale and Description

The ground between the charge station and the vehicle can become degraded due to increased resistance, poor connections, or failure of a conductor. This condition can result in communication stress (signal offset) causing partial or complete loss of communication. The pilot and proximity signals can be impaired. This test will introduce a ground offset in the ground connection to determine the reaction of the system. In some cases it is possible that the PEV and EVSE interpret different pilot or proximity states.

2.4.1.3 Test Setup

- Setup the AC breakout box as shown in Figure 16.

- Power the AC EVSE, if not already powered.

- Ensure all faults are cleared on the PEV and EVSE.

- Connect AC EVSE to AC breakout box; maintain disconnection between the AC breakout box and the PEV.

- Close switches S2_GND, S3_GND and S_R.

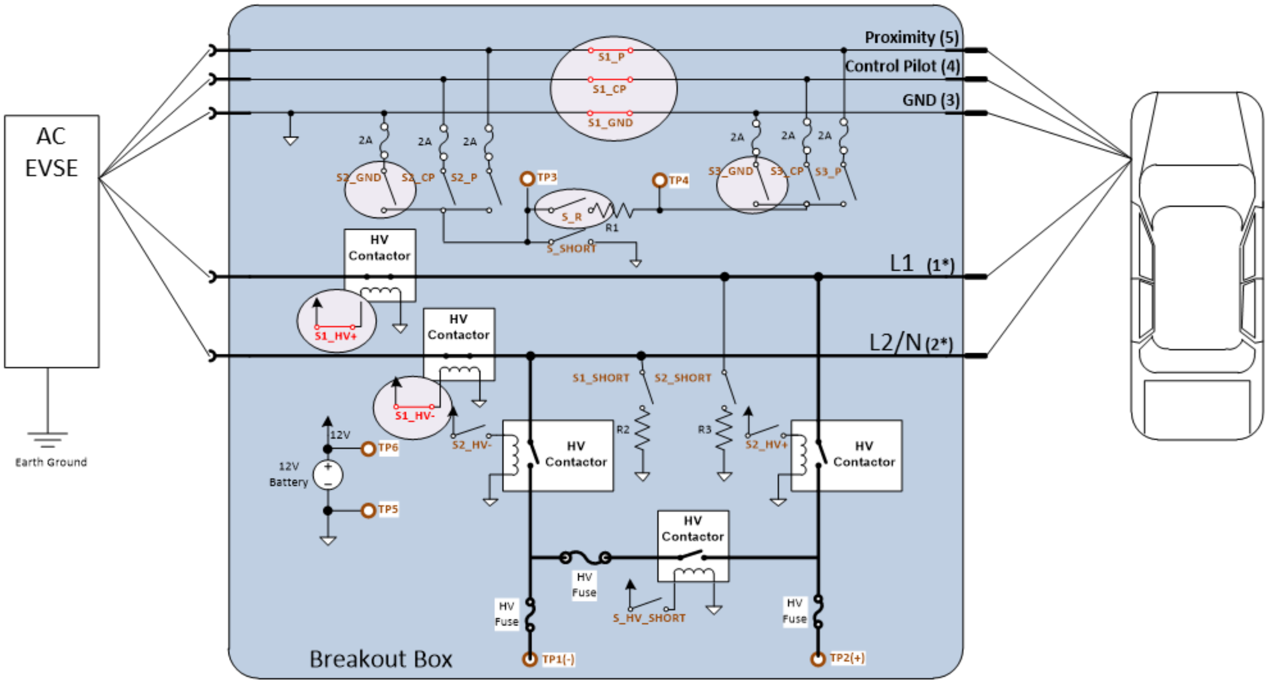

Figure 16: Chassis Ground Offset Test Setup

Table 9: Chassis Ground Offset Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																		
MANIPULATED DURING TEST																		
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.4.1.4 Test Procedure

<u>Chassis Ground Offset introduced before a charge session</u>

- Perform **Test Setup**.

- **Iterative Process:**

1. Introduce 1kΩ between TP3 and TP4 in the place of R1.
2. Open switch S1_GND, if not already opened.
3. Plug AC breakout box connector to PEV.
4. Observe the system behavior.
5. Measure and record voltage between TP3 and TP4.
6. Disconnect AC breakout box connector from PEV.
7. Record and clear any EVSE or PEV faults.
8. Power cycle and key cycle EVSE and PEV respectively, if necessary.
9. Repeat procedure **Iterative Process** 3 more times, introducing resistances of 100Ω, 47Ω, and 24Ω instead.

Chassis Ground Offset introduced during a charge session

- Perform **Test Setup**.

- **Iterative Process:**

1. Introduce 1kΩ between TP3 and TP4 in the place of R1.
2. Close switch S1_GND, if not already closed.
3. Plug AC breakout box connector to PEV.
4. Wait 30 seconds. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.
5. Open switch S1_GND.
6. Observe and record the system behavior.
7. Measure and record voltage between TP3 and TP4.
8. Disconnect AC breakout box connector from PEV.
9. Record and clear any EVSE or PEV faults.
10. Power cycle and key cycle EVSE and PEV respectively, if necessary.
11. Repeat procedure **Iterative Process** 3 more times, introducing resistances of 100Ω, 47Ω, and 24Ω instead.

2.4.1.5 Pass/Fail Criteria

For tests introducing faults prior to the charge session attempt, the following scenarios constitutes successful completion of a test:

- The EVSE and PEV system begins and ends a charge session as normal assuming the ground offset voltage is tolerable.
- The EVSE and PEV system does not begin a charge session and shall remain in a safe state. The EVSE and/or PEV may notify the user that a failure to charge had occurred.

For tests introducing faults during the charge session, the following scenarios constitute successful completion of a test:

- The EVSE and PEV shall continue to charge normally assuming the ground offset voltage is tolerable.
- The EVSE and PEV stops the charge session and enters a safe state.

2.4.2 12 Volt System Overvoltage Test

2.4.2.1 Purpose

This test will verify that the PEV and its charge system can function properly when the PEV's 12V system is at a voltage above its nominal range.

2.4.2.2 Rationale and Description

For a variety of reasons and fault conditions, it is possible the 12V system of a PEV be above nominal voltage levels. For example, this can occur when the 12V battery is being charged or jumped externally, or when the PEV on-board DC-DC converter is malfunctioning, but the root-cause of this disturbance is not the focus of this test. Rather, this test seeks to validate that the system can safely respond to an elevated 12V condition.

2.4.2.3 Test Setup

Note: The AC breakout box will not be used in the test. For a PEV where the 12 DC-DC converter is activated during PEV charging the DC-DC converters must be disconnected from the 12V bus.

- Disconnect the <u>all</u> 12V DC-DC converter outputs from the PEV 12V bus, if necessary.

  Note: an additional charger connected DC-DC converter or similar may also need to be disconnected depending on charging system architecture.

- Power the AC EVSE, if not already powered.

- Ensure all faults are cleared on the PEV and EVSE.

2.4.2.4 Test Procedure

<u>12V System Overvoltage</u>

1. Perform **Test Setup**.
2. Conduct an overvoltage test according to ISO 16750-2 for overvoltage conditions. (18volts for 60 minutes)
3. Plug the EVSE connector into the PEV inlet while applying the overvoltage condition.
4. Observe and record the system behavior. Wait 1 minute.
5. Record any faults on the EVSE or PEV.
6. Unplug the EVSE connector from the PEV inlet.
7. Set the DC Supply to 12V.
8. Plug the EVSE connector into the PEV inlet.
9. Verify that the EVSE and PEV start a charge session normally.

<u>12V System Jump Start Overvoltage</u>

1. Perform **Test Setup**.
2. Conduct an overvoltage test according to ISO 16750-2 for overvoltage conditions. (24volts for 60 seconds)
3. Plug the EVSE connector into the PEV inlet while applying the overvoltage condition.
4. Observe and record the system behavior. Wait 1 minute.
5. Record any faults on the EVSE or PEV.
6. Unplug the EVSE connector from the PEV inlet.

7. Set the DC Supply to 12V.
8. Plug the EVSE connector into the PEV inlet.
9. Verify that the EVSE and PEV start a charge session normally.

2.4.2.5 Pass/Fail Criteria

The PEV-charger system passes the test if it is brought to a safe state through either immediately halting charge or continuing the charge session to normal completion.

2.4.3 12 Volt System Undervoltage Test

2.4.3.1 Purpose

This test will verify that the PEV and its charge system can function properly when the PEV's 12V system is at a voltage below its nominal range.

2.4.3.2 Rationale and Description

It is possible the 12V system of a PEV be below nominal voltage levels. This can occur if there is a failure on the 12V output of the PEV DC-DC converter, if the 12V battery is failing, or if there is a large load accessory load on the 12V bus.

2.4.3.3 Test Setup

Note: The AC breakout box will not be used in the test. For a PEV where the 12 DC-DC converter is activated during PEV charging the DC-DC converters must be disconnected from the 12V bus.

1. Disconnect all 12V DC-DC converter outputs from the PEV 12V bus, if necessary. Note: a second DC-DC may be used from the charger to the 12V system, so care must be used to ensure that all DC-DC converters have been disconnected.
2. Power the AC EVSE, if not already powered.
3. Ensure all faults are cleared on the PEV and EVSE.

2.4.3.4 Test Procedure

12V System Undervoltage

1. Perform **Test Setup**.
2. Power the PEV 12V bus with an external supply to set to 13.2 V. Wait 1 minute.
3. Plug the EVSE connector into the PEV inlet.
4. Wait 30 seconds. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.

   Iterative Process:

   I. If external supply is set to 0V then end iterative process.
   II. Reduce the external supply voltage by 0.5 volts.
   III. Observe and record system behavior.
   IV. Wait 1 minute.
   V. Repeat iterative process.

5. Observe and record the system behavior. Wait 1 minute.
6. Unplug the EVSE connector from the PEV inlet.
7. Record any faults on the EVSE or PEV.
8. Set the DC Supply to 12V.
9. Key cycle the PEV if necessary.
10. Plug the EVSE connector into the PEV inlet.
11. Verify that the EVSE and PEV start a charge session normally.

2.4.3.5 Pass/Fail Criteria

The PEV-charger system passes the test if it is brought to a safe state through either immediately halting charge or continuing the charge session to normal completion.

2.4.4 12 Volt System Disturbance Test

2.4.4.1 Purpose

This test will verify that the PEV and its charge system can function properly when the PEV's realizes intermittent disturbance on its 12V system.

2.4.4.2 Rationale and Description

It is possible that a large, intermittent auxiliary 12V load can cause disturbances on a PEV's 12V system. This can occur if there is a load such as a fan, pump, aftermarket system, or jump start activity. It may be possible that this type of disturbance can cause PEV charging issues.

2.4.4.3 Test Setup

Note: The AC breakout box will not be used in the test. For a PEV where the 12 DC-DC converter is activated during PEV charging the DC-DC converters must be disconnected from the 12V bus.

1. Disconnect the 12V DC-DC converter output from the PEV 12V bus, if necessary.
2. Power the AC EVSE, if not already powered.
3. Ensure all faults are cleared on the PEV and EVSE.

2.4.4.4 Test Procedure

<u>12V System Undervoltage</u>

1. Perform **Test Setup**.
2. Connect a programmable load to the 12V system bus.
3. Set the load to 20A amps and toggle the load at a rate of 1Hz.
4. Plug the AC EVSE connector into the PEV inlet.
5. Observe and record the system behavior. Wait 1 minute.
6. Unplug the EVSE connector from the PEV inlet.
7. Record any faults on the EVSE or PEV.

8. Remove the programmable load from the 12V system bus.
9. Key cycle the PEV if necessary.
10. Plug the EVSE connector into the PEV inlet.
11. Verify that the EVSE and PEV start a charge session normally.

2.4.4.5 Pass/Fail Criteria

The PEV-charger system passes the test if it is brought to a safe state through either immediately halting charge or continuing the charge session to normal completion.

2.4.5 12 Volt System EMI/EMC Test

2.4.5.1 Purpose

The purpose of this test procedure is to determine if electromagnetic disturbances can affect the PEV charging system.

2.4.5.2 Rationale and Description

It is possible that large electromagnetic disturbances during a charge session can affect the low voltage power system and disturb communication between vehicle components. This test shall introduce this type of condition during a charge session and determine the reaction of the vehicle/charger system.

2.4.5.3 Test Setup

Note: The AC breakout box will not be used in the test.

1. Disconnect the 12V DC-DC converter output from the PEV 12V bus, if necessary.
2. Power the AC EVSE, if not already powered.
3. Ensure all faults are cleared on the PEV and EVSE.
4. Prepare the EMI/EMC equipment per SAE test procedures J1113-3, -4, -21, and -24.

2.4.5.4 Test Procedure

1. Perform **Test Setup**.
2. Conduct the EMI/EMC vehicle level SAE test procedures according to SAE J1113-3,-4,-21,-24 to the extent to which it is feasible.
3. Plug the EVSE connector into the PEV.
4. Wait 30 seconds. Observe and record the behavior of the system.
5. Discontinue the EMI/EMC test procedure.
6. Unplug the EVSE connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

2.4.5.5 Pass/Fail Criteria
The PEV-charger system passes the test if it is brought to a safe state through either immediately halting charge or continuing the charge session to normal completion.

2.4.6 PEV Movement Test

2.4.6.1 Purpose
The purpose of this test procedure is to determine if the drive-away interlocks of the vehicle are all functioning during a charge session and while the PEV is plugged into a connector.

2.4.6.2 Rationale and Description
It is possible that the operator of the vehicle will inadvertently try to drive off while the EVSE connector is connected to a PEV. It is also possible that the vehicle could roll away during a DC fast charge due to faulty park mechanism or park brake mechanism.

2.4.6.3 Test Setup
Note: The AC breakout box will not be used in the test.

1. Power the AC EVSE, if not already powered.
2. Ensure all faults are cleared on the PEV and EVSE.

2.4.6.4 Test Procedure

<u>Attempt to drive away attempt during a charge session</u>

1. Perform **Test Setup**.
2. Plug the EVSE connector into the PEV.
3. Wait 30 seconds. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.
4. Release the parking brake.
5. Observe and record system behavior.
6. Attempt to turn on the PEV.
7. Observe and record system behavior.
8. Attempt to move the gear shift lever to the Drive position.
9. Observe and record system behavior.
10. Attempt to move the gear shift lever to the Neutral position.
11. Observe and record system behavior.
12. Attempt to move the gear shift lever to the Reverse position.
13. Observe and record system behavior.
14. Unplug the EVSE connector from the PEV.
15. Record any faults on the EVSE or PEV.

16. Key cycle the PEV if necessary.
17. Plug the EVSE connector into the PEV inlet.
18. Verify that the EVSE and PEV start a charge session normally.

Drive away attempt while EVSE connected but not charging

1. Perform **Test Setup**.
2. Power off the EVSE.
3. Plug the EVSE connector into the PEV.
4. Wait 30 seconds.
5. Release the parking brake.
6. Observe and record system behavior.
7. Attempt to turn on the PEV.
8. Observe and record system behavior.
9. Attempt to move the gear shift lever to the Drive position.
10. Observe and record system behavior.
11. Attempt to move the gear shift lever to the Neutral position.
12. Observe and record system behavior.
13. Attempt to move the gear shift lever to the Reverse position.
14. Observe and record system behavior.
15. Unplug the EVSE connector from the PEV.
16. Record any faults on the EVSE or PEV.
17. Key cycle the PEV if necessary.
18. Power on the EVSE.
19. Plug the EVSE connector into the PEV inlet.
20. Verify that the EVSE and PEV start a charge session normally.

2.4.6.5 Pass/Fail Criteria

The PEV charger system passes the test if drive-away is not allowed and the system remains in a safe state.

2.4.7 Charge Connector Control Signal Disturbance Test

2.4.7.1 Purpose

The purpose of this test procedure is to determine if a disturbance to a control signal of the charging system impairs the PEVs ability to charge.

2.4.7.2 Rationale and Description

It is possible that control pilot and/or proximity signals become disturbed prior to or during a charge session. This can happen when there is a faulty connection or installation, or when the charge cable becomes worn and degraded. It is expected that the PEV and charging system mitigate any unsafe conditions that may be caused by this type of malfunction.

2.4.7.3 Test Setup

1. Setup the AC breakout box as shown in Figure 17.
2. Power the AC EVSE, if not already powered.
3. Ensure all faults are cleared on the PEV and EVSE.
4. Connect AC EVSE to AC breakout box; maintain disconnection between the AC breakout box and the PEV.

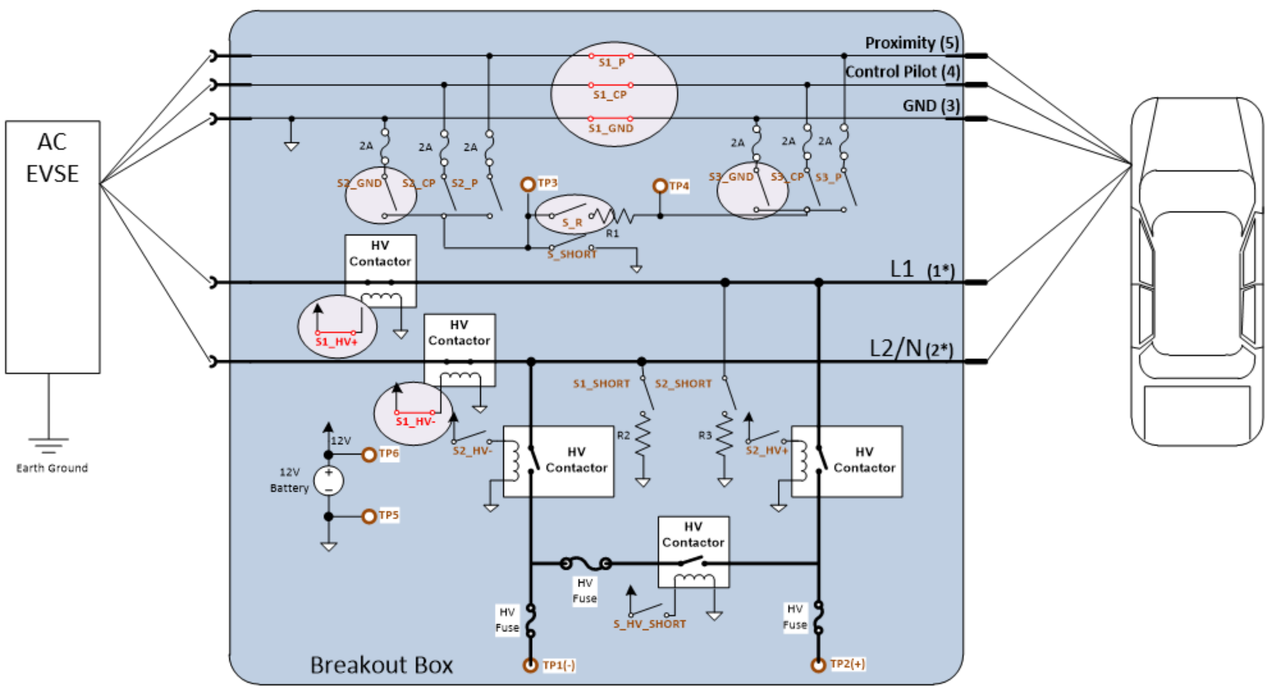

Figure 17: Charge Connector Control Signal Disturbance Test Setup

Table 10: Charge Connector Control Signal Disturbance Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.4.7.4 Test Procedure

Control Pilot interrupt during charging

1. Perform **Test Setup**.
2. Plug the AC breakout box connector into the PEV.
3. Wait 1 minute. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.
4. Break the control pilot connection between the PEV and EVSE by opening switch S1_CP in the AC breakout box.
5. Observe and record system behavior.
6. Unplug the AC breakout box connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

Control Pilot shorted to ground during charging

1. Perform **Test Setup**.
2. Plug the AC breakout box connector into the PEV.
3. Wait 1 minute. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.
4. Ground the control pilot connection between the PEV and EVSE by closing switches S2_CP and S_SHORT in the AC breakout box.
5. Observe and record system behavior.
6. Unplug the AC breakout box connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

Proximity interrupt during charging

1. Perform **Test Setup**.
2. Plug the AC breakout box connector into the PEV.
3. Wait 1 minute. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.

4. Break the control proximity connection between the PEV and EVSE by opening switch S1_P in the AC breakout box.
5. Observe and record system behavior.
6. Unplug the AC breakout box connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

Proximity shorted to ground during charging

1. Perform **Test Setup**.
2. Plug the AC breakout box connector into the PEV.
3. Wait 1 minute. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.
4. Ground the proximity connection between the PEV and EVSE by closing switches S2_P and S_SHORT in the AC breakout box.
5. Observe and record system behavior.
6. Unplug the AC breakout box connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

2.4.7.5 Pass/Fail Criteria

The PEV should end charging and enter a safe state once the control pilot or proximity circuit fault is initiated.

2.4.8 Charge Connector Field Ground Disturbance Test

2.4.8.1 Purpose

The purpose of this test procedure is to determine if a disturbance to the field ground connection of the charging system impair the PEVs ability to charge safely.

2.4.8.2 Rationale and Description

It is possible that the ground connection between the EVSE and PEV become disturbed prior to or during a charge session. This can happen when there is a faulty connection or installation, or when the charge cable becomes worn and degraded. Although most common EVSEs will identify a loss of grounding and end charging, the vehicle should also be able to identify this unsafe condition (loss of shared ground) in order to protect the operator from any possible AC high-voltage exposure from a possible unidentified fault.

2.4.8.3 Test Setup

1. Setup the AC breakout box as shown in Figure 18.

2. Power the AC EVSE, if not already powered.

3. Ensure all faults are cleared on the PEV and EVSE.

4. Connect AC EVSE to AC breakout box; maintain disconnection between the AC breakout box and the PEV.

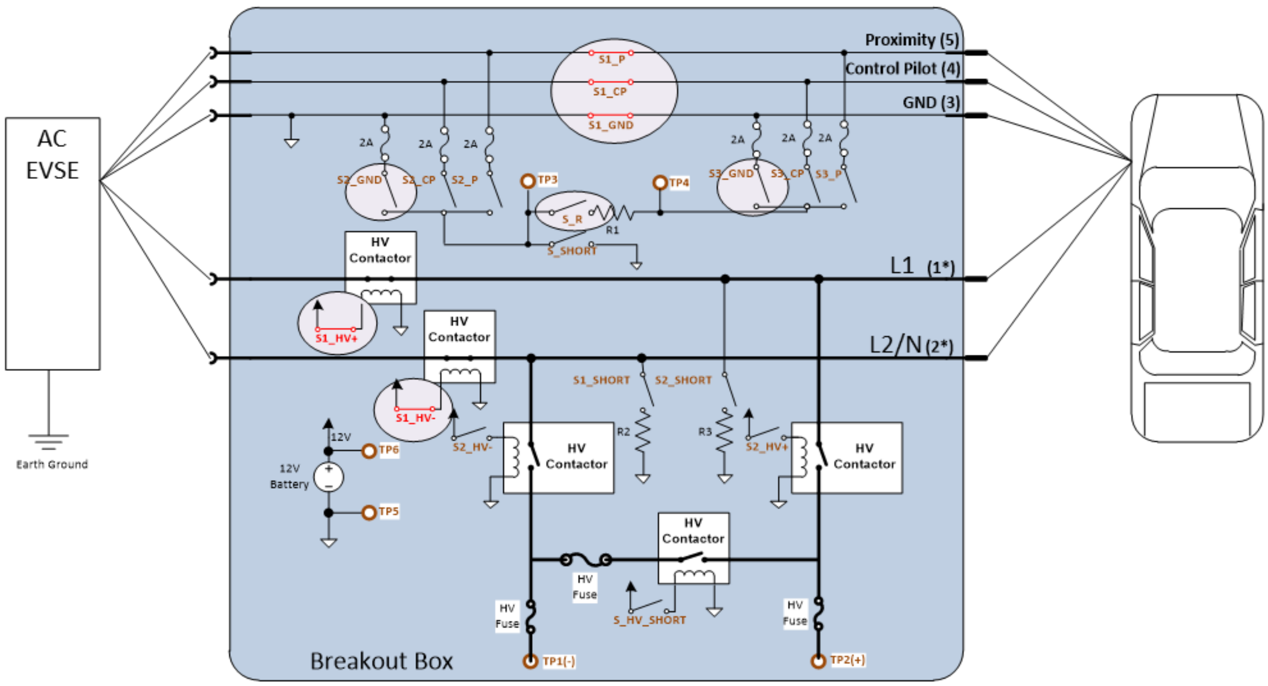

Figure 18: Charge Connector Field Ground Disturbance Test Setup

Table 11: Charge Connector Field Ground Disturbance Test - Initial Switch Configuration

CLOSED FOR INITIAL CONFIGURATION AT EQUIPMENT SETUP																	
MANIPULATED DURING TEST																	
S1_P	S1_CP	S1_GND	S2_P	S2_CP	S2_GND	S3_P	S3_CP	S3_GND	S_R	S_SHORT	S1_SHORT	S2_SHORT	S1_HV+	S1_HV-	S2_HV+	S2_HV-	S_HV_SHORT
CLOSED	CLOSED	CLOSED											CLOSED	CLOSED			

2.4.8.4 Test Procedure

<u>Field Ground interrupt during charging</u>

1. Perform **Test Setup**.

2. Plug the AC breakout box connector into the PEV.

3. Wait 1 minute. Verify the system is charging. If no charging occurs, record behavior and verify correct setup. Consult EVSE or PEV manufacture if necessary.

4. Break the field ground connection between the PEV and EVSE by opening switch S1_GND in the AC breakout box.

5. Observe and record system behavior.

6. Unplug the AC breakout box connector from the PEV.
7. Record any faults on the EVSE or PEV.
8. Key cycle the PEV if necessary.
9. Plug the EVSE connector into the PEV inlet.
10. Verify that the EVSE and PEV start a charge session normally.

2.4.8.5 Pass/Fail Criteria

If the EVSE has not already done so, PEV should request charging be halted due to the loss of shared ground.

3 DC and AC Charging Test Procedure Validation Information

This test report presents the results of testing and procedure validation for a range of select vehicles following the updated safety performance evaluation procedures developed and discussed within this research report. Although procedure feedback and revisions are provided, the following tests were not within the testing scope for either AC or DC testing and are therefore omitted from validation testing.

- Vehicle Crash or Bump Test
- 12V System EMI/EMC Test
- BMS Internal Fault Detection

It should be noted that state-of-charge information graphed in certain figures contained in this test report are the battery's BMS reported SOC and not necessarily useable SOC (0-100%) as seen by the driver on the display. This actual SOC typically varies from ~10 – 95%.

3.1 Device Under Test Information

The table below summarizes the vehicles used as test assets for the DC and AC test procedure validation. The DUT for the DC procedure evaluation and validation was Argonne's 2014 BMW i3 Rex with DC fast-charge capability via a SAE J1772 CCS charge port capable of roughly 50kW DC charge power capability. Several AC charge-capable vehicles, including the same BMW i3, were used for validating the AC test procedures and are also shown in the table below. While the Chevrolet Bolt, does have DC charge capability, it was only used to validate the AC procedures due to the previously successful validation efforts with the i3. Additional DC charging validation with a CHAdeMO equipped vehicle is currently under-way, but final validation results were not available at the time of report publication. The procedures have been written to accommodate either system if a correct breakout box is created.

Table 12: Device Under Test (Vehicle) Overview for Procedure Validation Testing

Vehicle	VIN	DC DUT	AC DUT
BMW i3 Rex – MY 2014	WBY1Z4C53EV273760	X	X
Toyota Prius Prime PHEV – MY 2017	JTDKARFP9H3002466		X
Chevrolet Bolt – MY 2017	1G1FX6S04H4178139		X
Honda Accord PHEV – MY 2016	JHMCR5F7XEC000547		X

3.2 Test Instrumentation/Equipment Information

The following instrumentation and equipment were used to conduct the validation testing.

- 24 kW IES (BOSCH) Combo Charge Station
  - 60 ADC max limit
- Clipper Creek AC High Power Electric Vehicle Charge Station
- ABC-170 Combo Charge System
  - 175 ADC max limit
  - Uses Argonne SpEC module for PLC communication and configuration
- Prototype breakout box (with both AC and DC connections)
- Fluke 87V Digital Multi-Meter
- IET Labs HPRS Series High Power Resistance Decade Box

Figure 19: Lab Setup for Testing

Figure 20: 24 kW IES (BOSCH) CCS Charge Station

Figure 21: Clipper Creek AC High Power Electric Vehicle Charge Station

Figure 22: ABC-170 Combo Charge System

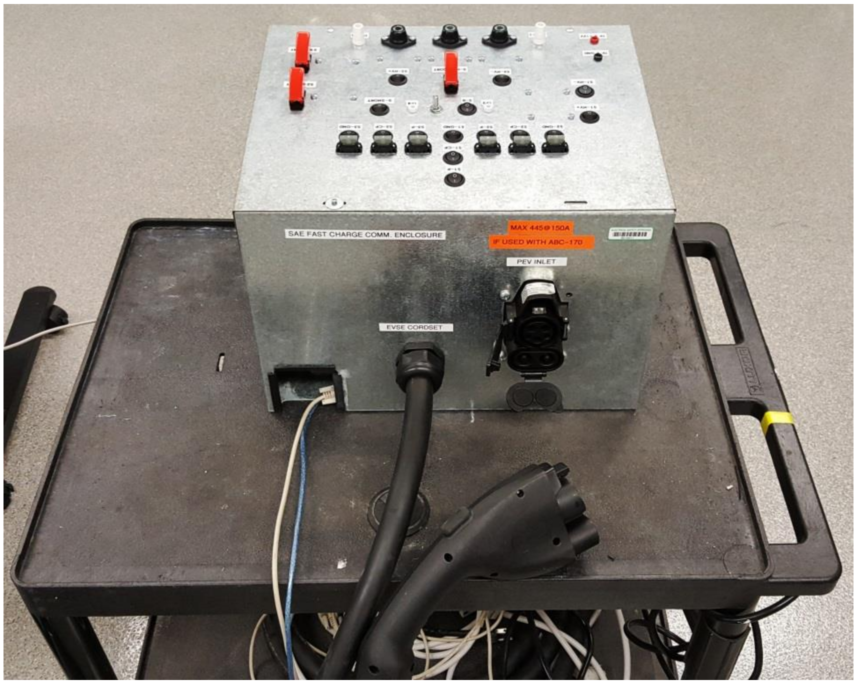

Figure 23: Prototype Breakout Box Constructed by ANL Engineers (DC Side Shown)

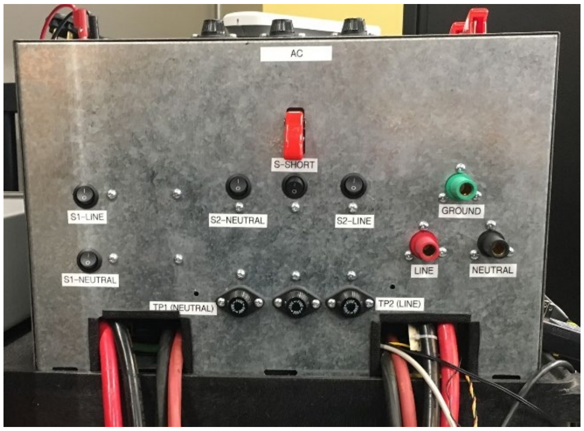

Figure 24: Prototype Breakout Box (AC Side Shown)

Figure 25: Fluke 87-V Digital Multi-Meter

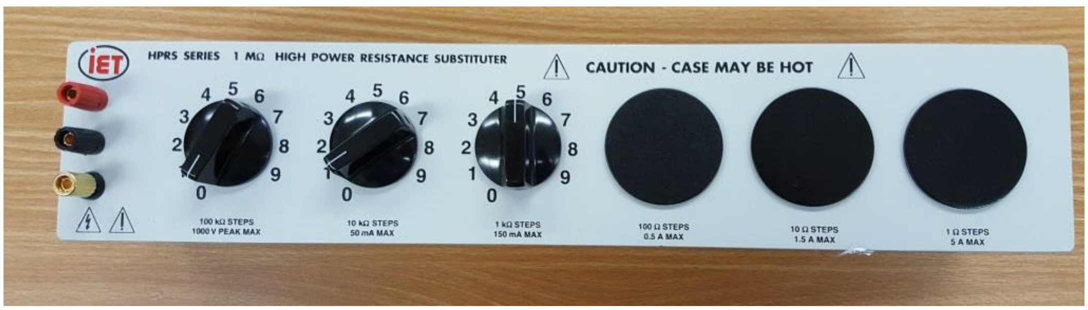

Figure 26: IET Labs HPRS Series High Power Resistance Decade Box

4 DC Charging Test Procedure Discussion, Feedback, and Validation Testing

The following sections provide background, feedback, and validation results for the functional safety evaluation procedures contained in the report.

4.1 Ground Fault Test

4.1.1 Procedure Feedback and Revisions

4.1.1.1 Procedure clarifications and removal of redundant ground removal tests

The original DC Fast-Charging research project describes procedures that introduce the ground faults before a charge session is initiated. One key implementation point is that the DC charger must be disconnected from the breakout box/PEV before the S1_short and S2_short switches are closed. Once closed the DC charger should then be plugged into the breakout box/PEV. It is assumed that the PEV will detect the ground fault, however this is dependent upon at what stage in the DC charge session the monitoring is performed. At the very least, a DC charge session should not be able to be performed.

The original documentation also describes procedures that introduce the ground faults during a charge session. It is uncertain whether the PEV will detect the ground fault first or if the charger would detect the ground fault first, but ultimately a safe state of the system should be the resulting condition.

Two "Fault – ground connection between station and vehicle removed" procedures have been removed from this section since it is redundant to the procedures of the "Charge Connector Field Ground Connection Disturbance" test discussed later in this document.

4.1.2 Validation Testing Results and Discussion

The Bosch DC charger was used in this test. Before testing a normal charge session was started with the PEV and using the breakout box the DC voltage with respect to DC+ and Ground (GND) was measured as ~171.7 VDC and the DC voltage with respect to DC- and GND was measured at ~-167.8 VDC. In order to incur an isolation of 100 Ω/volt a resistance of less than 16.78 kΩ was needed (100 Ω/volt *167.8 V = 16.78 kΩ). Therefore, a power resistor box set to 15 kΩ was used in the test to incur a 100 Ω/volt isolation fault.

4.1.2.1 DC+ to Gnd Before Charge Session

Following the test procedures a 15 kΩ resistance was placed between DC+ and GND before the charge station was connected to the PEV and a charge session was initiated. The charger was then connected to the PEV and a charge session was initiated. The charge session did not get past the Cable Check portion of the session (i.e., No charging occurred) and was shut down by the charger with an isolation fault. The charger's LCD displayed the text "EVSE Insulation Failure." The following DTC was set.

> *LIM 80551A DC charging: Fault at start of charging*

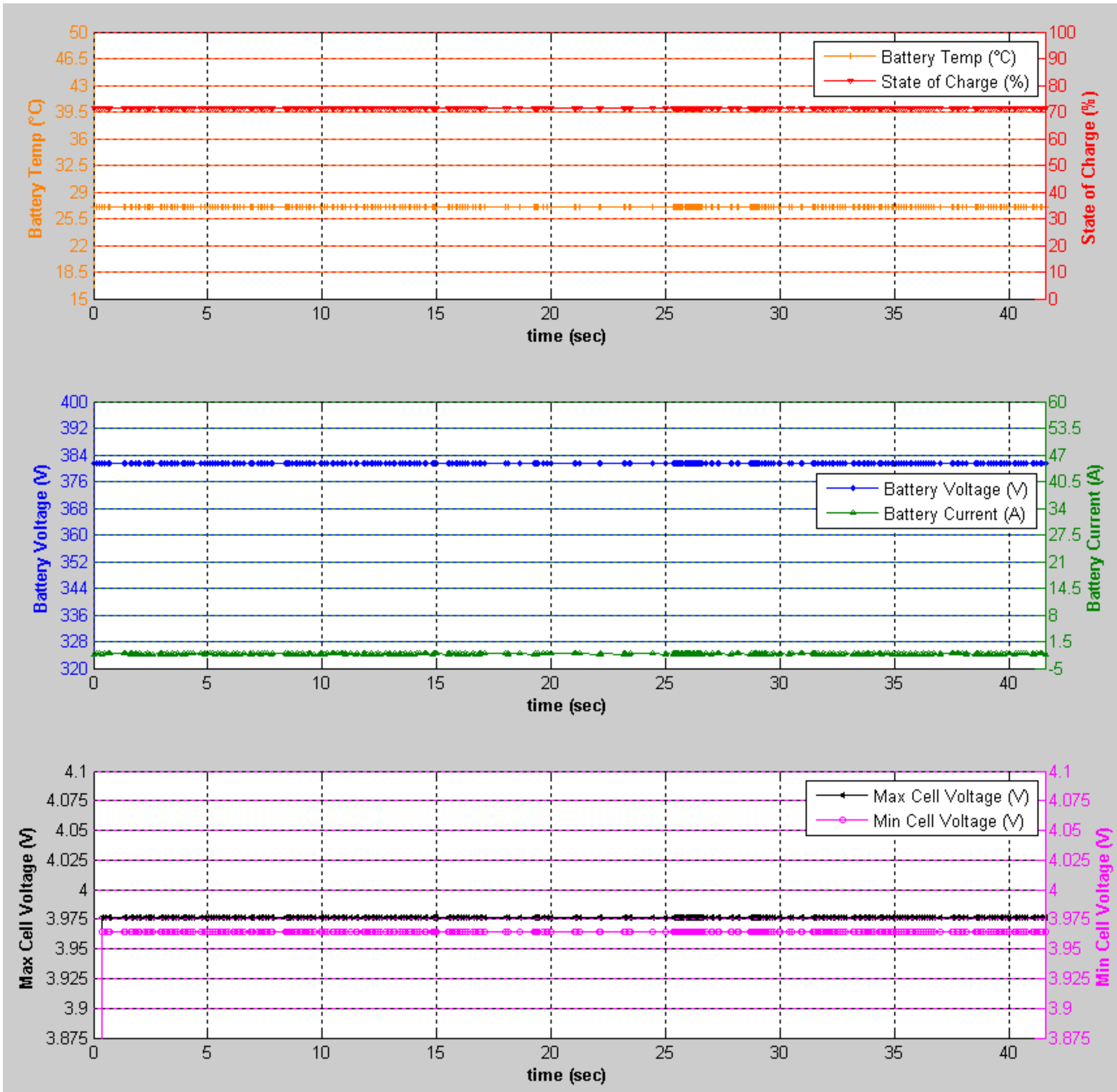

Figure 27: DC+ to Gnd Before Charge Session Charge Data

4.1.2.2 DC- to Gnd Before Charge Session

A 15 kΩ resistance was placed between DC- and GND before the charge station was connected to the PEV and a charge session was initiated. The charger was then connected to the PEV and a charge session was initiated. The charge session did not get past the cable check portion of the session (i.e., No charging occurred as evident in Figure 28) and was shut down by the charger with an isolation fault. The charger's LCD displayed the text "EVSE Insulation Failure." Vehicle was checked for DTCs from the PEV but no DTC's were set.

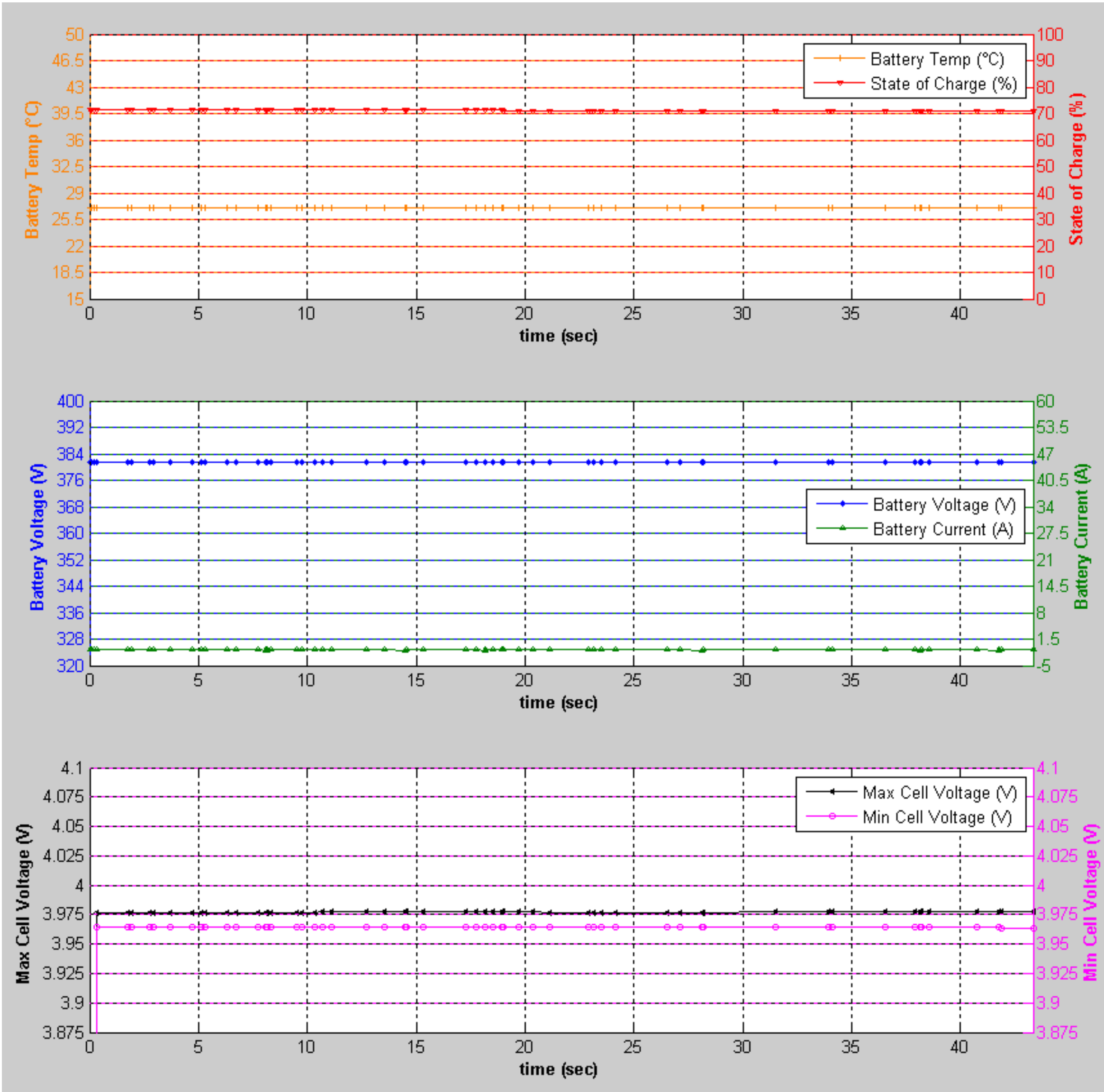

Figure 28: DC- to Gnd Before Charge Session Charge Data

4.1.2.3 DC+ to Gnd During Charge Session

A DC charge session was started and allowed to reach a steady state current of ~56 A before a 15 kΩ resistance was placed between DC+ and GND. When the isolation fault was triggered the charge session ended via an emergency shutdown via the charger as shown in Figure 29. The charger's LCD displayed the text "EVSE Insulation Failure." The PEV's display read "Charge Station Malfunction." Retrieved DTCs from the PEV include the following.

- *EME 222822 Charge management function: Check Control message (859)*
- *EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)*
- *LIM 805519 Load: PLC data line, communication fault*

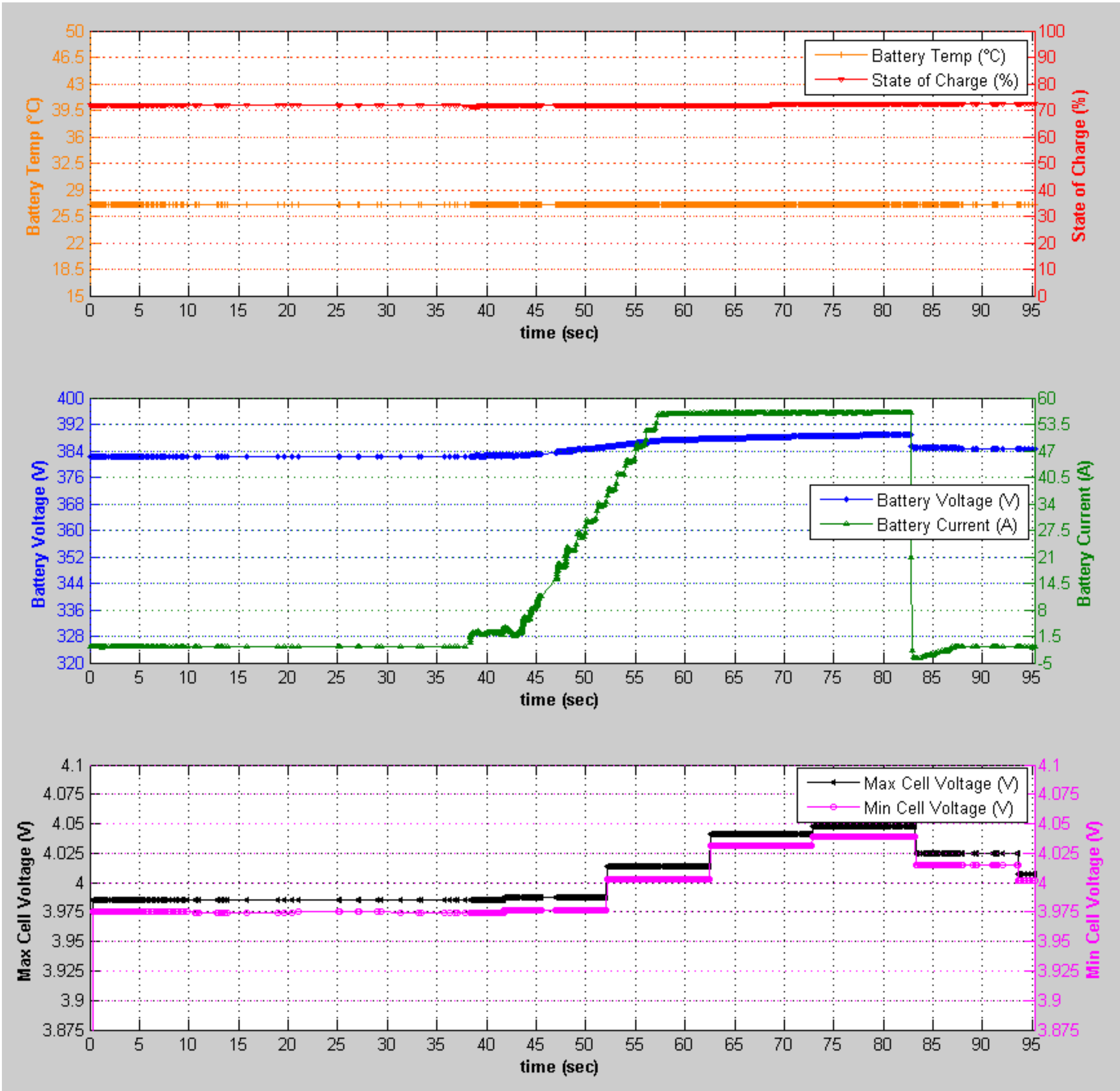

Figure 29: DC+ to Gnd During Charge Session Charge Data

4.1.2.4 DC- to Gnd During Charge Session

A DC charge session was started and allowed to reach a steady state battery current of ~56 A before a 15 kΩ resistance was placed between DC- and GND. When the isolation fault was triggered the charge session instantly ended via an emergency shutdown via the charger as shown in Figure 30. The charger's LCD displayed the text "EVSE Insulation Failure" and the PEV's display read "Charge Station Malfunction." The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

LIM 805519 Load: PLC data line, communication fault

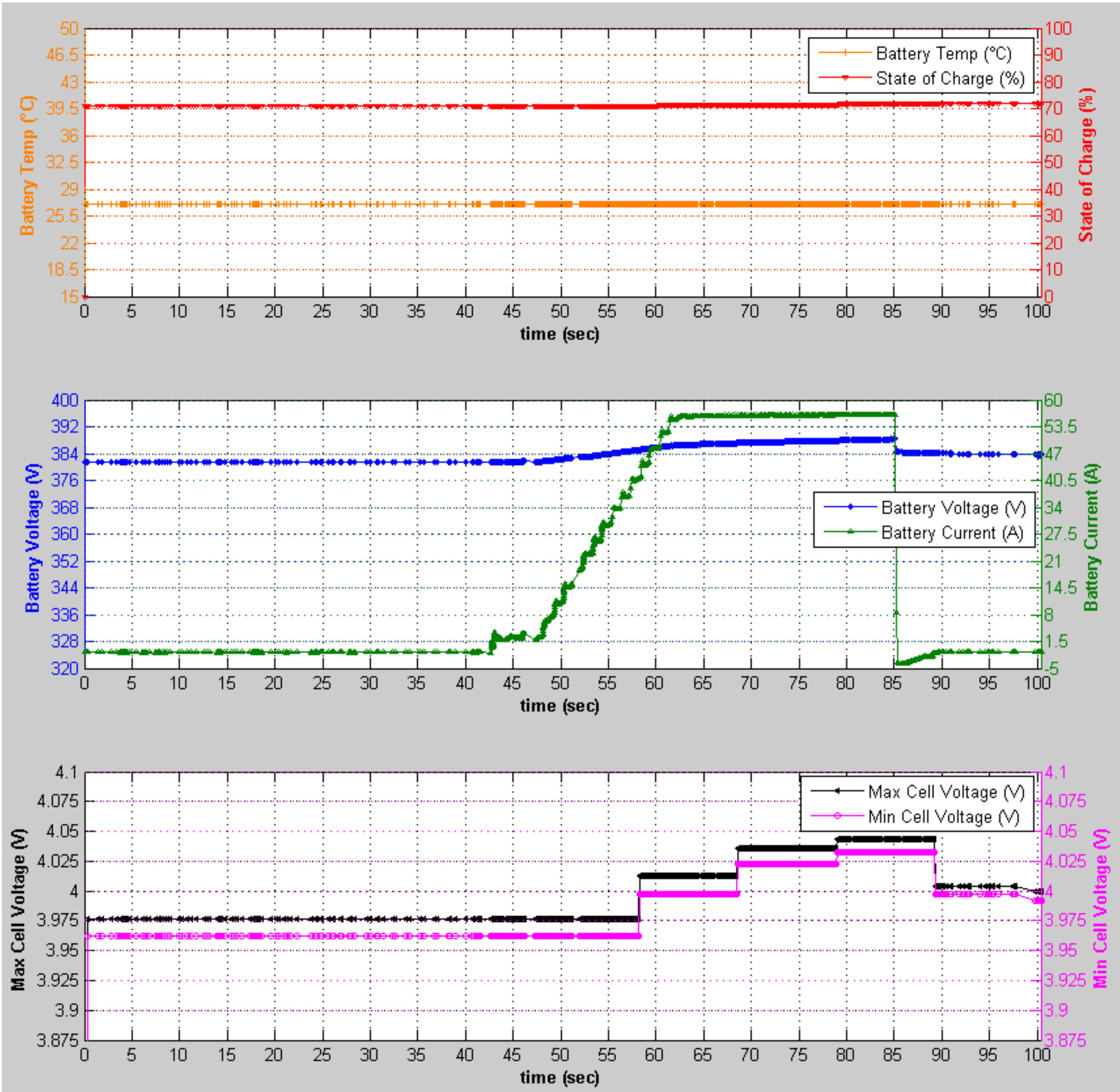

Figure 30: DC- to Gnd During Charge Session Charge Data

4.2 Chassis Ground Offset Test

4.2.1 Procedure Feedback and Revisions

4.2.1.1 Potentiometer versus fixed resistance values

The original research project documentation requires several resistances (1kΩ, 100Ω, 47Ω, 24Ω) to be switched in between the charger's earth ground and the PEV's chassis ground. By adding additional resistance between the connection of the two system grounds (Pin 3) the SAE J1772 control pilot and proximity circuits are affected and possibly to some extent the HPGP PLC digital communication signal used for communication between the vehicle and charger. The procedure calls for switching in these resistances before and during a DC charging session. It is unknown why the specific resistance values of 1kΩ, 100Ω, 47Ω, 24Ω were picked to simulate additional resistance between the charger's earth ground and PEV's chassis ground.

For a SAE J1772 charger, the DC charger shall produce a 5% pulse width modulated (pwm) duty cycle, when it is available and plugged into a PEV, in order to initiate a CCS DC charge session. The DC charger monitors the positive peak voltage of the pwm signal to determine the state of the charge session. SAE J1772 designates four DC voltage ranges, referred to as Pilot States, which include: State A, State B, State C, and State D. Figure 31 outlines the minimum, nominal, and maximum control pilot state voltages for the four control pilot states. Per SAE J1772, a DC charger must recognize the pilot state correctly when the state voltage falls within a valid range. However, there are dead bands between these valid pilot voltage ranges and it is left up to the DC charger manufacturer to decide how to handle an invalid pilot state voltage. By adding additional ground offset resistance the interpreted control pilot state voltage will diverge from the actual state voltage given zero ohm ground offset resistance.

To understand the effect of adding additional ground resistance on the control pilot and proximity circuits, circuit analysis was performed. The results of the circuit analysis for the control pilot are detailed in Figure 31 and Figure 32. SAE J1772 has designated voltage ranges for the given pilot states based on voltage and resistance tolerances. Given these state voltage maximum, nominal, and minimum values, a ground offset resistance sweep was performed to determine how the control pilot state voltage was affected. The DC charger is required to monitor and assess the control pilot state voltage. As can be seen from the control pilot graphs, by adding additional ground offset resistance, the perceived control pilot state voltage rises as ground offset resistance is increased.

The results of the proximity circuit analysis are detailed in Figure 33 and Figure 34. As is the case with the control pilot, SAE J1772 defines valid voltage ranges for the proximity circuit. As can be seen from the proximity graphs, by adding additional ground offset resistance the perceived proximity voltage raises as ground offset resistance is increased. It should be pointed out that the unplugged voltage range is not affected by additional ground offset resistance because the DC charger is physically unplugged from the PEV inlet.

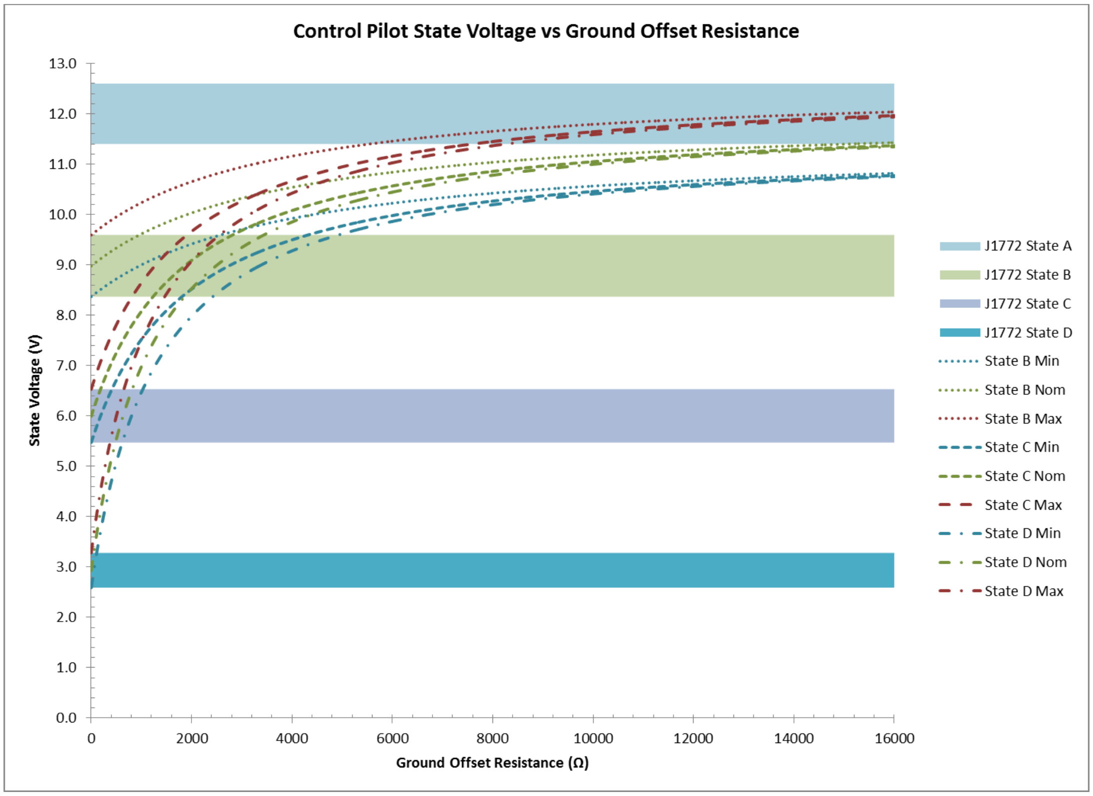

Figure 31: SAE J1772 Control Pilot State Voltage VersusGround Offset Resistance (0 - 16 kΩ)

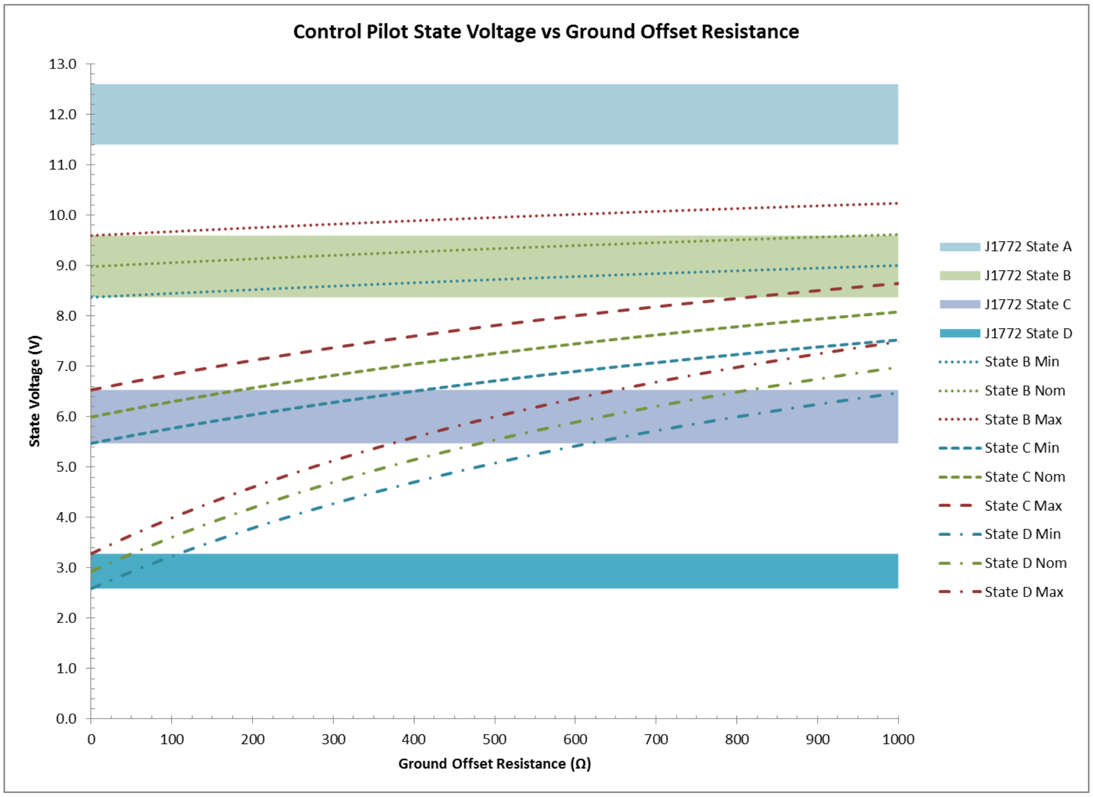

Figure 32: SAE J1772 Control Pilot State Voltage Versus Ground Offset Resistance (0 - 1 kΩ)

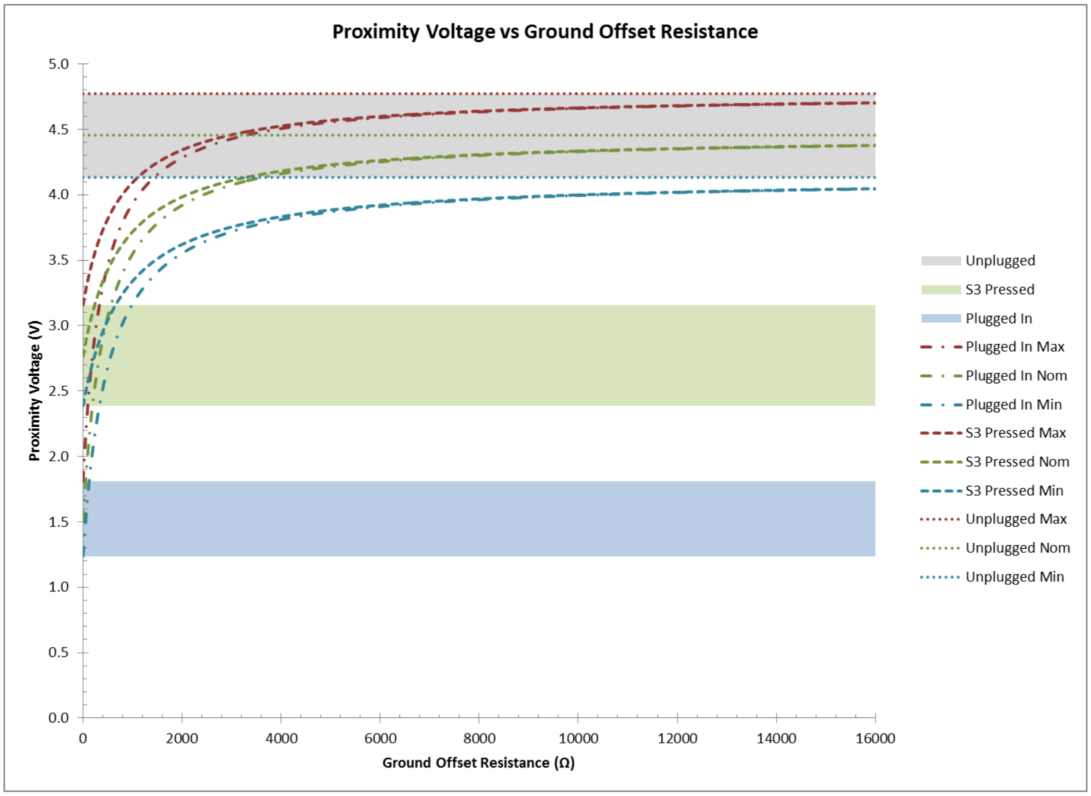

Figure 33: SAE J1772 Proximity Voltage VersusGround Offset Resistance (0 - 16 kΩ)

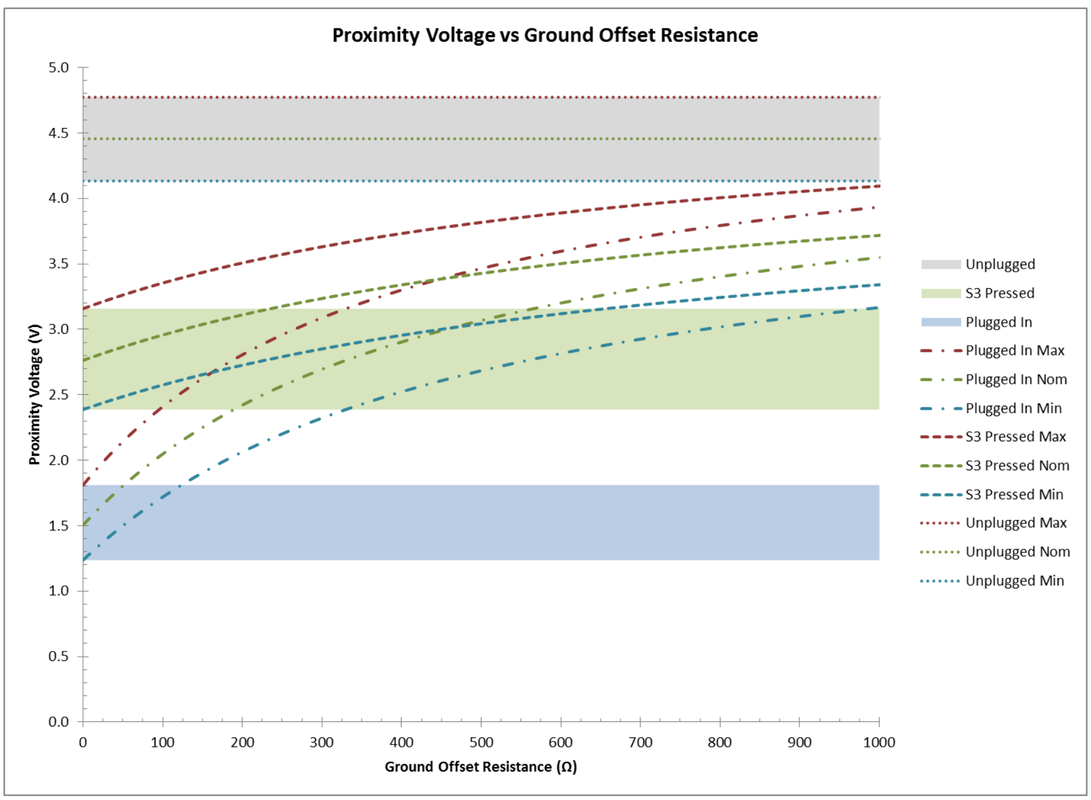

Figure 34: SAE J1772 Proximity Voltage VersusGround Offset Resistance (0 - 1 kΩ)

For the revised test procedures, a 20 kΩ potentiometer is to be used in place of the four fixed resistors in the test breakout box. This will allow the technician to test a wider range of offset resistances and to capture the results.

In order for the PLC digital communication to begin in a DC charging session both the PEV and DC charger must measure a valid plugged in proximity voltage and the DC charger must measure a valid State B voltage. If these requirements are not met, a compliant PEV and DC charger will not start a communication session and will not charge. During a charge session an SAE J1772 compliant DC charger should immediately stop the charge session when a control pilot state voltage other than “valid” is measured. Similarly, an SAE J1772 compliant PEV should request a termination of the charge session if a proximity voltage other than a valid plugged in value is measured.

Since these tests should be focused on safety and not on SAE J1772 compliance the pass/fail criteria should be changed to only fail a PEV if by adding additional ground offset resistance an unsafe condition occurs. It should also be pointed out that if an unsafe condition does occur the offending device (PEV or DC charger) should be determined.

4.2.2 Validation Testing Results and Discussion

The Bosch DC charger was used for all of the chassis ground offset tests. A 20 kΩ potentiometer was used in place of resistor R1 in the breakout box. The resistance of the potentiometer was set prior to plugging the charger into the breakout box and the breakout box’s CCS connector into the PEV. The resistance between earth GND and chassis GND was verified at 1.001 kΩ prior to plugging in. The charger displayed “Charger is ready, waiting for vehicle.” A voltage of 2.992 V at earth GND with respect to chassis GND was measured. A charge session did not begin and the charger displayed that the session had timed out. No faults were displayed at the EV interface. A voltage of 1.88 V at earth GND with respect to chassis GND was measured after the timeout. Although a charge session did not begin, Figure 35 shows data for this test.

The following DTC was set.

LIM 805616 AC Charging, unlocking charging plug (Type 1): Continuous operation

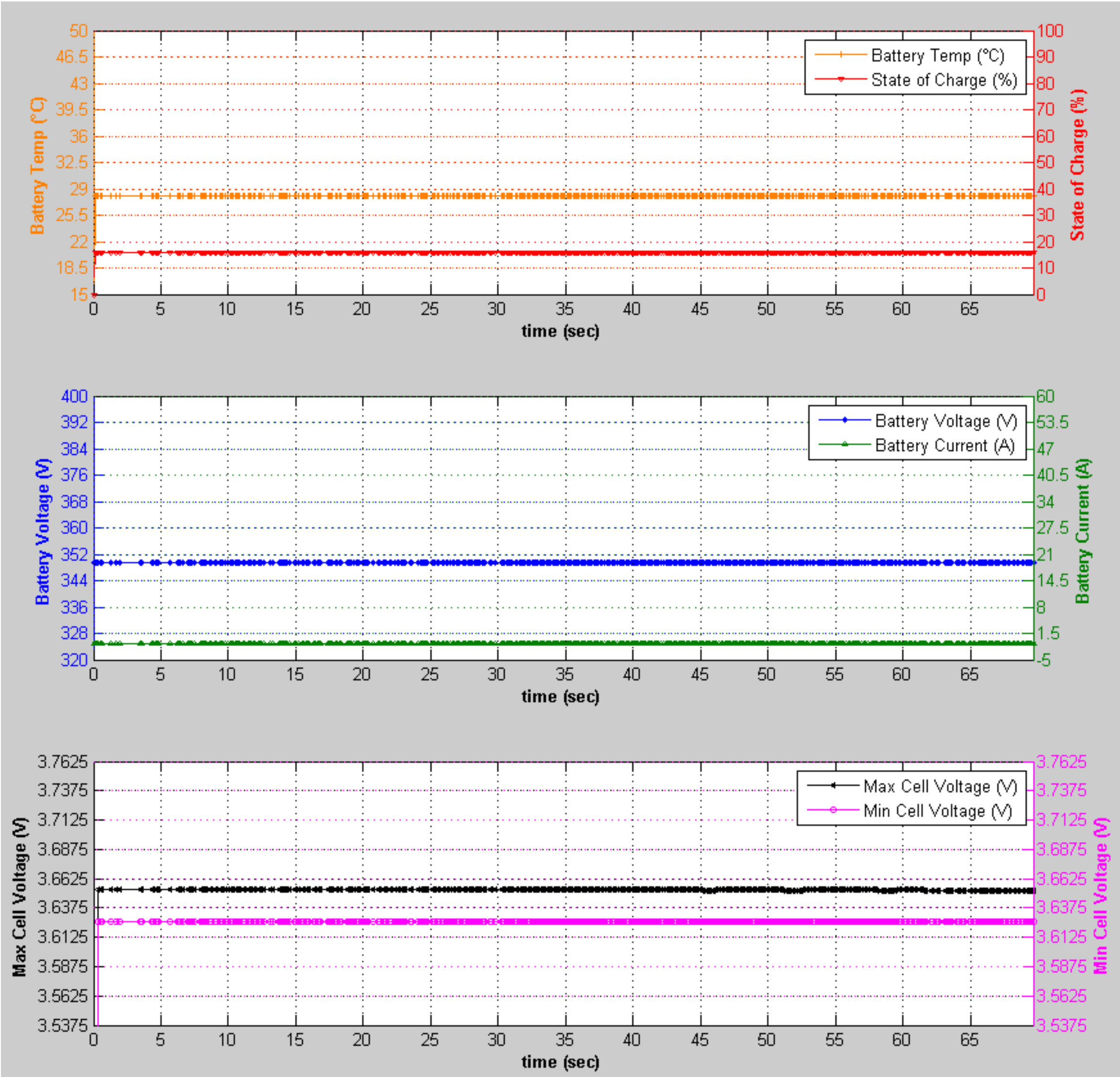

Figure 35: 1 kΩ Before Charge Session Charge Data

4.2.2.1 100 Ω Before Charge Session

The resistance between earth GND and chassis GND was verified at 101.9 Ω prior to plugging in. The charger displayed "Charger is ready, waiting for vehicle." A voltage of ~801 mV at earth GND with respect to chassis GND was measured. A charge session did not begin and the Charge displayed that the session had timed out. No faults displayed at the EV interface. A voltage of ~522 mV at earth GND with respect to chassis GND was measured after the timeout. Although a charge session did not begin, Figure 36 shows data for this test.

The following DTC was set.

LIM 805617 AC Charging, Charging plug detection implausible

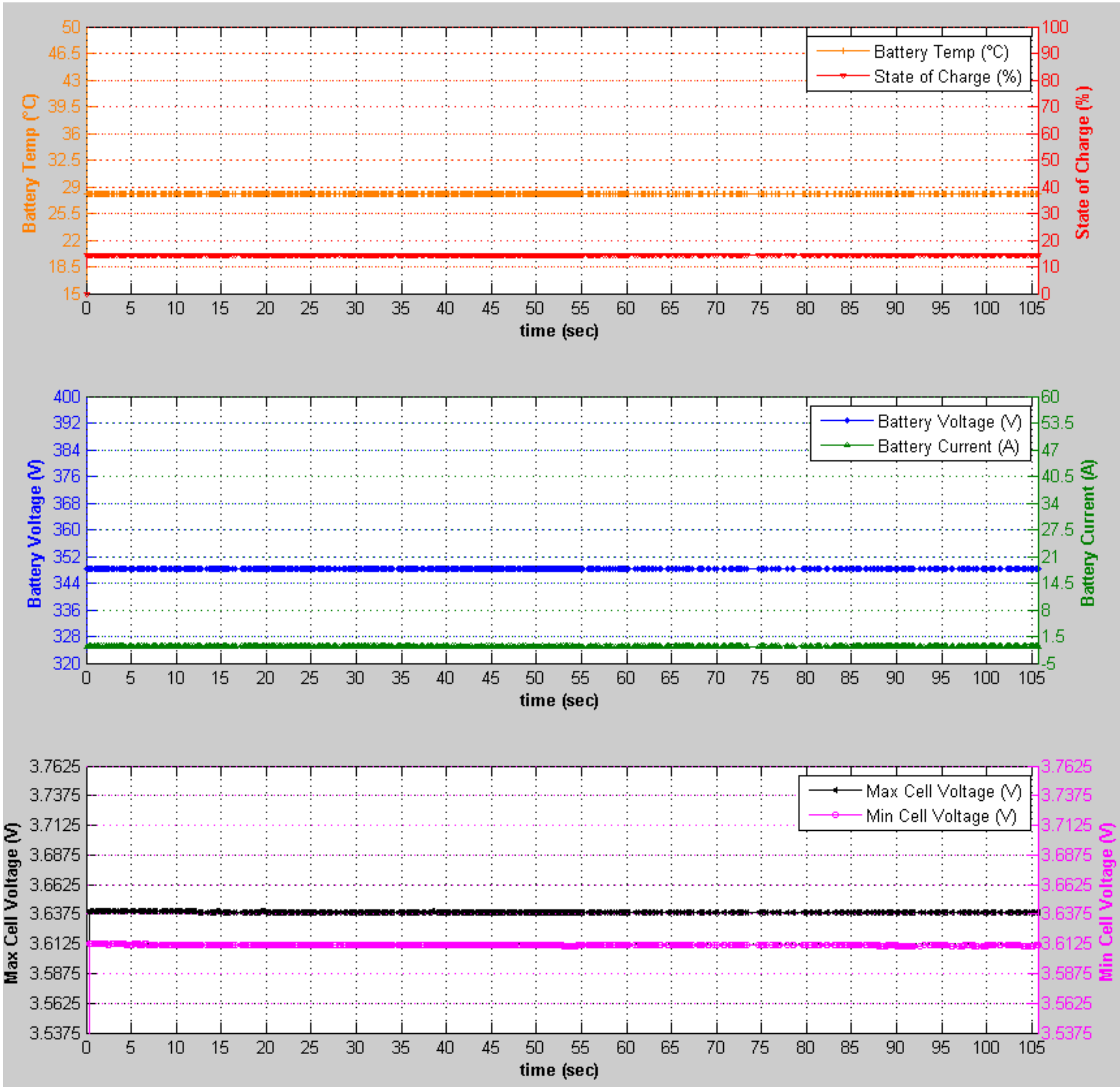

Figure 36: 100 Ω Before Charge Session Charge Data

4.2.2.2 47 Ω Before Charge Session

The resistance between earth GND and chassis GND was verified at 46.3 Ω prior to plugging in. The charger displayed "Charger is ready, waiting for vehicle." A voltage of ~400 mV at earth GND with respect to chassis GND was measured. It seemed as though charge session communication began with the charger indicating the EV was charging on its display. However, before the output of the charger was enabled the Charger displayed an internal fault on its display and stopped the session. A voltage of ~270 mV at earth GND with respect to chassis GND was measured after the timeout. Although a charge session did not begin, Figure 37 shows data for this test.

The following DTCs were set.

EME 222820 Charge management function: Check Control message 874, unable to rapid charge

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

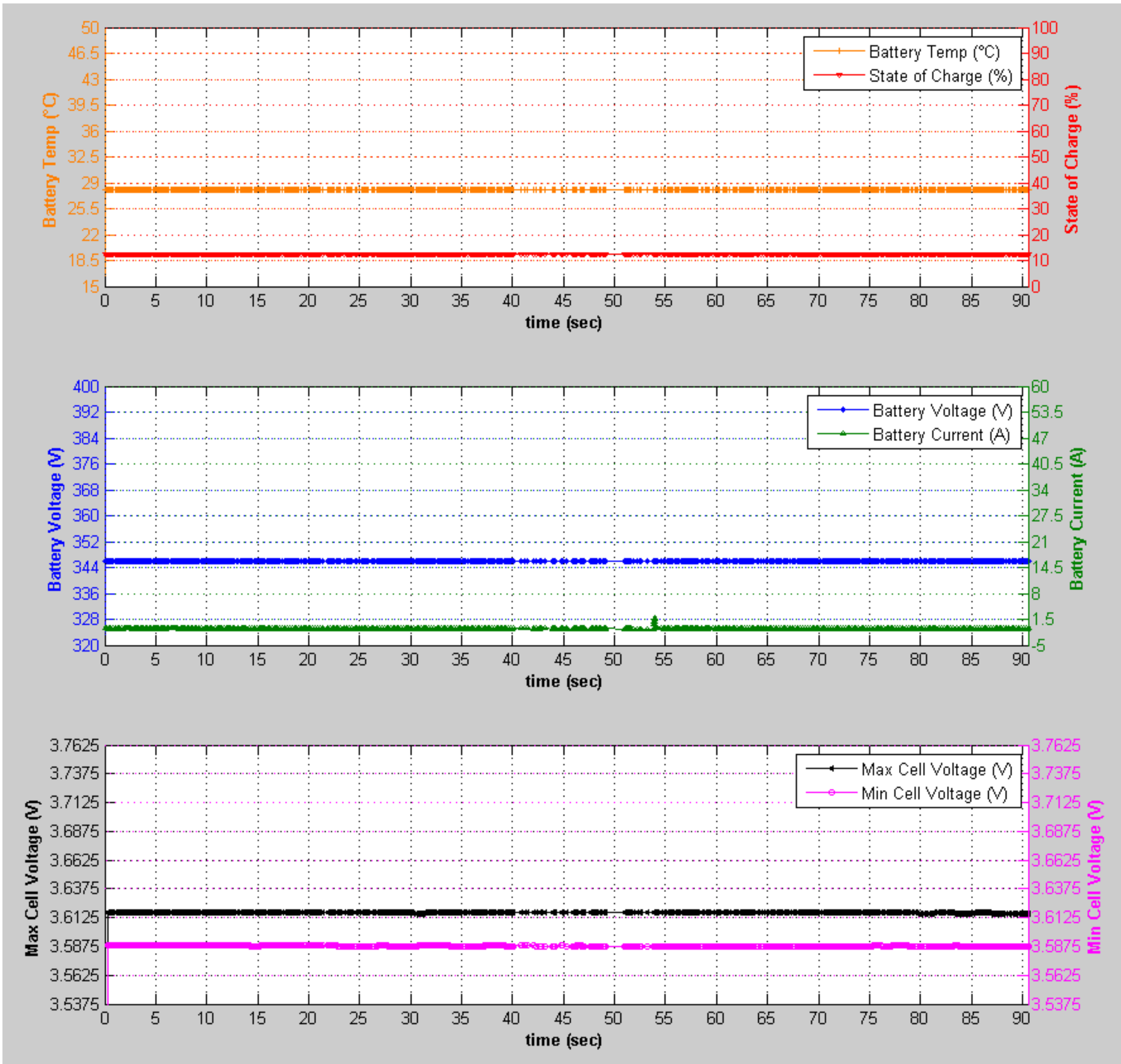

Figure 37: 47 Ω Before Charge Session Charge Data

4.2.2.3 24 Ω Before Charge Session

The resistance between earth GND and chassis GND was verified at 25.3 Ω prior to plugging in. The charger displayed "Charger is ready, waiting for vehicle." A voltage of ~226 mV at earth GND with respect to chassis GND was measured. Due to pretesting A charge session began and the PEV was allowed to charge for ~ 30 seconds before being shut down by the test operator. Figure 38 shows the charging data for this test.

No DTCs were set during this test.

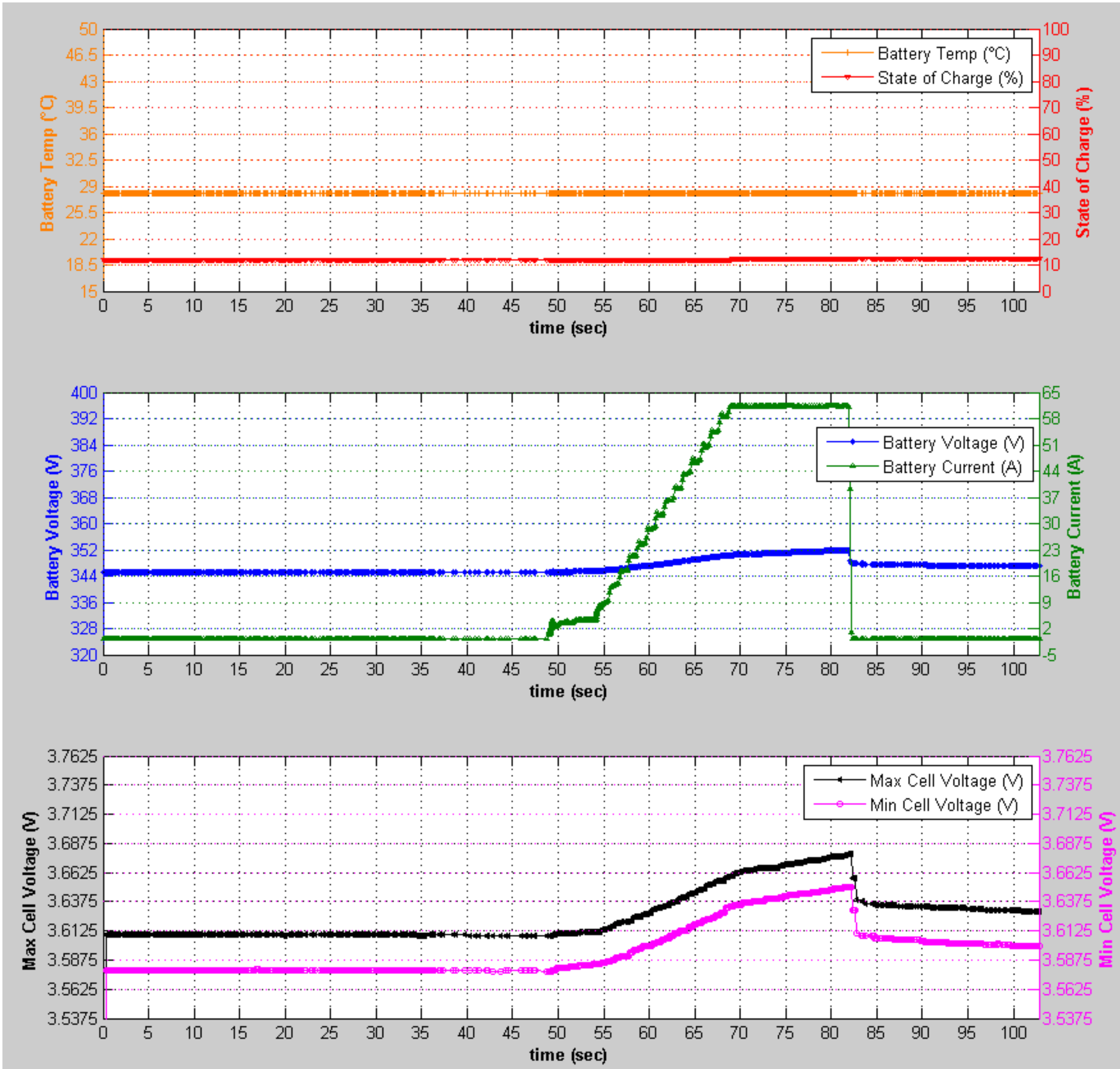

Figure 38: 24 Ω Before Charge Session Charge Data

4.2.2.4 1 kΩ During Charge Session

The resistance between earth GND and chassis GND was verified at 0 Ω prior to plugging in. A charge session began and switch S1_GND was opened leaving ~1 kΩ of resistance between Earth and Chassis ground. The charge session instantly stopped and the charger indicated an internal fault on its display. A voltage of ~2.997 V at earth GND with respect to chassis GND was measured. Figure 39 shows the charging data for this test.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

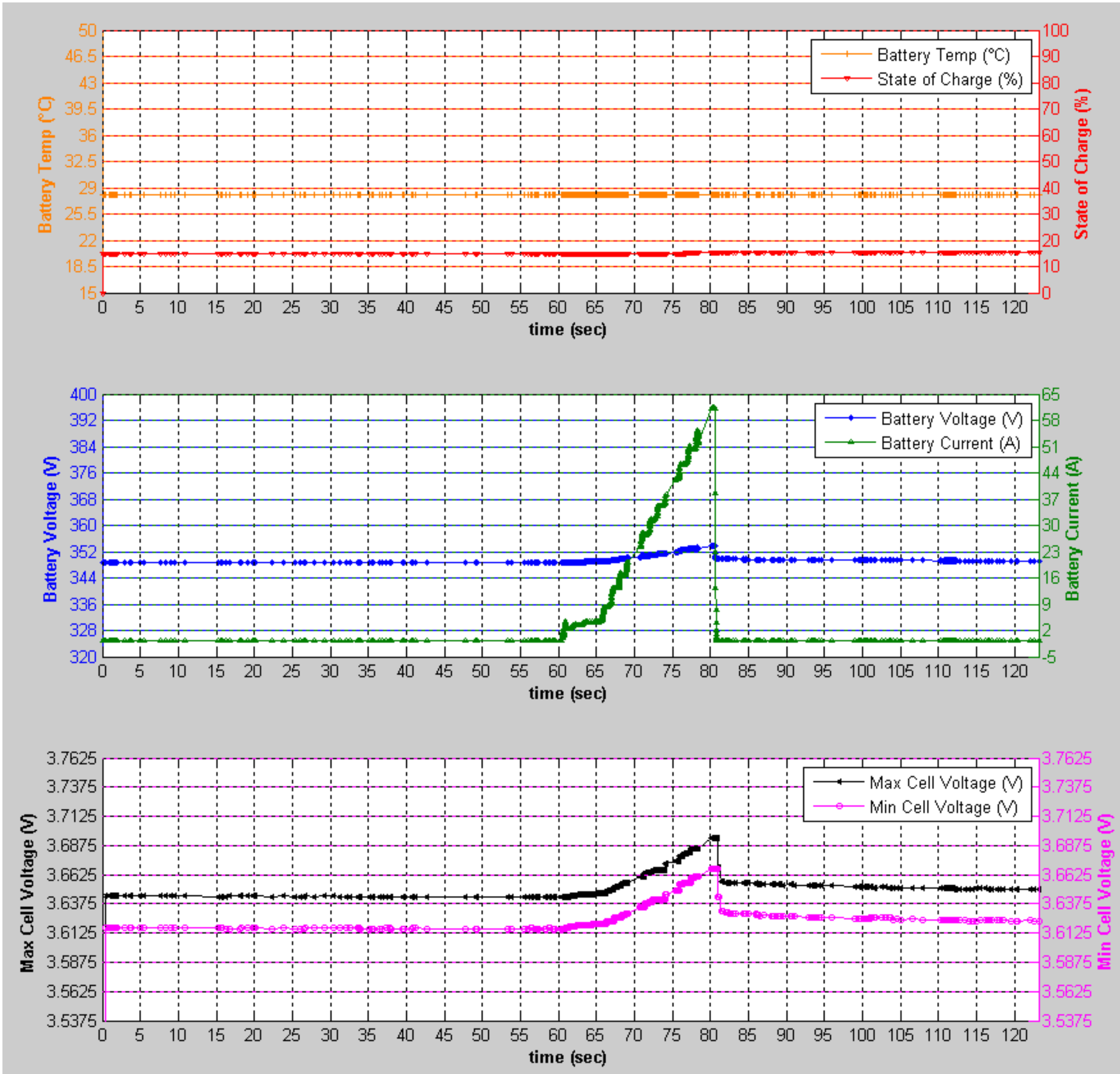

Figure 39: 1 kΩ During Charge Session Charge Data

4.2.2.5 100 Ω During Charge Session

The resistance between earth GND and chassis GND was verified at 0 Ω prior to plugging in. A charge session began and switch S1_GND was opened leaving ~100 Ω of resistance between Earth and Chassis ground. The charge session instantly stopped and the charger display indicated that the charging was complete, or charging was paused by the vehicle. A voltage of ~801 mV at earth GND with respect to chassis GND was measured. Figure 40 shows the charging data for this test.

The following DTC was set.

LIM 805529 DC charging: Unexpected high voltage detected at charging socket

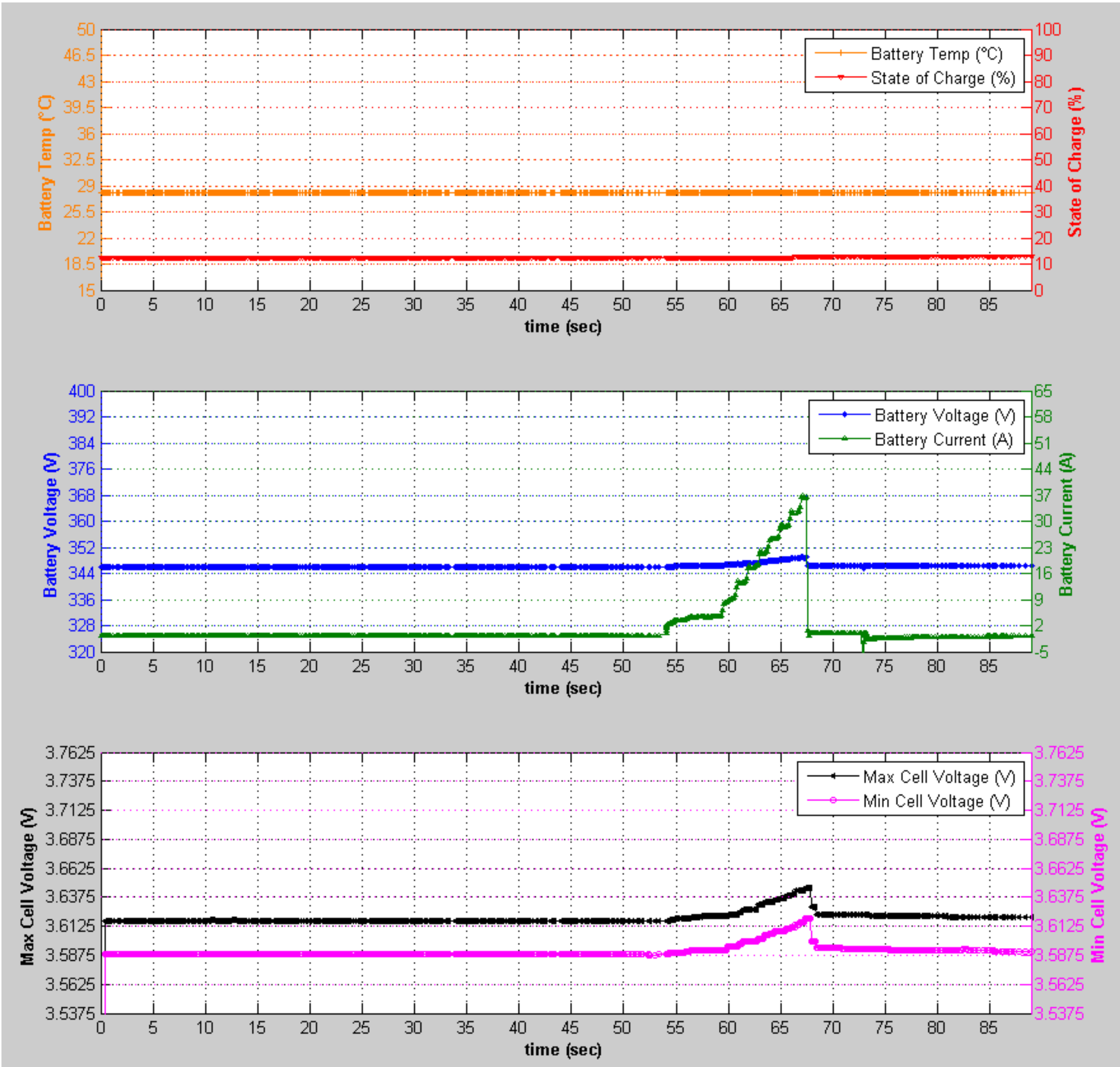

Figure 40: 100 Ω During Charge Session Charge Data

4.2.2.6 47 Ω During Charge Session

The resistance between earth GND and chassis GND was verified at 0 Ω prior to plugging in. A charge session began and switch S1_GND was opened leaving ~47 Ω of resistance between Earth and Chassis ground. The charge session instantly stopped and the charger display indicated that the charging was complete, or charging was paused by vehicle. A reliable voltage at earth GND with respect to chassis GND was not made due to the chargers reaction to shutoff its pilot signal. Figure 41 shows the charging data for this test.

The following DTCs were set.

EME 222820 Charge management function: Check Control message 874, unable to rapid charge

EME 222842 Charge management function: Fault during the charging procedure

EME 22287D DC charging: Switch contactors were unexpectedly opened or not activated

LIM 80551A DC charging: Fault at start of charging

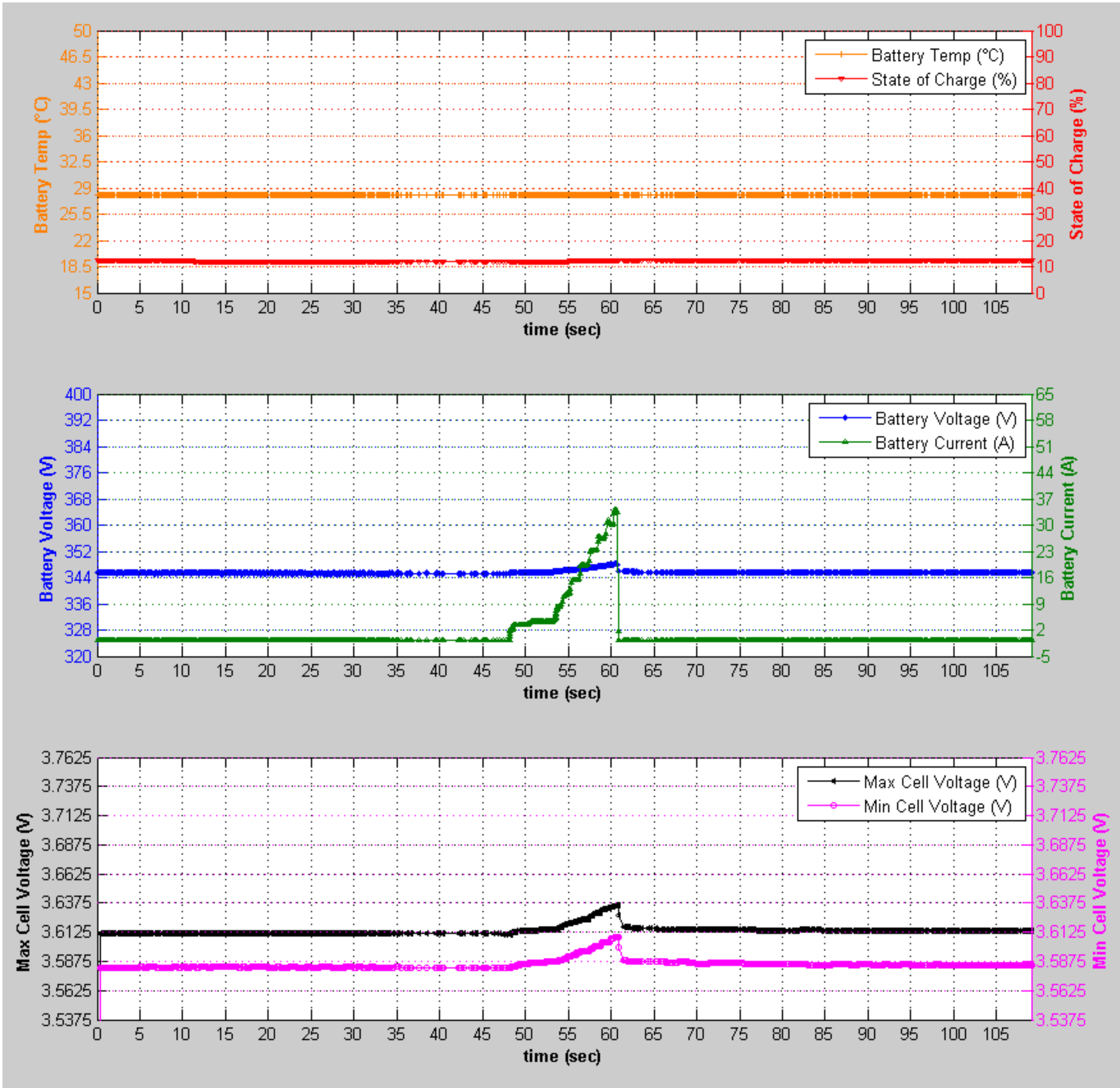

Figure 41: 47 Ω During Charge Session Charge Data

4.2.2.7 24 Ω During Charge Session

The resistance between earth GND and chassis GND was verified at 0 Ω prior to plugging in. A charge session began and switch S1_GND was opened leaving ~25.3 Ω of resistance between Earth and Chassis ground. Due to previous testing that showed the vehicle ended charging at a safe state under the same conditions, the charge session was finally ended by the test operator. A voltage of ~286 mV at earth GND with respect to chassis GND was measured. Figure 42 shows the charging data for this test.

No DTCs were set during this test.

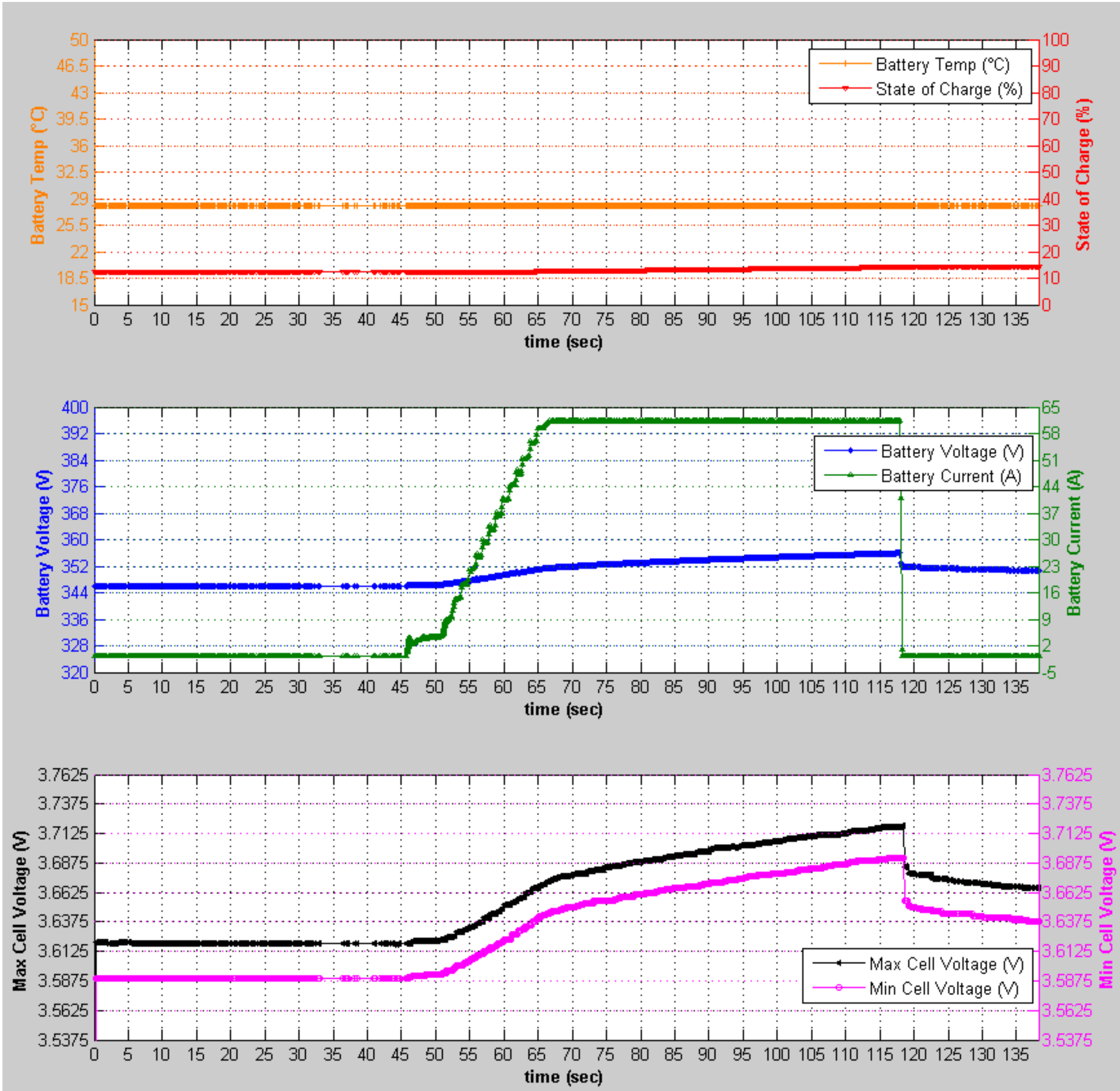

Figure 42: 24 Ω During Charge Session Charge Data

4.2.2.8 Gradual Decrease Before Charge Session

Although not in the test procedures this test was performed to determine the ground offset resistance at which the charge session would begin. The resistance between earth GND and chassis GND was set to at 120Ω prior to plugging in. The charger was plugged into the breakout box and the breakout box's connector was plugged into the PEV. The potentiometer was slowly reduced towards zero. Before reaching the necessary resistance to allow a charge session the charger timed out. Although a charge session did not begin, Figure 43 shows the charging data for this test.

No DTCs were set during this test.

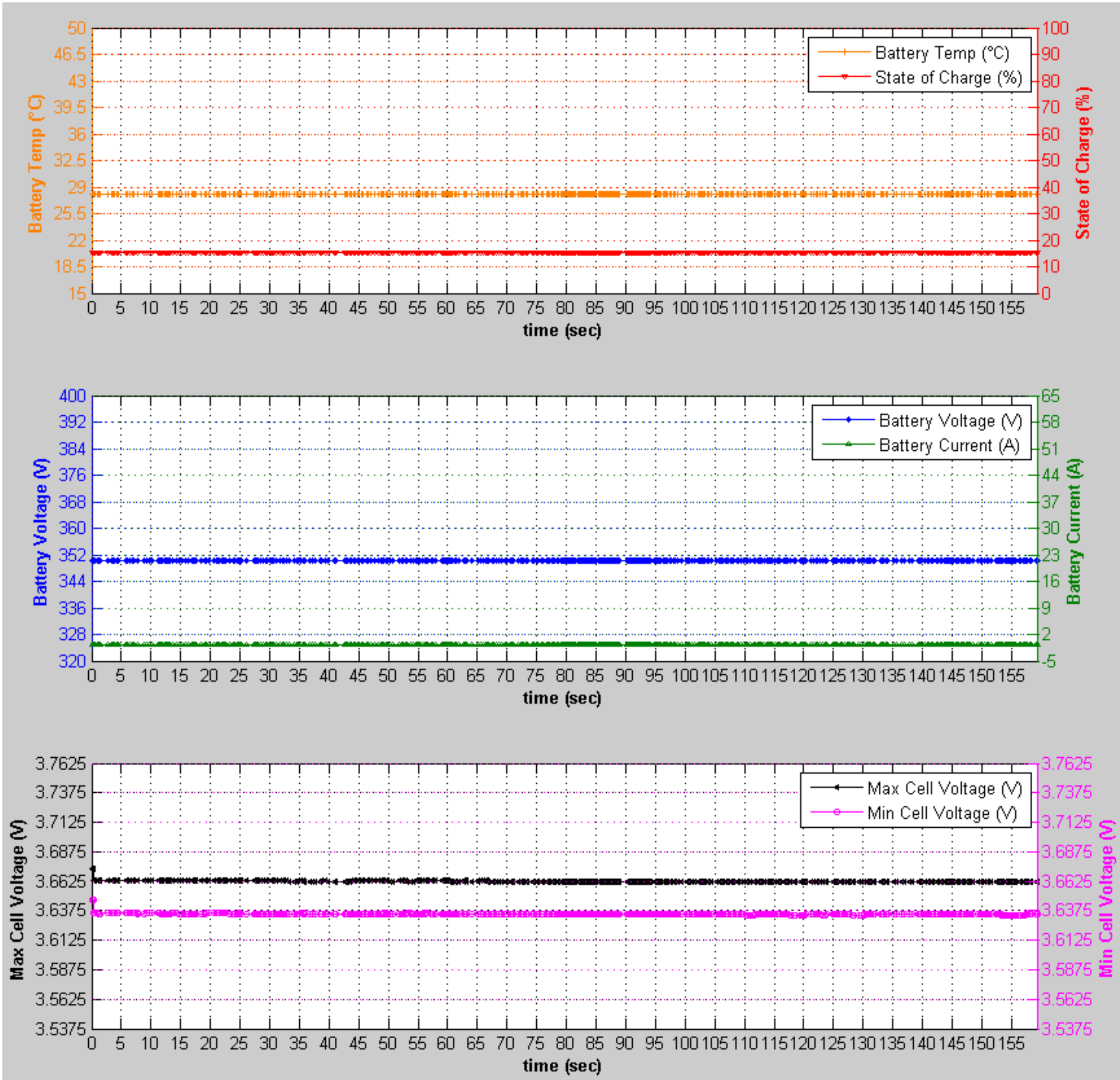

Figure 43: Gradual Decrease Before Charge Session Charge Data

4.2.2.9 Gradual Increase During Charge Session

Although not in the test procedures this test was performed to determine the ground offset resistance at which the charge session would end. The resistance between earth GND and chassis GND was verified at 0 Ω prior to plugging in (i.e., potentiometer set to 0 Ω). A charge session began and the ground resistance was increased until the charging stopped. The charger display indicated that the charging was complete, or charging was paused by vehicle. A voltage of ~244 mV at earth GND with respect to chassis GND was measured with a ground resistance of 41.8 Ω. Figure 44 shows the charging data for this test.

Retrieved DTCs from the PEV include:

> *EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)*
>
> *EME 222822 Charge management function: Check Control message (859)*

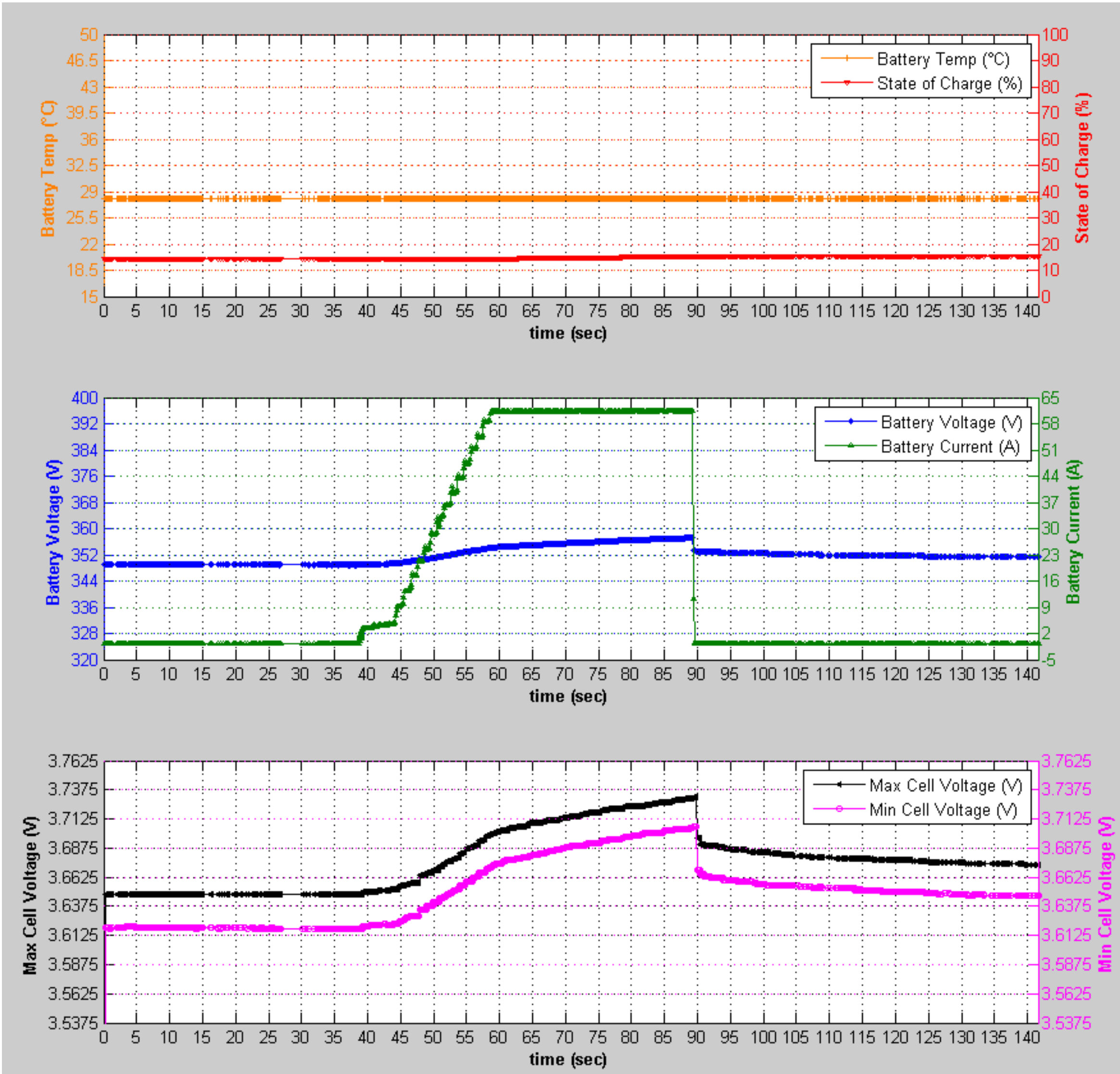

Figure 44: Gradual Increase During Charge Session Charge Data

4.3 DC Bus Short Test

4.3.1 Procedure Feedback and Revisions

This test calls for DC + to be shorted to DC – before a charge session and to determine if a charge session is allowed to begin. SAE J1772, for example, requires a DC Charger to check for a short between DC+ and DC- before the charger's output is enabled, so this test is in line with common practice for DC charging.

4.3.1.1 Updated HV fusing recommendations

In the original documentation, Step 5 calls out for the measurement of a single fuse between TP1-TP2. However, there are technically 3 fuses between these two measurement points on the breakout box schematic. These HV fuses should also be rated for the maximum output current of the charge system under test.

4.3.1.2 "Start" of charging recommendation

The pass/fail criteria for this procedure describes that when a short is present between DC+ and DC- a charge session shall not start. A description of "start" must be defined. It is assumed the original authors of the original research project documentation define "start" as the DC charging session making it to the Energy Transfer phase.

4.3.2 Validation Testing Results and Discussion

A short was introduced between DC+ and DC- prior to initiating a charge session. The resistance between DC+ and DC- was measured at 1.7 Ω. Upon plugin the charger displayed it was ready and waiting for a vehicle. Shortly after the charger displayed an internal fault on its display and a charge session did not begin. Once the charger was disconnected from EV the fault cleared on its own. The resistance between DC+ and DC- was measured again to be 1.5 Ω, thus the fuses did not blow.

No DTCs were set during this test.

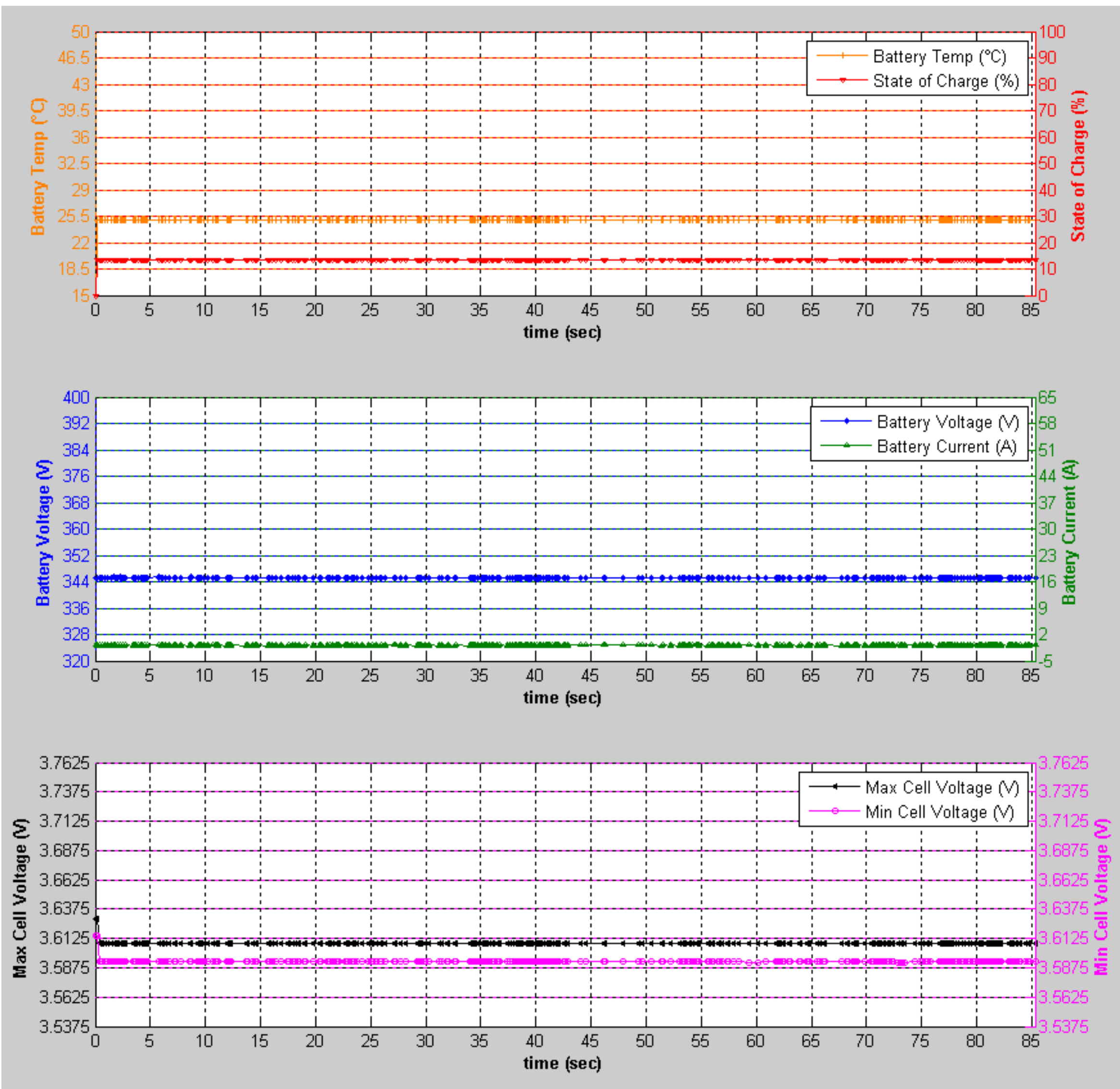

Figure 45: DC Bus Short Test Charge Data

4.4 DC Bus Held High Test

4.4.1 Procedure Feedback and Revisions

Placing high voltage on the DC bus before plugging in/starting a charge session could affect the DC charger and PEV differently. From the DC charger perspective if it measures a high voltage without its output enabled it would assume the PEV's contactors are unexpectedly closed (a fault condition). From the PEV's perspective if it measures high voltage at the inlet without its contactors closed it would assume the EVSE has malfunctioned. Either the PEV, DC charger, or both will fault before a charging session when the DC bus is held high.

The procedure also calls for the DC bus to be held high after a charge session. When the DC bus is held high after a charging session, a vehicle should not unlock the charge connector from the inlet until the bus voltage has dropped below 60V DC. If the PEV unlocks the connector while high voltage is present at the extended pins of the inlet this poses a potential safety situation.

It should also be pointed out that the systems could possibly react differently depending on whether the high voltage was enabled on the connector/inlet while connected or disconnected. The test procedure only focuses on the use case in which the charger connector is connected to the breakout box and the breakout box is connected to the PEV inlet to emulate a "plugged in" situation.

4.4.1.1 Revised test sequencing

Section 6.4.5 of the original documentation details two test procedures (DC bus held high before and after a charge session). The DC bus held high before a charge session procedure requires the HV power supply output to be set at a voltage of 60 VDC and the maximum current to 1A. Step 4 of this procedure then requires a charge session to be started. It is suggested that two tests are performed: one in which the HV is enabled while plugged in before a charge session and one in which the HV is enabled before being plugged in.

The DC bus held high after charging session test has similar procedures to the DC bus held high before a charge session test. Again, the vehicle should not unlock the charge connector from the inlet until the bus voltage has dropped below 60V DC. The high voltage setting for all DC Bus Held High tests should be set at a voltage > 60 V DC.

4.4.2 Validation Testing Results and Discussion

4.4.2.1 Before Charge Session (Revised 60V Test condition)

While the original draft procedure document allowed for a passing test to initiate a charge session at 65V or below applied to the HV bus, this value was reduced to be at or below 60V in subsequent procedure revisions for commonality with FMVSS 305. This section shows the updated results for the revised 60V application to the HV bus prior to testing. The charger was connected to the breakout fixture with +60 VDC on HV+ with respect to HV-. Once plugged into the PEV, the charger detected the high voltage and displayed an internal fault. A charge session did not begin; therefore the EV did not lock the connector to the inlet. The following DTC was set.

LIM 805529 DC charging: Unexpected high voltage detected at charging socket

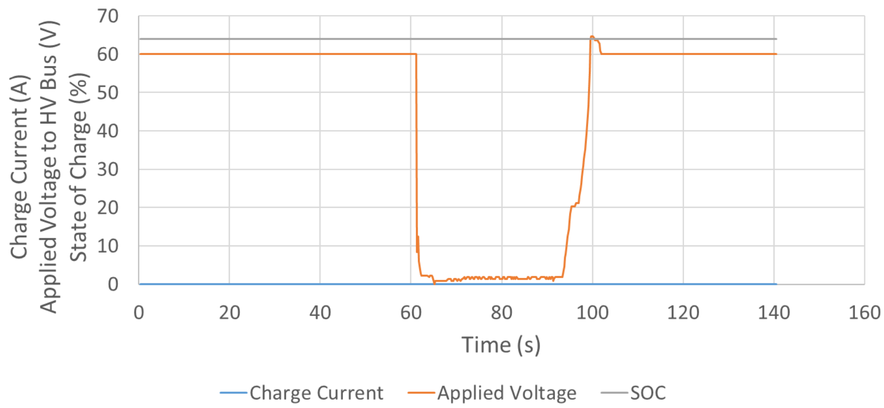

Figure 46: Before Charge Session Charge Data (60V applied to HV bus)

4.4.2.2 Before Charge Session (65V Test condition)

In the original draft procedure research document, the original voltage recommendation for testing was 60V (-0/+5V). During the first round of validation testing a value of 65V was used as the supplied voltage for this testing (as opposed to 60V). As discussed above subsequent revisions brought the maximum threshold to 60V to be consistent with FMVSS 305. The charger was connected to the breakout fixture with +65 VDC on HV+ with respect to HV-. Once plugged into the PEV, the charger detected the high voltage and displayed an internal fault. A charge session did not begin; therefore the EV did not lock the connector to the inlet. Switch S2_HV+ was toggled twice, applying +65 VDC to the HV bus as shown in Figure 47.

The following DTC was set.

LIM 805529 DC charging: Unexpected high voltage detected at charging socket

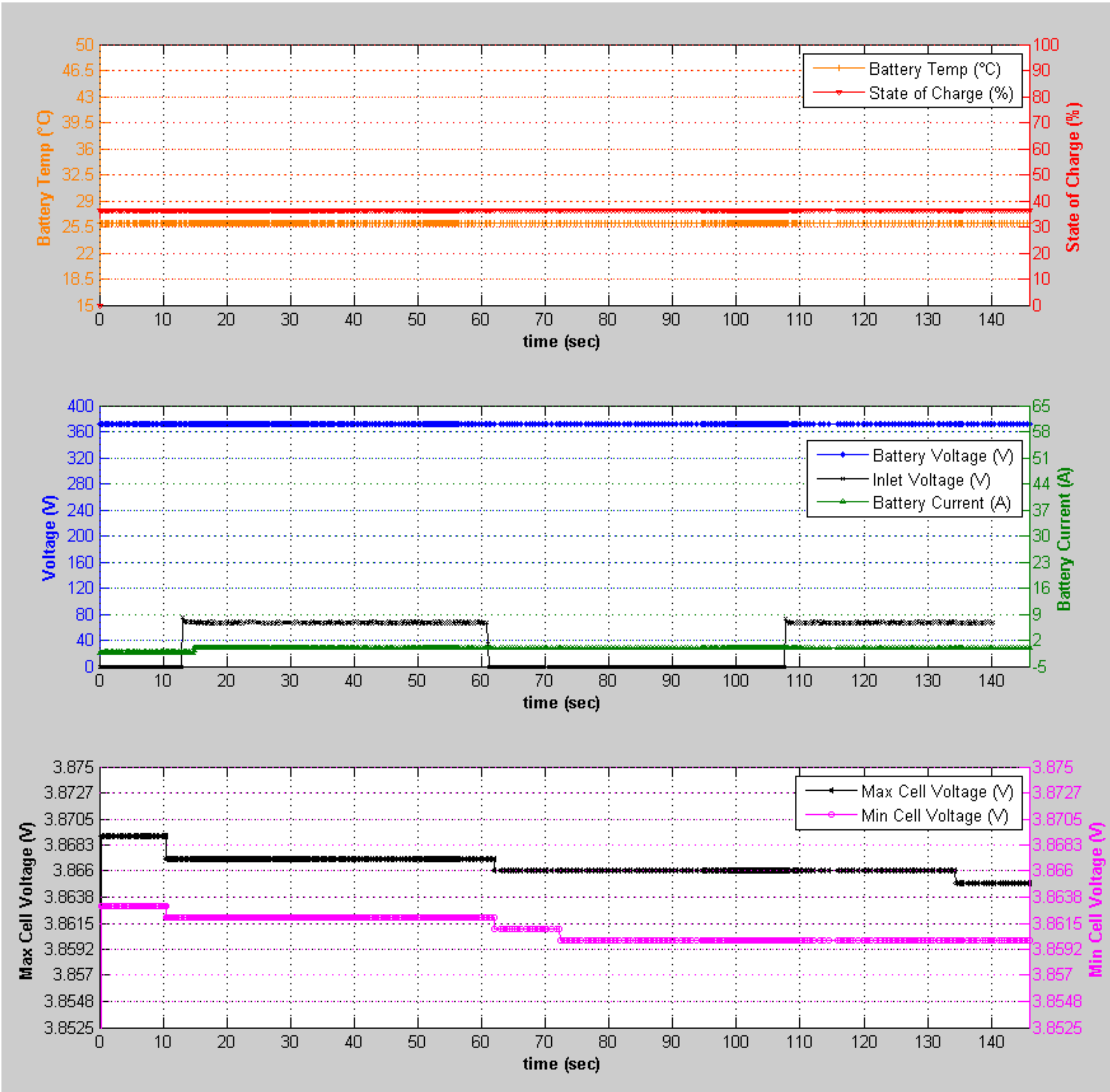

Figure 47: Before Charge Session Charge Data (65V applied to HV bus)

4.4.2.3 During Charge Session

A normal charge session was started through the breakout box. Once the charge current stabilized at ~60A @ 380 VDC, 385 VDC was placed on the DC bus with an external high power DC supply at around ~92 seconds from the start of the log file. The charge session continued and was stopped by the test operator at ~ 150 seconds into the test as shown in Figure 48. The connector remained locked in the PEV's inlet. The output of the high power DC supply was then reduced until the voltage reached ~77 VDC (~215 sec into the test) upon which the PEV unlocked the connector.

The following DTCs were set.

EME 222807 Charge management function: Request for switching off the high-voltage system

EME 222834 Charge management function: Check Control message 804, unable to charge

LIM 805523 DC charging, contactor: Negative terminal, contactor sticking

LIM 805524 DC charging, contactor: Positive terminal, contactor sticking

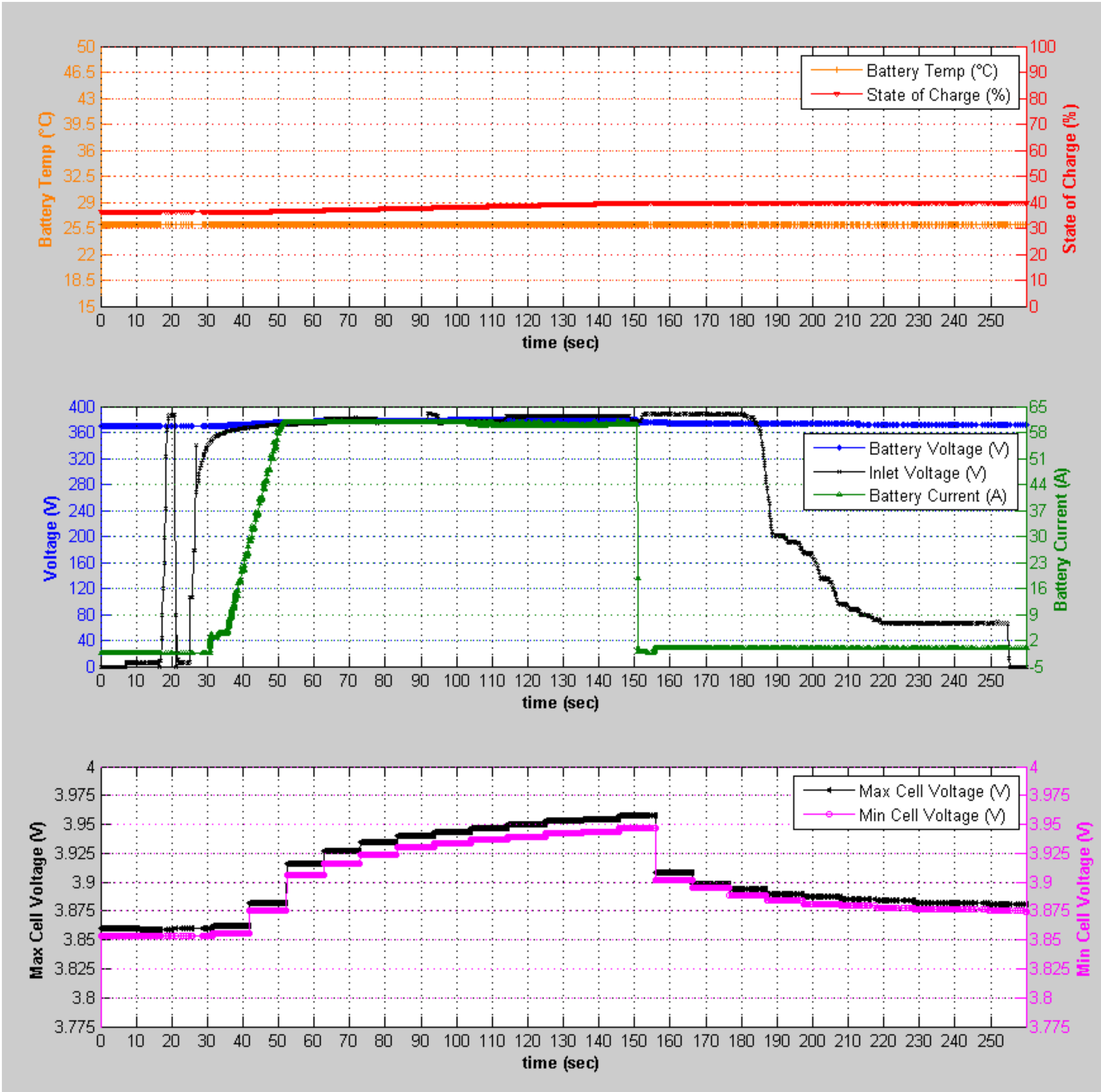

Figure 48: During Charge Session Charge Data

4.5 System Over-Voltage Test (12V Board Net)

4.5.1 Procedure Feedback and Revisions

4.5.1.1 Removal of 24V over-voltage test condition contained in original procedure document

A 12V system over voltage would not be uncommon for PEV's if the 12V battery was 'drained'. However, a BEV would never need to be "jump" started and rarely would a PHEV need to be "jump" started with the associated large increase of voltage due to the power demands required to start the vehicle's engine. With this in mind, the higher over-voltage condition (24V) may be unduly taxing on the vehicle's low-voltage system while not introducing a relevant safety check.

4.5.1.2 Procedure adjustment

This test details applying an 18V source to the 12V system for 60 min and then starting a charge session. In addition to applying these conditions before a charge session and then starting a charge session, the conditions could also be applied during a charge session. The pass/fail criteria for this test could to be better defined for vehicle-specific behaviors, but a :"safe" state as described in the procedures is sufficient from a safety perspective. If a DC charge session is allowed to start or continue during a 12 V system over voltage, either the CCS system should not end the charge or, if charging is stopped, the result should not be an unsafe condition.

4.5.2 Validation Testing Results and Discussion

For this test the PEV's 12 VDC battery and DC/DC converter was disconnected from the +12 VDC bus of the PEV and the ABC-170 was connected to the +12 VDC bus. The breakout box was not used in this test. The test deviated from the test procedure and was not performed for the full 60 minutes. The jump start condition over-voltage test (24V for 60 seconds) from the previous draft of the test procedure document and subsequently removed from the test procedures was not performed based on the fear of damaging the ECU's of the PEV and per the previous discussion regarding relevance and subsequent removal of the test.

The output of the ABC-170 was regulated to +18 VDC and a charge session with the IES Charger was initiated. Charging commenced around ~80 seconds from the start of the trace file as seen in Figure 49. The charge session continued for another 100 seconds until it was ended by the test operator.

The following DTCs were set.

BDC 030018 Power window regulator, driver's door: Switch-off of drive due to overvoltage.

BDC 03001D Power window regulator, driver's door: Supply voltage to sensors switched off (overvoltage)

BDC 030020 Power window regulator, driver's door: system not normalized.

BDC 030098 Front passenger door power window regulator: Drive shutdown due to overvoltage or under voltage

BDC 03009D Front passenger door power window regulator: Supply voltage sensors switched off (overvoltage)

BDC 0300A0 Front passenger door power window regulator: system not normalized.

RDME 111001 Battery voltage 1: Voltage too high (KL30B)

RDME 111002 Battery voltage 2: Voltage too high (KL15N)

RDME 113001 Information vehicle speed: Not plausible

REME 21DE06 REME: Overvoltage detected

KLE 21E605 KLE: Overvoltage

EME 222218 DC/DC converter, component protection: Switch-off due to 12 V vehicle electrical system overvoltage

EME 22223D EME: internal fault (DC/DC converter)

EME 222D22 Parking lock module, activation: Voltage is outside of operating range

DSC 480965 DSC: Overvoltage of control unit detected

KAFAS 800AB8 KAFAS: Overvoltage detected

IHKA 80120E Overvoltage detected

CON 801406 CON: Overvoltage

FZD 801A39 FZD: Overvoltage detected

GWS 802698 Supply voltage: Overvoltage detected

BDC 8041E3 Lights, voltage protection active

BDC 80444E Inside mirror, Overvoltage detected

TBX 806181 TBX: Overvoltage

KOMBI B7F676 Instrument cluster: Overvoltage detected

HU-H B7F86C HU-H: Overvoltage

KOMBI E12C20 KAFAS interface (traffic sign identification, 0x287): Signal invalid

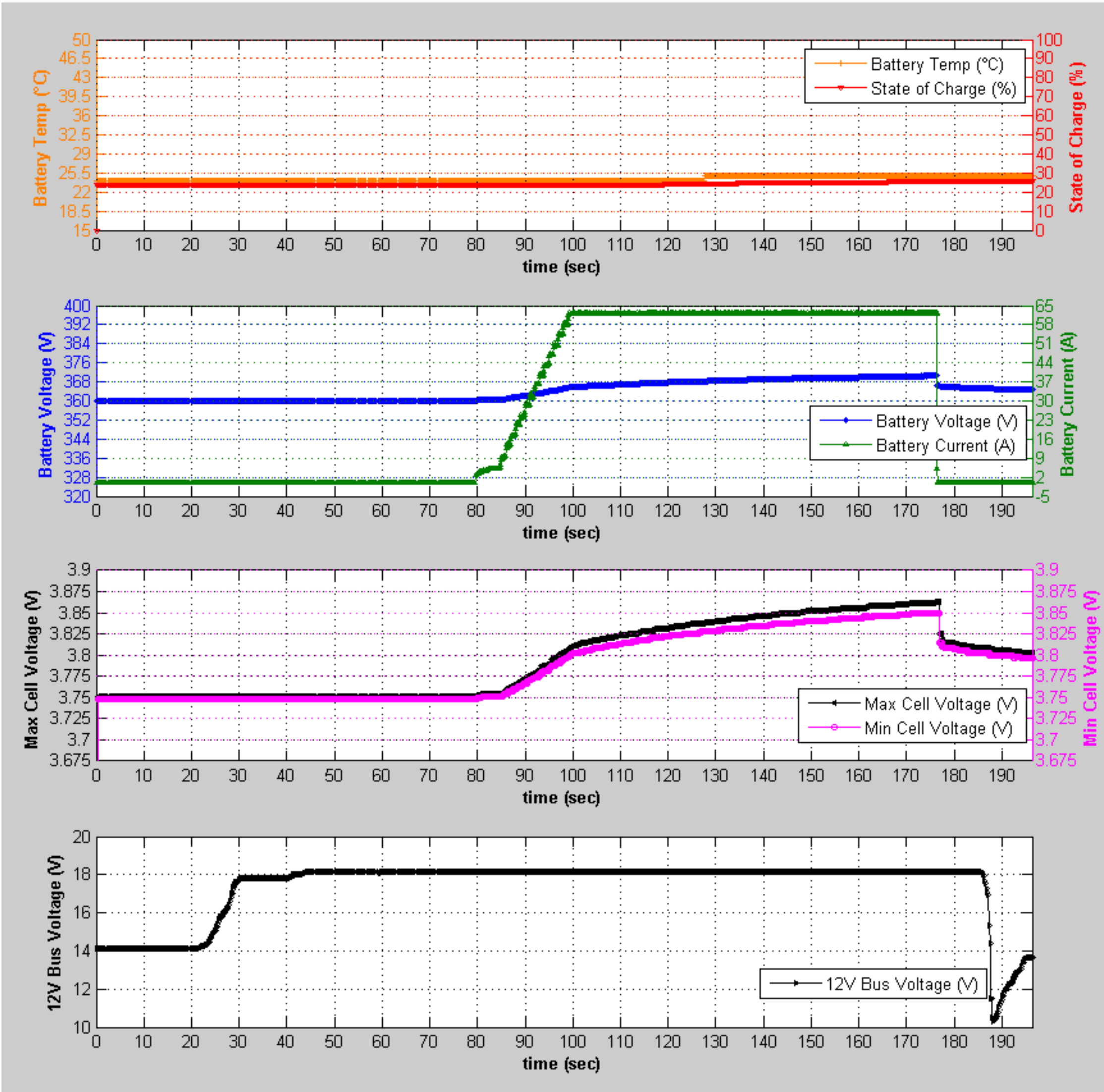

Figure 49: 12V System Over-Voltage Charge Data

4.6 12V System Under-Voltage Test

4.6.1 Procedure Feedback and Revisions

It is assumed that as the 12 V system source voltage is reduced to 0V, the source voltage will reach a point in which vehicle and charge system ECUs will shut down resulting in the charge session ending. When this occurs, issues such as the connector not unlocking or the PEV contactors remaining open should be explored.

4.6.1.1 Procedure Feedback

The procedure contained in the original project documentation is defined well and no additional feedback is offered.

4.6.2 Validation Testing Results and Discussion

For this test the PEV's 12 VDC battery and DC/DC converter was disconnected from the +12 VDC bus of the PEV and the ABC-170 was connected to the +12 VDC bus. The breakout box was not used in this test. The output of the ABC-170 was regulated to +13.2 VDC and a charge session with the IES Charger was initiated. Charging commenced around ~40 seconds from the start of the trace file. The output of the ABC-170 was reduced at a rate of ~0.5V/minute as seen in Figure 50. During the transition from ~ 9.7 VDC to ~9.2 VDC the charge session abruptly stopped at around ~446 seconds from the start of current flowing. The charger displayed an internal fault condition. The indicator light around the PEV inlet was not on, or flashing. The dash indicator on the PEV was blank, likely due to the low 12V network voltage level.

The following DTCs were set.

BDC 030018 Power window regulator, driver's door: Switch-off of drive due to overvoltage.

BDC 030020 Power window regulator, driver's door: system not normalized

BDC 030098 Front passenger door power window regulator: Drive shutdown due to overvoltage or undervoltage

BDC 0300A0 Front passenger door power window regulator: system not normalized.

RDME 111004 Battery voltage 1: Voltage too low (KL30B)

RDME 111005 Battery voltage 2: Voltage too low (KL15N)

RDME 113001 Information vehicle speed: Not plausible

KLE 21E606 KLE: Undervoltage

KLE 21E60C KLE: Internal hardware fault

EDME 21E707 Power management, battery condition: Total discharge

EME 222218 DC/DC converter, component protection: Switch-off due to 12 V vehicle electrical system overvoltage

EME 222224 EME: internal fault (DC/DC converter)

EME 22223D EME: internal fault (DC/DC converter)

EME 222807 Charge management function: Request for switching off the high-voltage system

EME 222820 Charge management function: Check Control message 874, unable to rapid charge

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

EME 222870 High-voltage power management, signal evaluation: Signals of EME invalid or not received

EME 22287D DC charging: Switch contactors were unexpectedly opened or not activated

EME 222B43 EME: internal fault (DC/DC converter)

EME 222B45 EME: internal fault (DC/DC converter)

EME 222D22 Parking lock module, activation: Voltage is outside of operating range

EME 222D81 Electrical vacuum pump, activation: Switch-off due to undervoltage

DSC 480964 DSC: Undervoltage at control unit, major

EPS 4823FC EPS voltage supply: Undervoltage control unit, reduction steering assistance

IHKA 80120D Undervoltage detected

BDC 80402F Power management, battery condition: Total discharge

BDC 80444D Inside mirror: Undervoltage detected

BDC 80490C Seat heating, front passenger: Undervoltage detected

BDC 80491C Seat heating, driver: Undervoltage detected

ACSM 930AA1 Supply voltage: Undervoltage

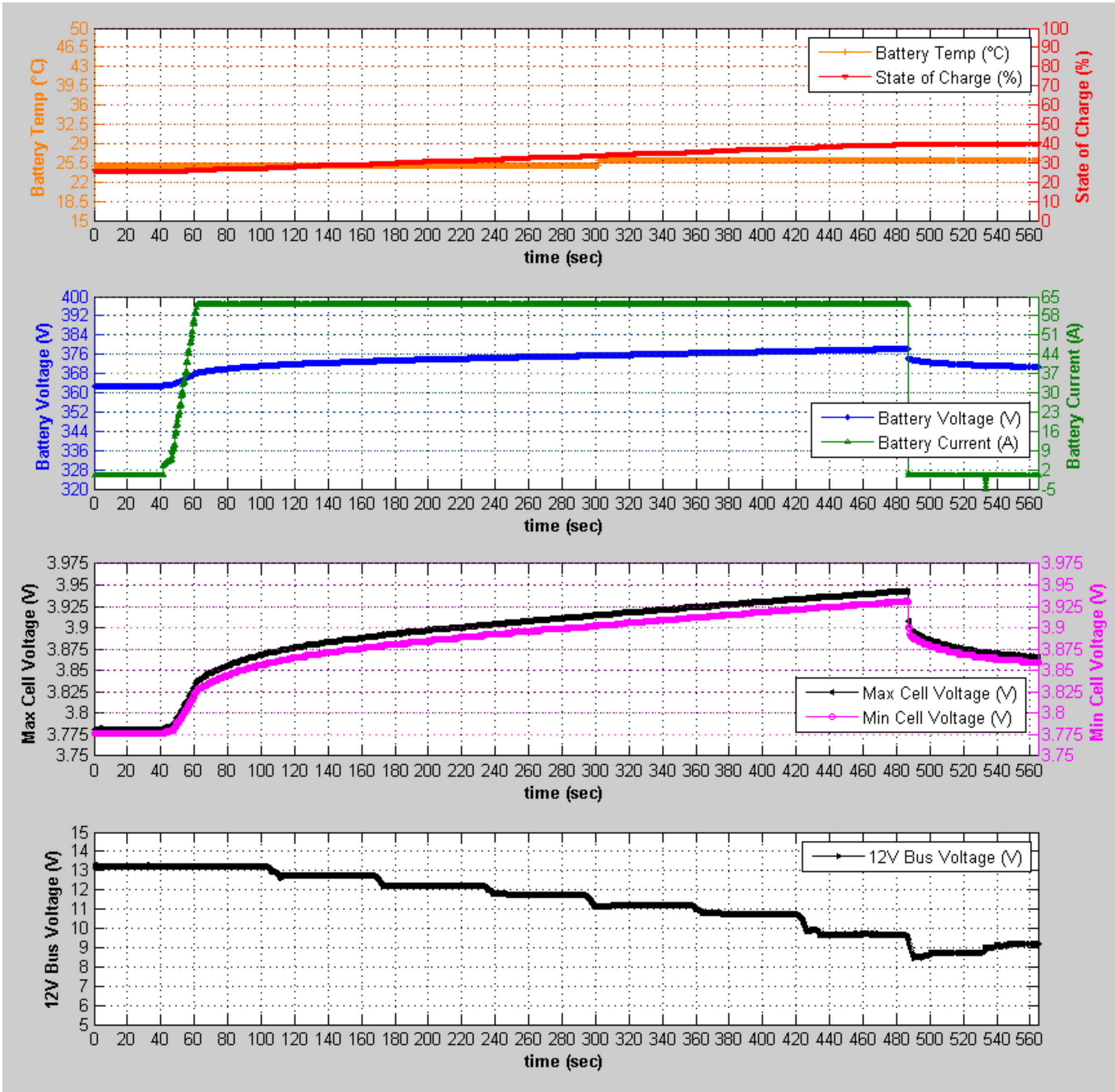

Figure 50: 12V System Under-Voltage Charge Data

4.7 12V System Disturbance Test

4.7.1 Procedure Feedback and Revisions

Without proper filtering an ECU could reset or malfunction due to noise or spikes on the 12 V system source bus.

4.7.1.1 Modified pass/fail criteria to include safe interruption of charging

The pass/fail criteria for this procedure states that the test shall be considered a pass if the vehicle or charger does not react to the load switching and the DC charge session is not interrupted. The pass/fail criteria should be modified to allow for a pass if the DC charge session was interrupted as long as the session ended in a safe condition.

4.7.2 Validation Testing Results and Discussion

For this test the ABC-170 was placed configured to be a current source and programmed to sink 20A at a rate of 1 Hz. This emulated 20A load was connected to the +12 VDC bus. The breakout box was not used in this test. Charging commenced around ~40 seconds from the start of the trace file. The effect of the 20A load on the +12 VDC bus created a ~100 mV peak-to-peak ripple on the bus as seen in Figure 51. The 20 A load did not have an effect on the charge session. The charge session was stopped by the test operator. No DTCs were set.

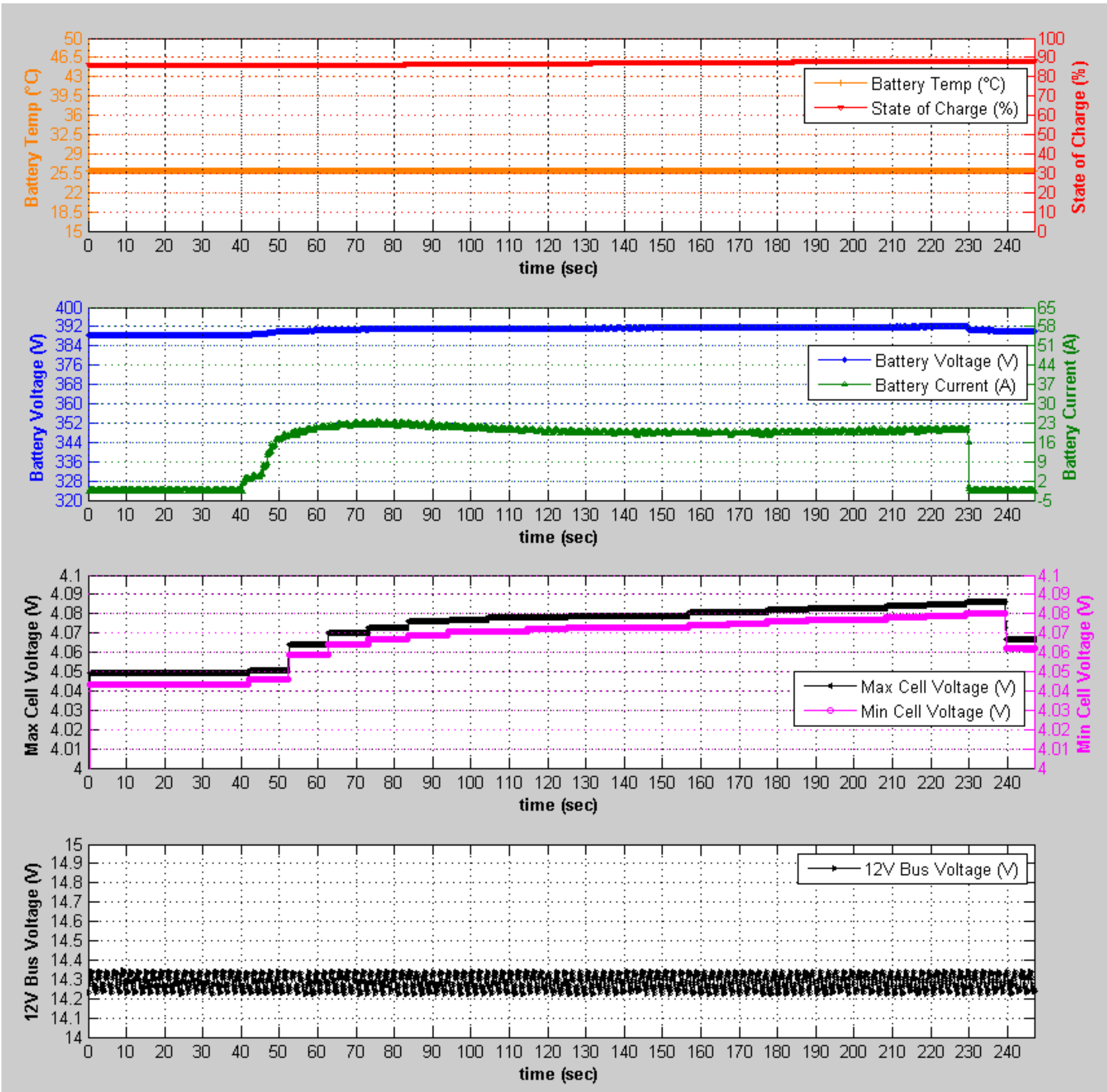

Figure 51: 12V System Disturbance Charge Data

4.8 12V System EMI/EMC Test

4.8.1 Procedure Feedback and Revisions

Although the authors are not familiar with the SAE J1113-3,-4,-21,-24 test procedures (Electromagnetic Compatibility Measurement Procedures…) if each ECU that comprises the charging system and controls on the PEV complies with these SAE test procedures this test procedure could possibly be redundant in that the system components are all individually robust to interference.

The procedure of Section 6.8.5 of the original research documentation is basic and only requires the procedures SAE J1113-3,-4,-21,-24 to be performed while observing the behavior of the CCS system. Although it may be worthwhile to occasionally assess both component and system EMI issues, these tests may be redundant and could possibly be removed.

4.9 Vehicle Movement Test

4.9.1 Procedure Feedback and Revisions

A PEV shall prevent operator initiated vehicle movement when the charge connector is mated to the vehicle inlet. Charging should not occur or be stopped if the vehicle is unable to confirm application of a parking brake/park pawl or other means of impeding unexpected vehicle movement or rollaway.

4.9.1.1 Procedure Feedback

The vehicle movement test includes two procedures. The first procedure checks to see if the PEV power-train is disabled during a charge session. The procedure should also be performed when not charging (i.e., connector still plugged into inlet).

The second procedure simulates vehicle movement during a DC charge session by attempting to rotate the PEV's wheels. The procedure should require that all 4 wheels be rotated in both directions to ensure that both the front and rear wheel sensors are tested adequately and that any possibly sensing setup is comprehended. In the preliminary draft form of this procedure the document does not specify what wheel to be rotated.

The pass/fail criteria should be edited to fail any PEV that allows vehicle movement beyond 150mm while the connector is mated to the vehicle inlet.

For the simulated vehicle movement test, it was unknown whether simply turning a wheel is enough to "trick" the PEV into believing the PEV is actually moving and therefore initiate a charge session shutdown as described in the original research report documentation. Additionally, a revise test was developed for the BMW i3's specific parking pawl mechanics to highlight the protections the vehicle uses to avoid charging with an open parking pawl (and thus rollaway risk). Through the validation of the procedure, it was concluded that while the specific steps taken for the BMW i3 DUT were successful, it is unlikely a generalizable procedure can be developed to accommodate a range of methods for impeding vehicle motion (i.e., parking brake versus parking pawl and their assorted methods of implementation).

4.9.2 Validation Testing Results and Discussion

4.9.2.1 Drive Attempt Before a Charge Session (Plugged-In)

The PEV was placed on a lift for this test and lifted high enough so the tires were not touching the ground. The IES charger connector was then plugged into the PEV's CCS inlet but a charge session was not initiated by the test operator. The parking brake was engaged and disengaged while plugged in. The

PEV would not turn on and the display suggested disconnecting the charge cable. The PEV would not shift to Drive, Neutral, or Reverse.

Retrieved DTCs from the PEV:

LIM 805519 Load: PLC data line, communication fault

4.9.2.2 Drive Attempt During Charge Session

A normal charge session was started with the IES charger and the PEV without the breakout box. Charging started to occur around ~42 seconds into the log file as shown in Figure 52. The parking brake was able to be engaged and disengaged while the PEV was charging. The PEV would not turn on and would not shift into Drive, Neutral, or Reverse.

4.9.2.3 Simulated PEV Movement During Charge Session (original draft procedure)

Figure 52 shows that at approximately 95 seconds into the test the rear driver side wheel was allowed to rotate, although there was some resistance the tire was rotated to a speed of ~3 MPH. The rear passenger wheel was then rotated with similar resistance to ~3 MPH. The front driver wheel (~6 MPH) and front passenger wheel (~5 MPH) rotated with no resistance. Rotating all four tires did not cause the charge session to stop. It should be noted that when the PEV was placed back down on the ground the test operator attempted to push the PEV forcefully and could not achieve any tire rotation. The test operator initiated the end of the charge session. There were no DTCs set for this test.

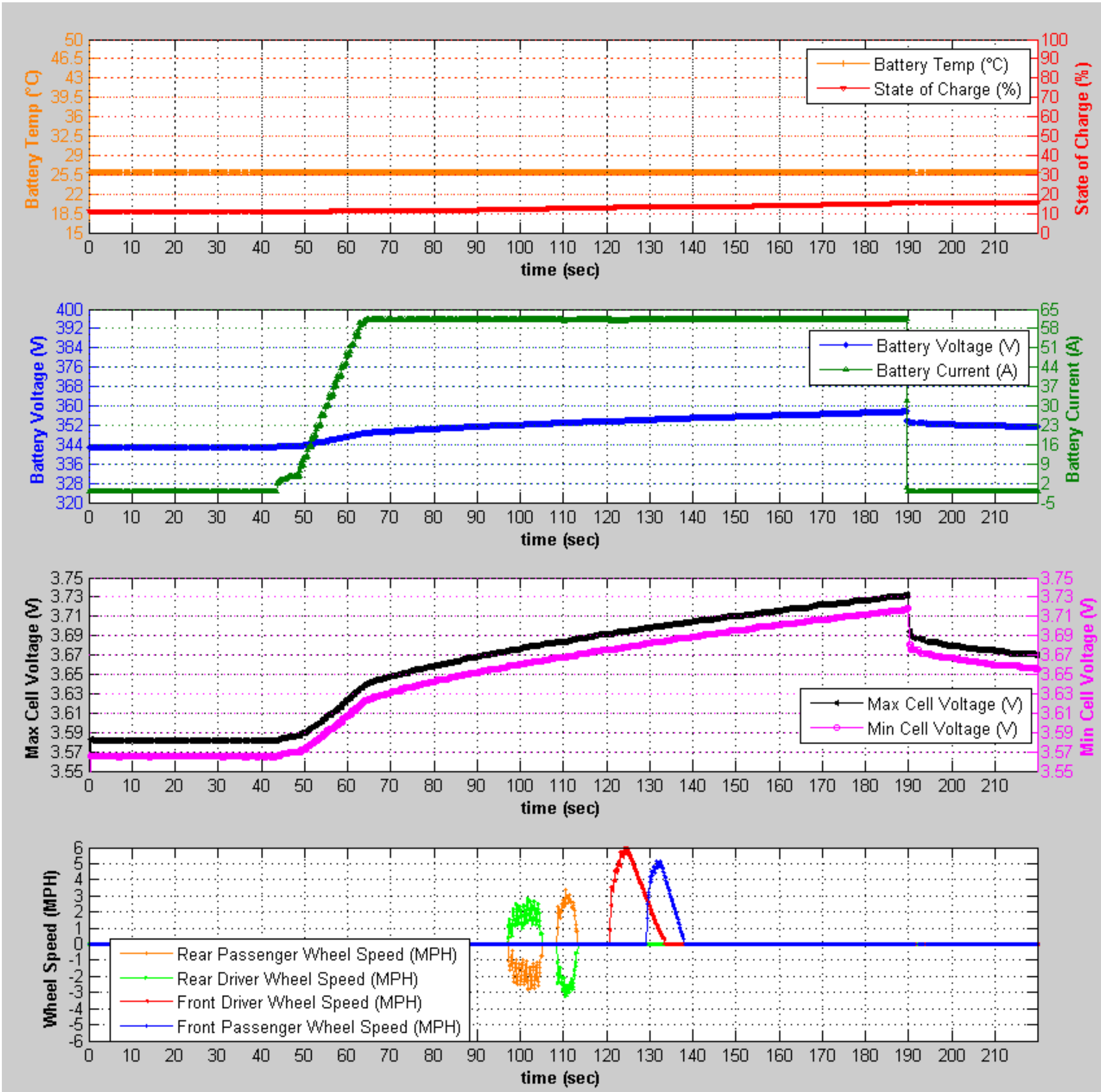

Figure 52: Drive Attempt while Charging and Simulated PEV Movement Data

From these results, it is unclear if the vehicle can detect movement using this test alone. Although the wheels could spin, the driven wheels (rear for the Rear-Drive DUT) could only spin in opposite directions due to the open differential allowing for opposing direction wheel spin. The wheels could not be spun in the same direction, thus this is not an adequate method to investigate a vehicles protections against movement during charging. Additionally, from the implementation of the i3's parking pawl mechanism, it appeared very difficult to create a fault while charging. Thus a revised, vehicle-specific procedure was developed for the i3's specific parking pawl mechanism and related actuation systems.

4.9.2.4 Protection Against Unexpected (non-propulsion-based) PEV Movement During Charge Session (vehicle specific evaluation procedure)

The goal of the revised test was to see if a fault condition or unexpected input/alteration to the parking pawl system could leave the vehicle with an open parking pawl while also allowing for a charge session to begin. The following steps were taken to evaluate the vehicle:

1. Elevate vehicle on lift to prevent unintended rollaway (or block wheels if lift is unavailable
2. Activate vehicle normally and put in drive (with brake applied)
3. Open charging port door/cover in case this is later locked due to fault conditions
4. Remove power to parking pawl activation power connector to disable pawl in "open" state
5. Turn off vehicle and confirm open park pawl (vehicle can be rolled or driven wheels can be spun in same direction if on a lift)
6. Attempt to charge with removed pawl connector
7. Replace connector to return system to "normal" state (but pawl still open)
8. Attempt to charge the vehicle

The following bullets summarize the vehicle's response to the "failed-open" pawl condition:

- Numerous fault codes due to removed pawl connector (shown in figures below) (faults codes shown even when door opened)
- Numerous faults on dashboard when trying to charge
- Charging port door locked due to fault (can't access port if not left open prior to causing fault)
- Charging not allowed with pawl connector disconnected
- When connector returned to normal and charging attempted, pawl was closed (i.e., system appears to attempt to close pawl (or confirm closure) prior to activating a charge session)

Figure 53: BMW i3 Fault Codes Displayed on Dash When Attempting to Charge With an Open Parking Pawl

Although this testing required a vehicle/implementation specific procedure to evaluate the response to this situation, a requirement that a vehicle not initiate a charge session is still applicable as evidenced by the numerous faults and protections displayed by the DUT to avoid charging with an open parking pawl.

4.10 Vehicle Crash or Bump Test

4.10.1 Procedure Feedback and Revisions

This test procedure uses both a front and rear impact collision as defined in CFR 49 Part 581 (Bumper Standard) as a test procedure input. The condition verified during this test is the PEV's strategy to monitor for vehicle impacts while DC charging. Several significant safety hazards can be encountered if a vehicle is struck or damaged during charging and the vehicle/charging system does not handle the situation appropriately.

4.10.1.1 Procedure Feedback
The procedure in the original research documentation is defined well, although it obviously will be a destructive test in order to truly observed the vehicle response during charging.

4.11 Charge Operation Disturbance Test

4.11.1 Procedure Feedback and Revisions

The original research project documentation describes six "abnormal" actions performed by the operator. These actions include: premature disconnect attempt, operator interference at the charger, wiggling of the connector, operator interference at the vehicle, operator interference at with the vehicle key fob, and operator interference with a remote telematics command.

4.11.1.1 Per-sub procedure pass/fail criterion
Each sub-procedure has been provided a pass/fail criterion.

4.11.2 Validation Testing Results and Discussion

A normal charge session was initiated with the IES charger and the PEV without the breakout box. The test operator attempted to disconnect the EVSE from the EV inlet without pressing the connector's latch button (S3), the connector did not disconnect. Attempted to start the EV and change the drive mode, the session continued. The test operator attempted to roll the vehicle while in park. The vehicle did not roll, and the charge session continued. The test operator locked, unlocked, opened the hood, opened the trunk, and pressed the panic button. The charge session continued. The test operator wiggled and shook the connector, the charge session continued.

The only two interfaces on the IES charger are the RF card reader and the emergency stop button. The test operator pressed the emergency stop button as shown in Figure 54 around ~265 seconds into the test. The charger display informed the user to return the connector to the holster and that the session was finished.

The following DTCs were set.

> *EME 222822 Charge management function: Check Control message (859)*
>
> *EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)*

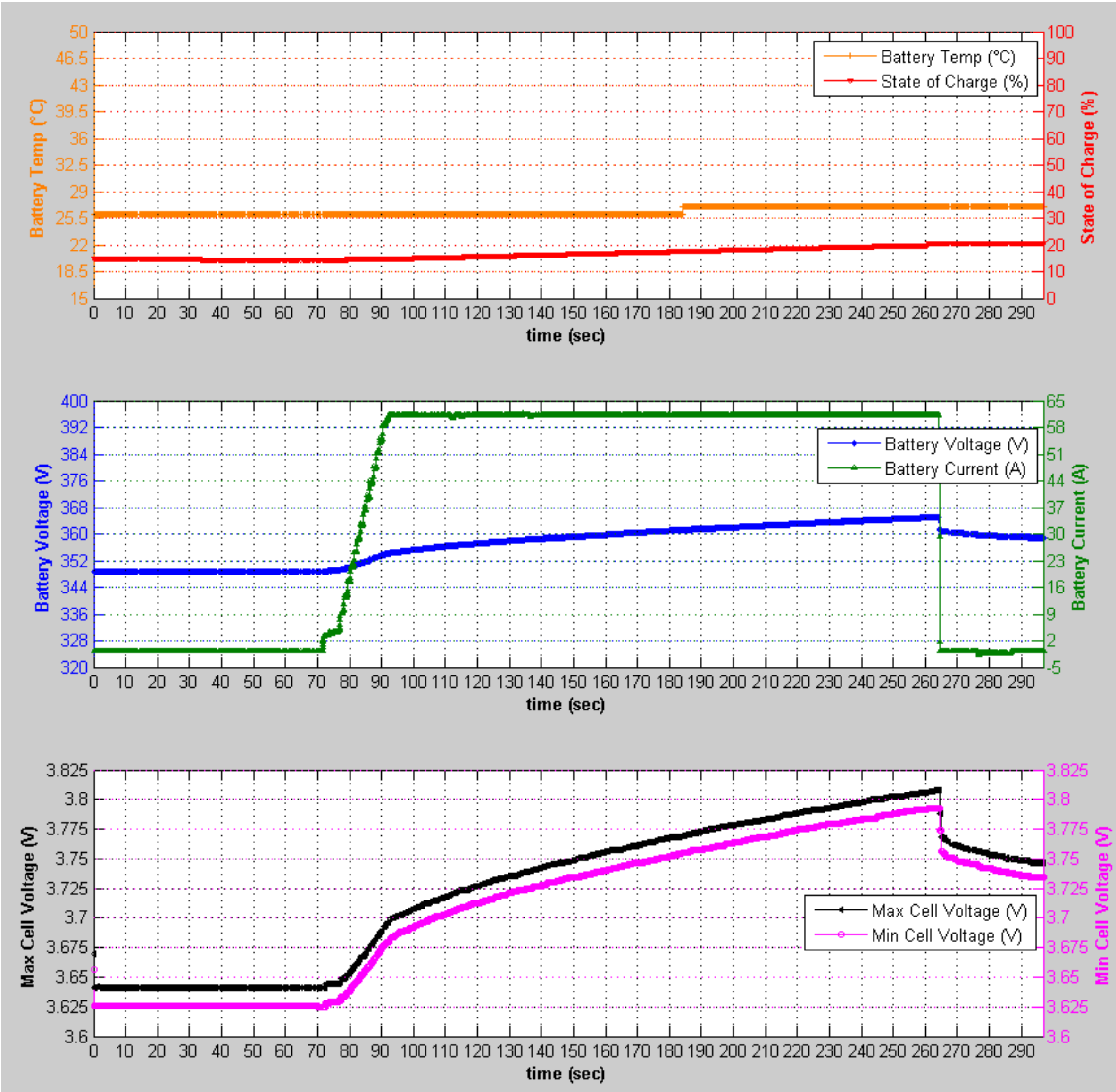

Figure 54: Charge Operation Disturbance Charge Data

4.12 Charge Connector Control Signal Disturbance Test

4.12.1 Procedure Feedback and Revisions

In the original rationale for this test, CAN communication is described as a control signal for the charge event. The CCS standards (applicable to the 1772 charger used in testing) do not use CAN communication between the off-board DC charger and PEV but rather PLC. The procedure goes on to describe control pilot and proximity disturbance tests as well as CAN bus tests. The control pilot tests include opening and shorting the control pilot during a charge session as well as introducing high resistance on the control pilot before and during a charge session. The proximity circuit tests include opening and shorting the control pilot during a charge session as well as introducing high resistance on the proximity circuit before and during a charge session.

To determine the effect of adding additional resistance to the control pilot, a circuit analysis was performed on the circuit of Figure 55. By adding the additional resistance Rs to the control pilot circuit the perceived control pilot state voltage measured by the DC EVSE and PEV will differ by the voltage dropped across the resistance Rs. The circuit analysis for the control pilot circuit of Figure 55 showed that adding additional series resistance at pin 4 of the coupler, results in the exact same state voltage seen by both the PEV and EVSE as adding additional series ground resistance as detailed in Section 4.2. Given this information this test may be redundant to the procedures outlined in Section 6.2 (Chassis Ground Offset Test) of the original research project documentation.

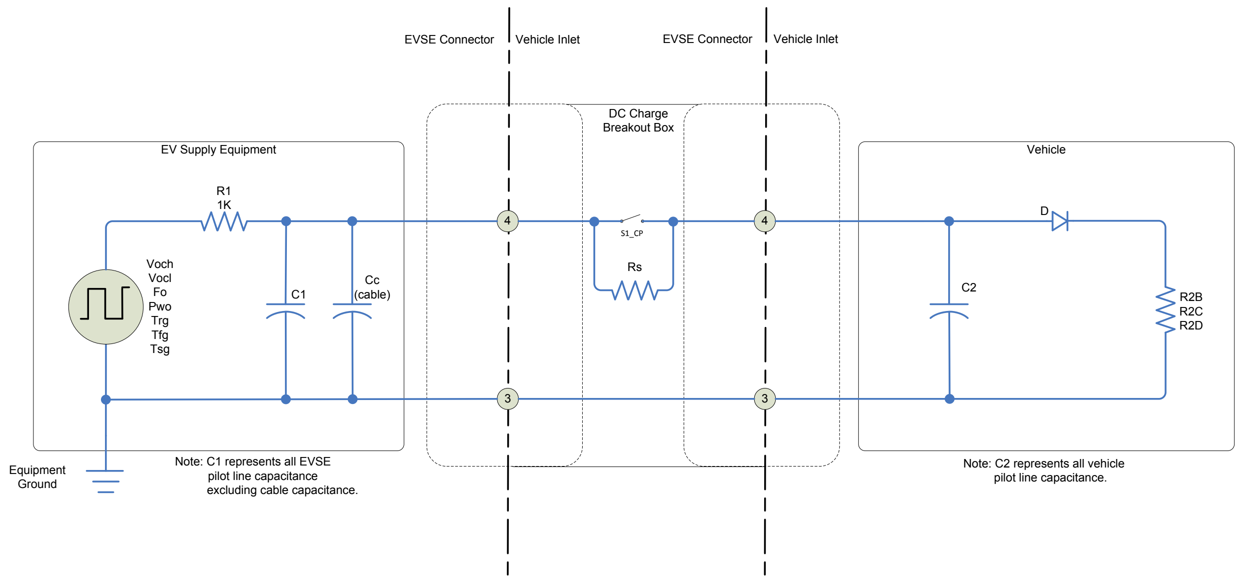

Figure 55: CCS Control Pilot Circuit With Added Series Resistance Rs.[2]

To determine the effect of adding additional resistance to the proximity circuit, a circuit analysis was performed on the circuit of Figure 56. By adding the additional resistance Rs to the proximity circuit the perceived proximity voltage measured by the DC EVSE and PEV will differ by the voltage dropped across the Rs resistance. The circuit analysis for the proximity circuit of Figure 56 showed that adding additional series resistance at pin 5 of the coupler, results in the exact same proximity voltage seen by both the PEV and EVSE as adding additional series ground resistance as detailed in Section 4.2. Given this information this test may be redundant to the procedures outlined in the “Chassis Ground Offset Test” test section.

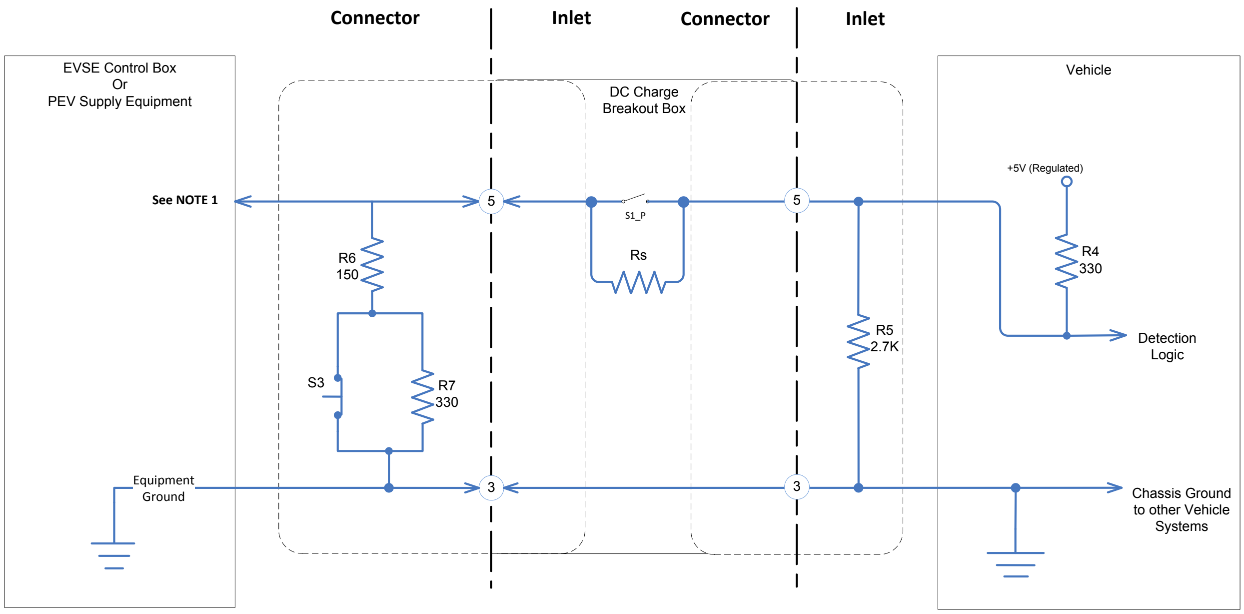

Figure 56: CCS Proximity Circuit With Added Series Resistance Rs.[2]

4.12.1.1 Streamlined testing and removal of redundant tests

The original project documentation details 12 procedures to disturb the control pilot, proximity and CAN circuits. Since the CCS communication protocol does not use CAN but rather PLC the 4 CAN disturbance tests could be eliminated since they are not a true "Charge Connector Control Signal." In the place of the CAN disturbance tests, specific control message protocol-centric disturbance tests could be performed (PLC in the case of the CCS used for this validation testing).

The following four procedures can be eliminated since it was shown the same results occur when performing the procedures of the Chassis Ground Offset Test.

- Introduce high resistance on the control pilot before a charge session
- Introduce high resistance on the control pilot during a charge session
- Introduce high resistance on the proximity signal before a charge session
- Introduce high resistance on the proximity signal during a charge session

A similar argument can also be made that the following 2 tests are redundant to the "Charge Connector Field Ground Connection Disturbance Test."

- Communication connection interrupted in breakout box during charge session (Control pilot interruption through breakout box)
- Communication connection interrupted in breakout box during charge session (Proximity interruption through breakout box)

Since the pilot and proximity circuits are series circuits, opening the pilot and proximity circuit at either pin 4/5 or pin 3 of the CCS coupler will result in the same perceived voltages.

4.12.2 Validation Testing Results and Discussion

4.12.2.1 Control Pilot Open During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and allowed to reach maximum current (~60A). At around ~79 seconds into the test the Control Pilot was opened. The charge session ended immediately as shown in Figure 57. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

LIM 805519 Load: PLC data line, communication fault

LIM 805532 High-voltage charging socket: Charging plug lock, status implausible

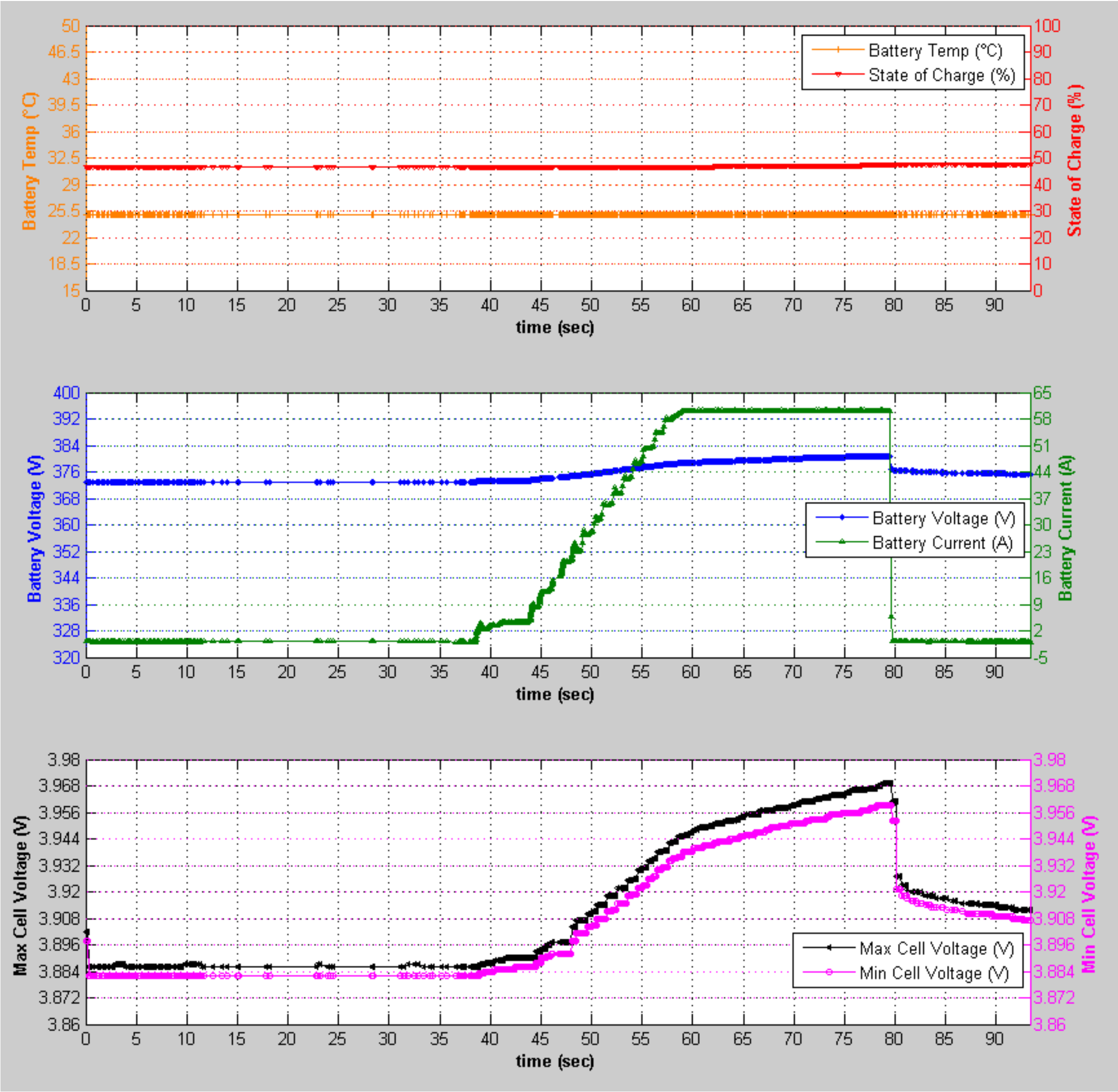

Figure 57: Control Pilot Open During Charge Session Charge Data

4.12.2.2 Control Pilot Short to Gnd During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and allowed to reach maximum current (~60A). At around ~62 seconds into the test the Control Pilot was shorted to earth ground. The charge session ended immediately as shown in Figure 58. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulated signal change (charger)

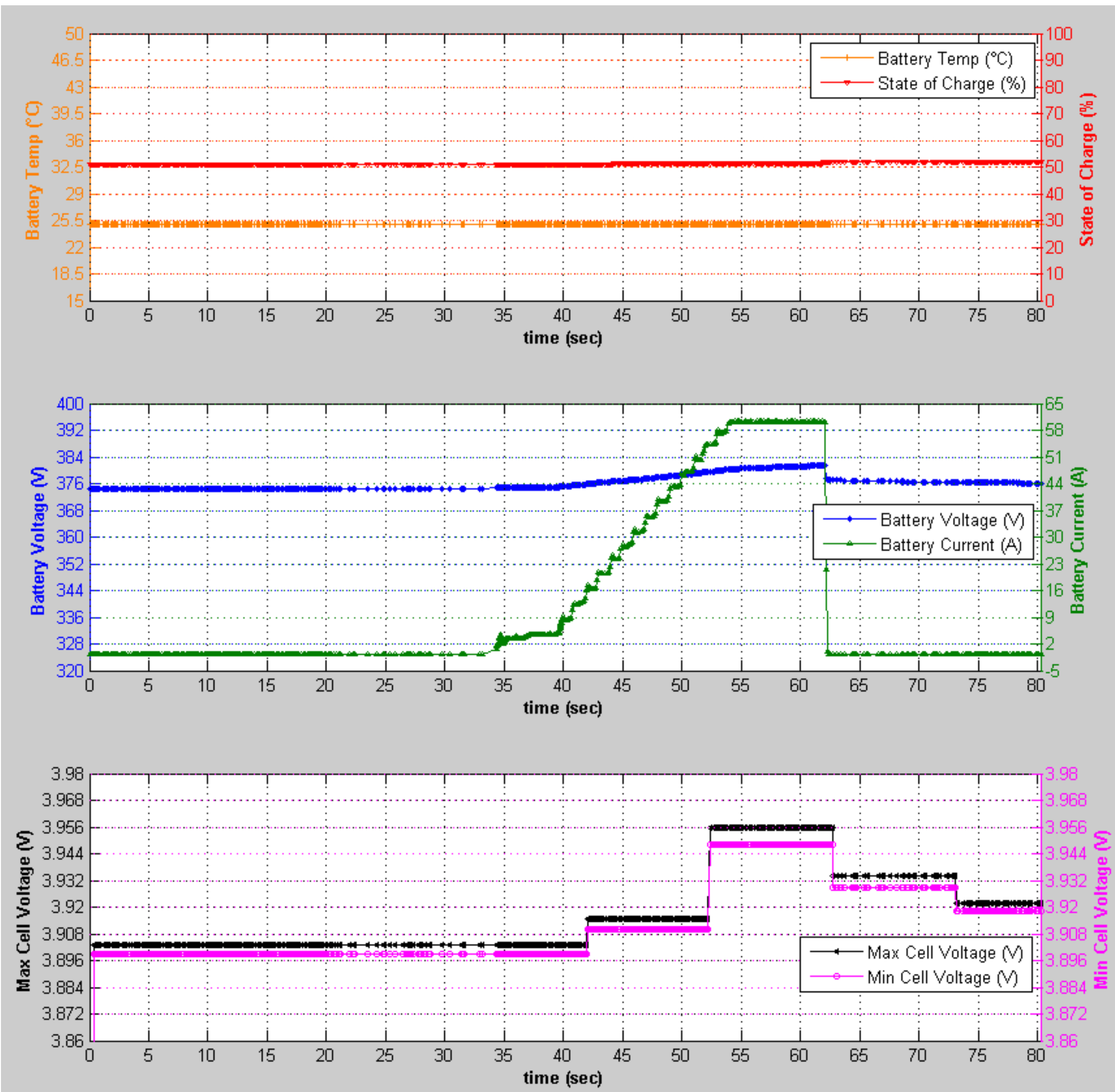

Figure 58: Control Pilot Short to Gnd During Charge Session Charge Data

4.12.2.3 Proximity Open During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. It should be noted that the breakout box's connector was modified and the proximity circuit was removed from this connector to allow manipulation of the proximity circuit from the breakout box. A charge session was started and allowed to reach maximum current (~60A). At around ~55 seconds into the test the Proximity line was opened. The charge session ended immediately as shown in Figure 59. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

LIM 805529 DC charging: Unexpected high voltage detected at charging socket

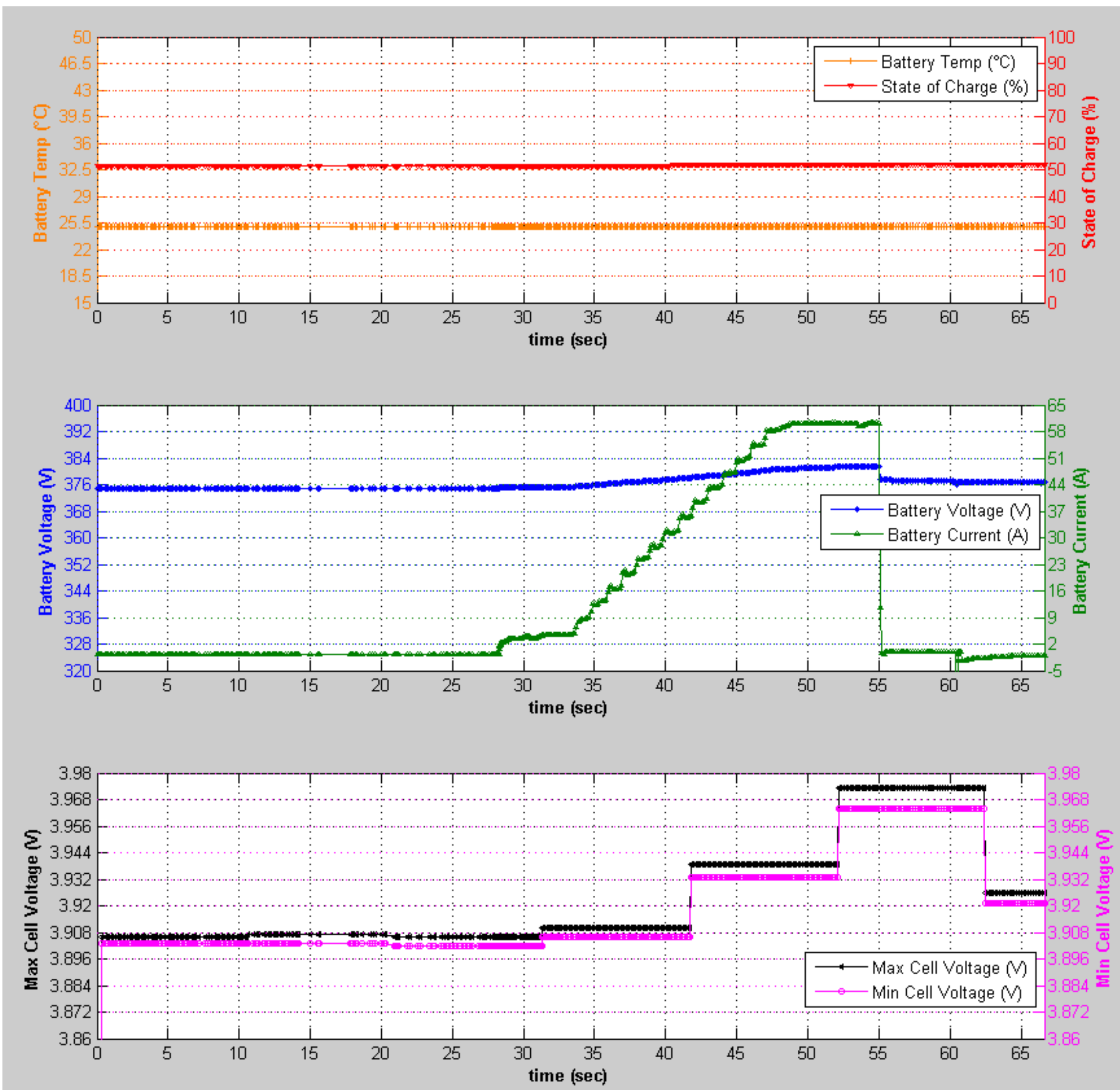

Figure 59: Proximity Open During Charge Session Charge Data

4.12.2.4 Proximity Short to Gnd During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. It should be noted that the breakout box's connector was modified and the proximity circuit was removed from this connector to allow manipulation of the proximity circuit from the breakout box. A charge session was started and allowed to reach maximum current (~60A). At around ~65 seconds into the test the Proximity line was shorted to earth ground. The charge session ended immediately as shown in Figure 60. No faults were displayed by the PEV or the charger.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

LIM 805529 DC charging: Unexpected high voltage detected at charging socket

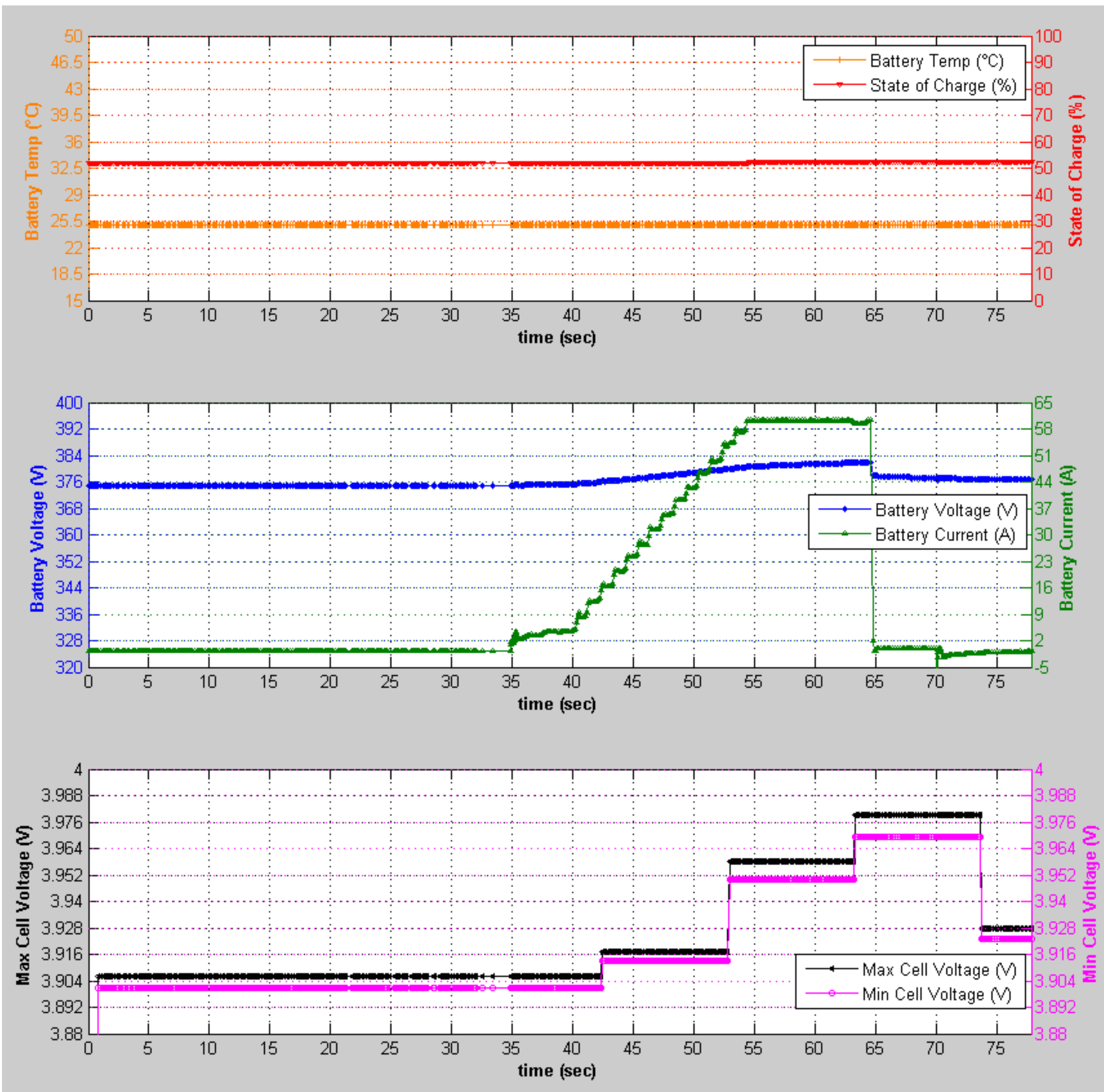

Figure 60: Proximity Short to Gnd During Charge Session Charge Data

4.13 Charge Connector Field Ground Connection Disturbance Test

4.13.1 Procedure Feedback and Revisions

By removing the connection between the PEV chassis ground and charger earth ground, the pilot, proximity, and PLC (communications/controls) circuits are affected.

4.13.1.1 Procedure refinement and removal of redundant test

Section 6.13.5 of the original documentation outlines two procedures. The first procedure is to remove the field ground between the PEV and charger during a fast charge session. The procedure needs to be updated with what switch to use (S1_GND) to perform this action. Table 6 of this section also needs updated.

The second procedure requires removing the field ground but using an external ground strap to connect the charger's earth ground to the PEV's chassis ground. The "removing the field ground connection, but maintain earth ground using external ground straps" test is redundant to the chassis ground offset test and has been removed. If the resistance of the connection between the charger earth ground to the PEV's chassis ground is negligible the systems will perform as normal. If the resistance is not negligible the same results will be seen as the results of the chassis ground offset test.

4.13.2 Validation Testing Results and Discussion

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and while the current was still ramping up at around ~55 seconds, the earth/chassis ground was disconnected. The charge session ended immediately as shown in Figure 61. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

> *EME 222822 Charge management function: Check Control message (859)*
>
> *LIM 805529 DC charging: Unexpected high voltage detected at charging socket*
>
> *IHKA E71465 No message (configuration of switch for driving dynamics 2, 0x3E6), receiver IHKA, transmitter DSC/ICM*

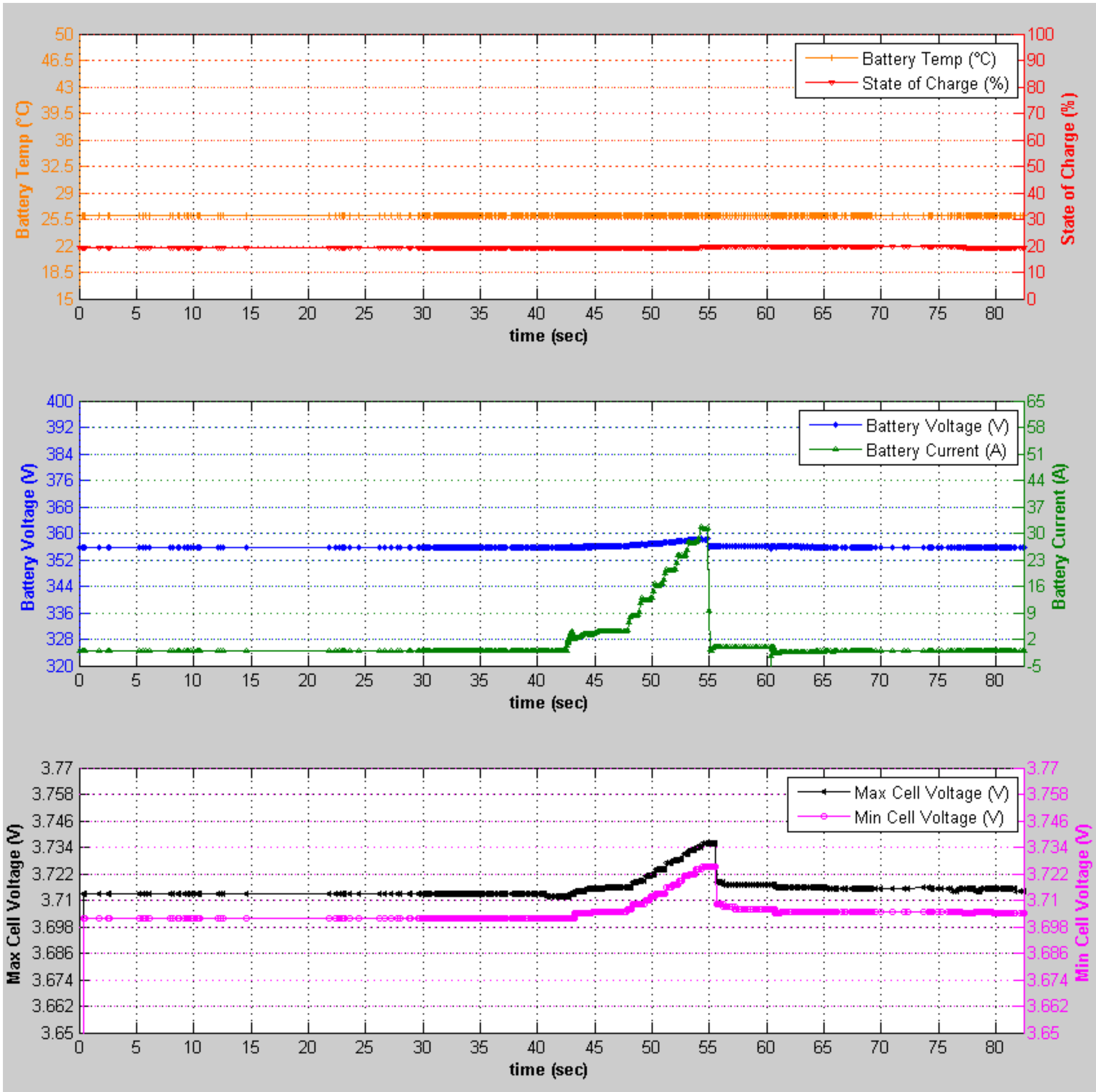

Figure 61: Charge Connector Ground Disturbance Charge Data

4.14 Charge Connector HV Connection Disturbance

4.14.1 Procedure Feedback and Revisions

The original research project documentation postulates that it is possible the HV DC connection between the DC charger and PEV can become degraded (increased resistance) or interrupted during a charge. Unfortunately, this specific test only focuses on HV interruption during a charge and not degradation (which is more difficult to emulate).

In order to test degradation high power series resistors would need to be added to the breakout box. These resistors would heat up but would not be at the interface of the actual CCS connector/PEV inlet HV connection points. During the Energy Transfer phase of a CCS charging session the charger is in a constant current mode. The PEV requests a target current and it is the job of the charger to regulate its output to maintain the target current from the PEV. Following ohm's law (I = V/R) in order to maintain a constant current as the resistance increases voltage must also increase. In other words, by adding additional resistance to the HV lines the output voltage of the charger will need to increase accordingly to maintain the target current request. This would work to the point of thermal failure of the coupler or hitting the maximum voltage output of the charger to maintain the target current request. If the actual output voltage of the charger reaches the maximum limit of the charger but could not sustain the target current request of the PEV, the PEV would probably end the charge session due to the charger's inability to follow the requested current signal.

An SAE J1772 CCS compliant connector is required to have an internal temperature sensor, while it is optional in the PEV CCS inlet. If there was additional resistance due to contact degradation the temperature sensor in a J1772 CCS compliant connector would measure the increase in temperature and the charger would likely disable its output. The temperature range for safe operation is not defined in SAE J1772; this is left up to the manufacturer to determine.

4.14.1.1 Evaluate opening (+), (-), or both DC lines

Section 6.14.5 of the original procedure documentation details the procedure for the charge connector HV connection disturbance test. Step 4 allows the procedure operator the choice of opening either the DC+ or DC- lines. It is believed this test should be performed three times. The first test should open the DC+ line and the second test should open the DC- line. The third test would be to open both the DC+ and DC- lines at the same time.

4.14.2 Validation Testing Results and Discussion

4.14.2.1 Disconnect HV+ During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and allowed to reach maximum current (~60A). At around ~85 seconds into the test the HV + line was opened. The charge session ended immediately as shown in Figure 62. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

> *EME 222820 Charge management function: Check Control message 874, unable to rapid charge*
>
> *EME 222822 Charge management function: Check Control message (859)*
>
> *EME 222842 Charge management function: Fault during the charging procedure*
>
> *EME 22287D DC charging: Switch contactors were unexpectedly opened or not activated*
>
> *LIM 805519 Load: PLC data line, communication fault*

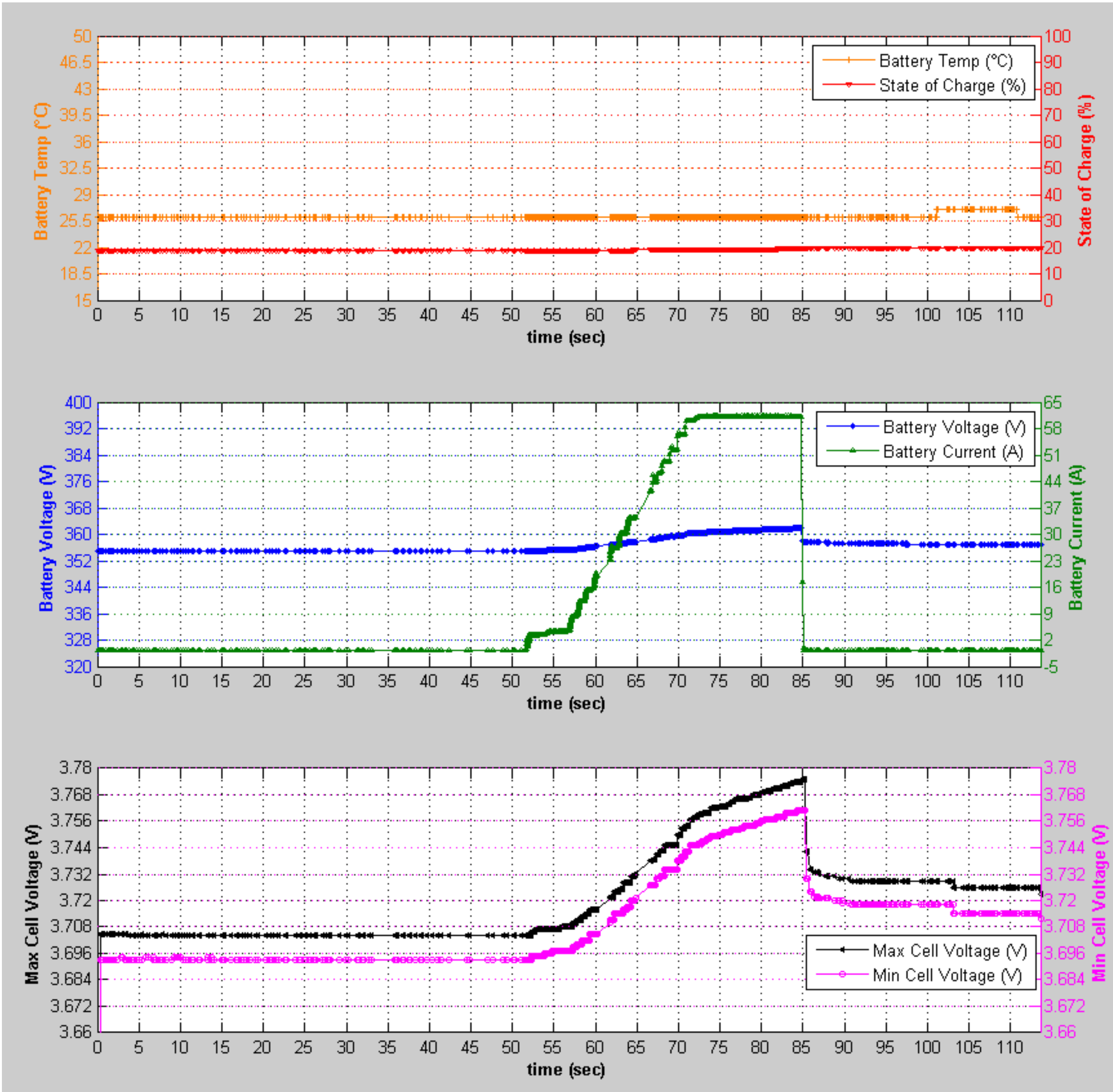

Figure 62: Disconnect HV+ During Charge Session Charge Data

4.14.2.2 Disconnect HV- During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and allowed to reach maximum current (~60A). At around ~82 seconds into the test the HV - line was opened. The charge session ended immediately as shown in Figure 63. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

> *EME 222822 Charge management function: Check Control message (859)*
>
> *EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulation signal change (adapter)*
>
> *LIM 805519 Load: PLC data line, communication fault*

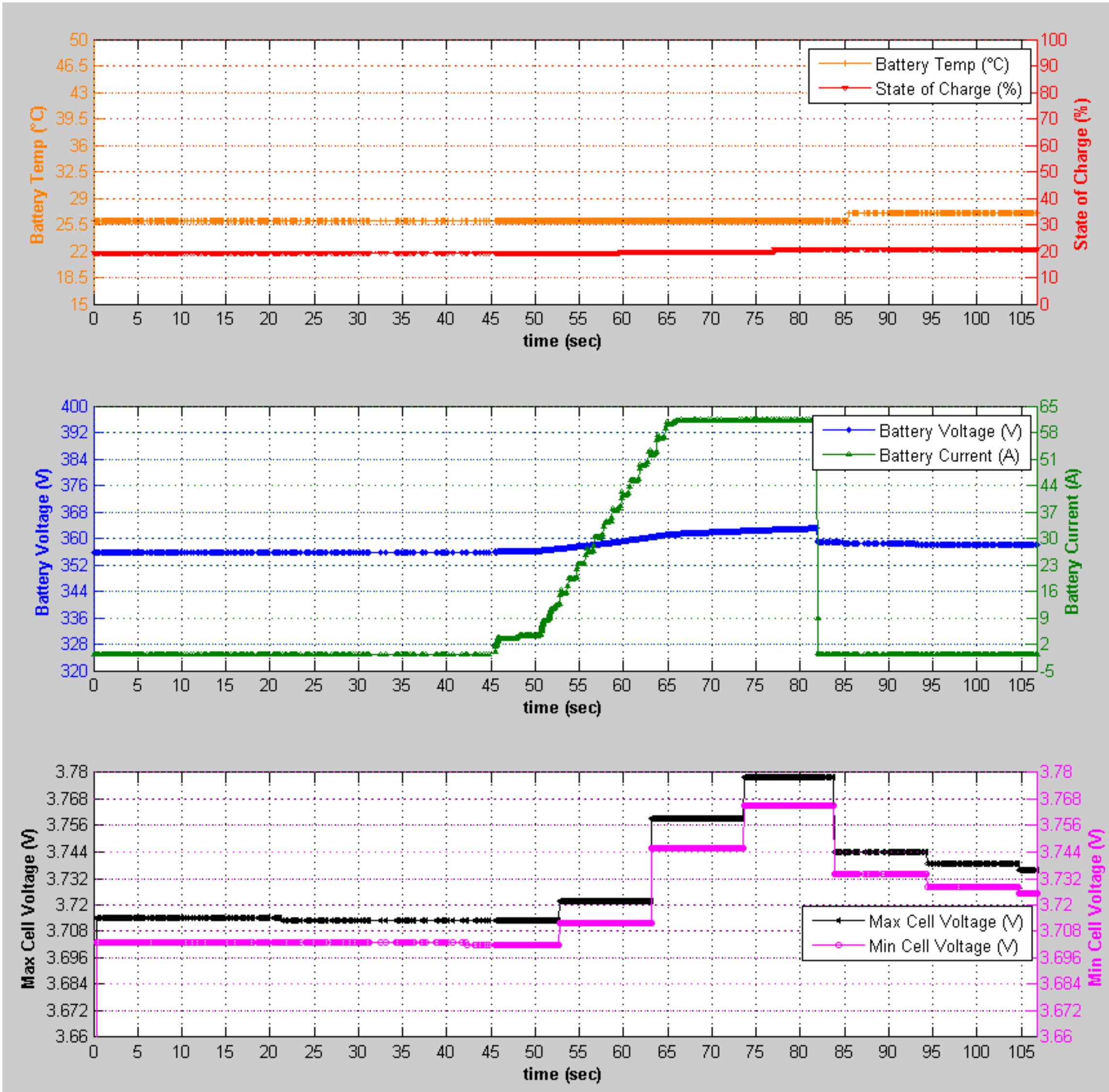

Figure 63: Disconnect HV- During Charge Session Charge Data

4.14.2.3 Disconnect HV- & HV+ During Charge Session

The IES charger was connected to the breakout box and the breakout box's connector was plugged into the PEV. A charge session was started and allowed to reach maximum current (~60A). At around ~70 seconds into the test the HV + and HV - lines were opened simultaneously. The charge session ended immediately as shown in Figure 64. No faults were displayed by the PEV. The charger display indicated an internal fault was detected.

The following DTCs were set.

EME 222822 Charge management function: Check Control message (859)

EME 222839 Charge management function: Charging procedure was terminated due to pulse-width modulation signal change (adapter)

LIM 805519 Load: PLC data line, communication fault

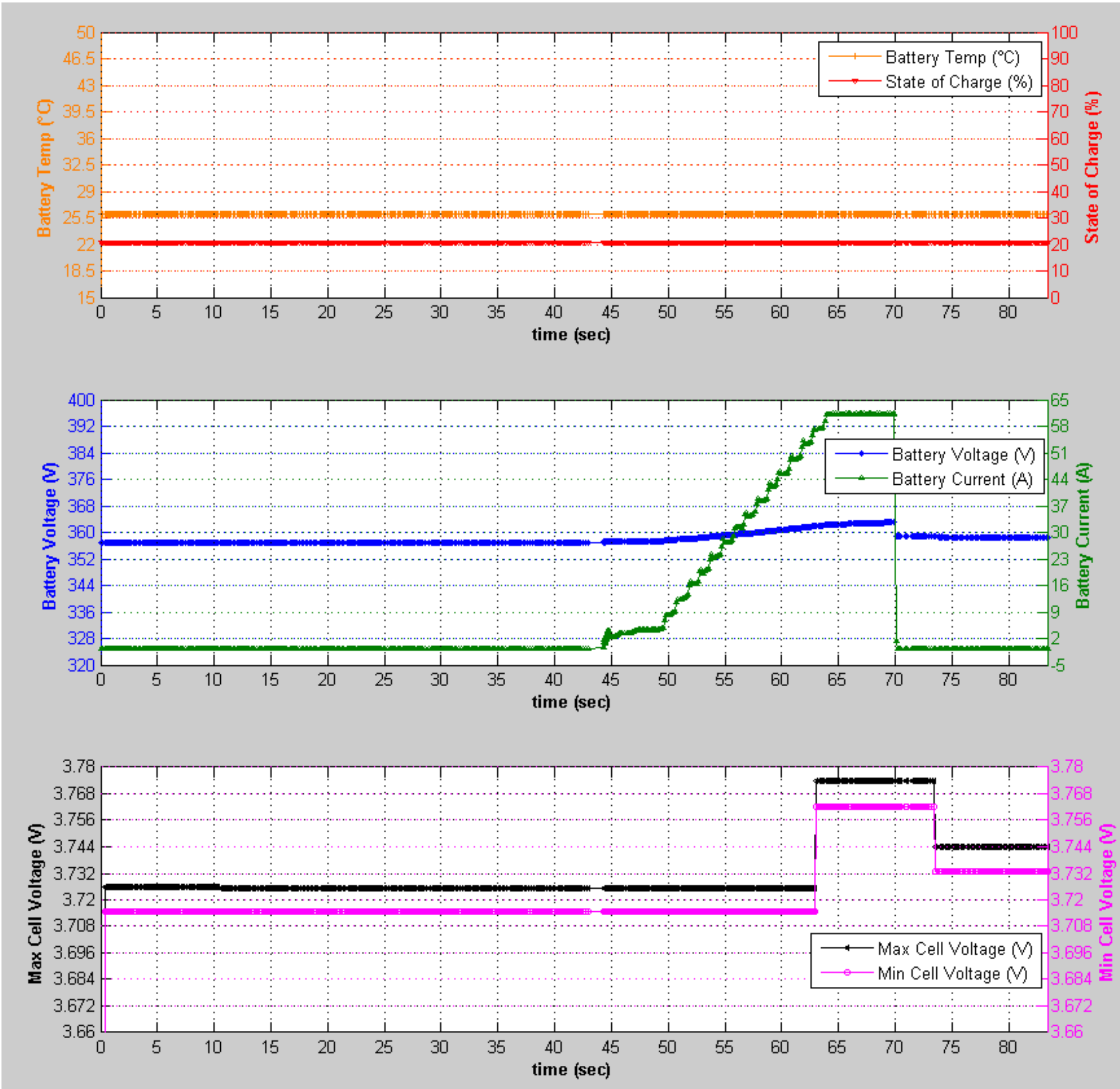

Figure 64: Disconnect HV- & HV+ During Charge Session Charge Data

4.15 Failed Battery Cooling/Heating System Test

4.15.1 Procedure Feedback and Revisions

This test assumes the PEV has an active RESS cooling/heating system, but can assess extreme temperature operation regardless of cooling system type with sufficient pre-conditioning.

4.15.1.1 Procedure Feedback

The procedures outlined in Section 6.16.3 of the original documentation requires modification of the PEV's cooling and heating system to reduce each system's effectiveness to heat or cool the battery pack. Unfortunately, by modifying the cooling system of the PEV, the risk of thermal runaway is real. Unlike other procedures performed in the original documentation that don't require modifications with internal PEV systems, this procedure requires tampering with the cooling/heating system of the PEV in order to inhibit the cooling or heating effectiveness of these systems, potentially leading to a thermal event or at the very least cell degradation of the PEV under test if other onboard systems do not detect these thermal issues. It may be advantageous to contact the OEM manufacturer to gather their feedback on the sample preparation and procedures before performing the tests.

4.15.2 Validation Testing Results and Discussion

4.15.2.1 High Ambient Temperature Test

The PEV was placed in Argonne's APRF thermal 4-wheel drive dynamometer test chamber at an ambient temperature of 35° C and allowed to soak for 24 hours. The test operator removed all refrigerant from the HVAC system since the pack is cooled by the air conditioner. As shown in Figure 65, the battery temperature was ~34.5° C at the start of the test. The ABC-170 was first used to charge the PEV for the first ~8.5 minutes of the test. Unfortunately, the ABC-170 charge system was configured to be current limited to 5 A from a previous test. In order to troubleshoot this issue the IES charger was brought into the chamber and a session began at ~9 min into the test and allowed to reach a maximum charge current of 60 A before that session was ended. The configuration for the ABC-170 was then updated to allow a maximum of 150 A and a new session was started at ~18 minutes into the test.

Normally at ~12% SOC the PEV would charge at a maximum 125 A, however the BMS curtailed the charge to 90 A and then pulled back the charge current over a 2 min time span until leveling off at ~70 A at around 20.5 minutes into the test. During this third charge session the pack temperature rose from ~34.5° C to ~36° C.

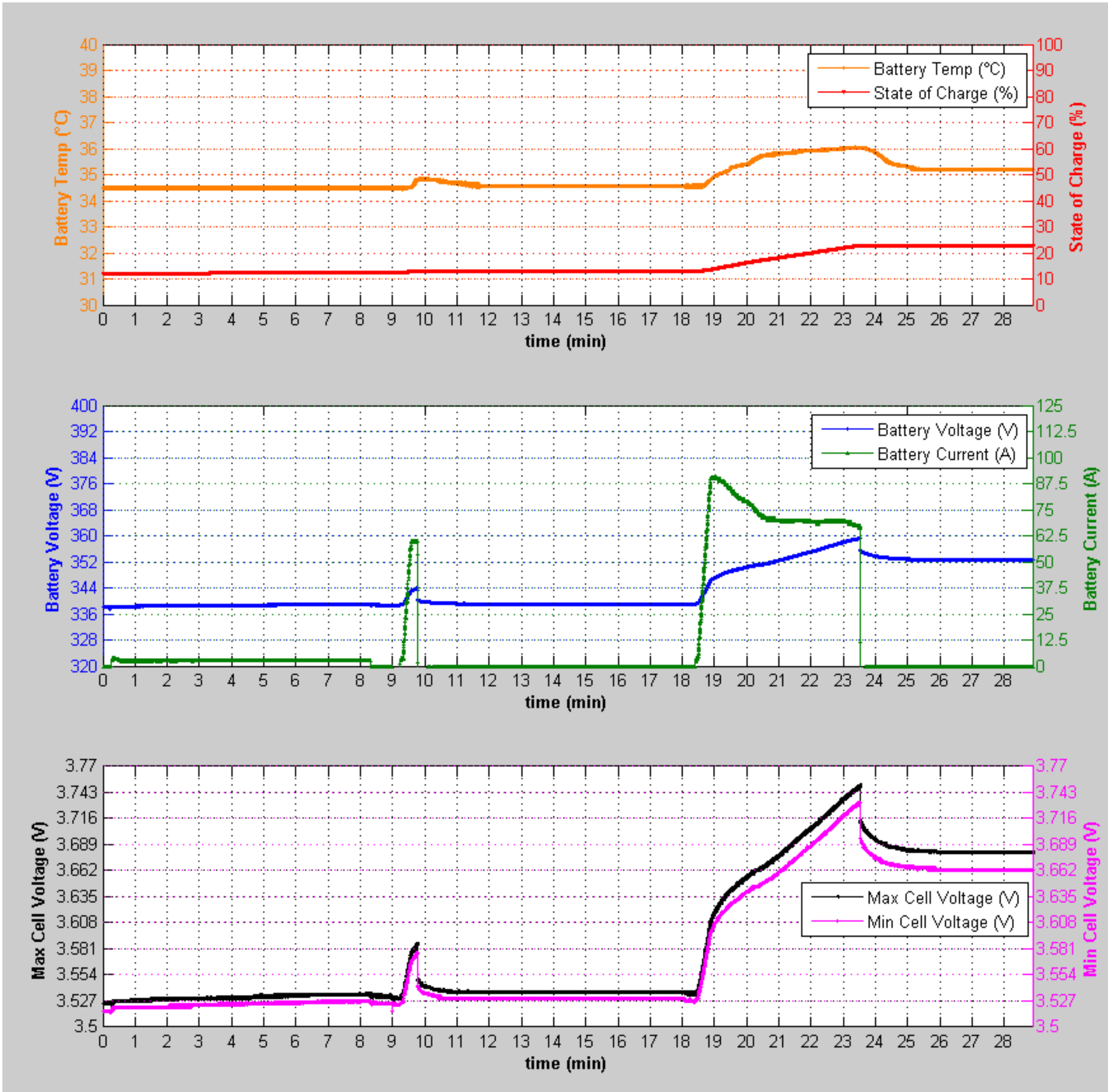

Figure 65: High Ambient Temperature (No Coolant) Charge Data

The test operator then replaced the refrigerant and using the ABC-170 performed another charge session to witness how the charge rate would be affected with refrigerant at high temperatures. As shown in Figure 66, the maximum charge current at the beginning of the charge session was curtailed to ~90 A instead of the maximum 125 A that the PEV usually charges at with the ABC-170 and rolls off to ~75 A before slowly increasing. At ~10 minutes into the test the charge current levels off at ~90 A. Once the battery SOC reaches ~70%, the charge current starts to decrease logarithmically and pack temperature seams to decrease linearly.

Retrieved DTCs from the PEV (see "High Ambient Temperature Charge.pdf"). The following DTCs were set.

Code	Description	Mileage	Class
S 0240	No communication possible with: Electric-machine electronics	720	
21F251	High-voltage battery: Loading cancelled due to excess temperature in the battery cells	12628	Information
804363	Refrigerant pressure sensor: Short circuit to ground	12586	
805519	Load: PLC data line, communication fault	12628	Information
D1AD13	Signal (status of I-Brake parametrisation, 0xEF) invalid, transmitter DSC	12586	Information
D1AD36	Signal (braking torque, 63.1.4) invalid, transmitter DSC	12586	Information
E06C43	Signal (warning object coordination status, 0x21F) invalid, transmitter DSC / ICM	12586	Information

.

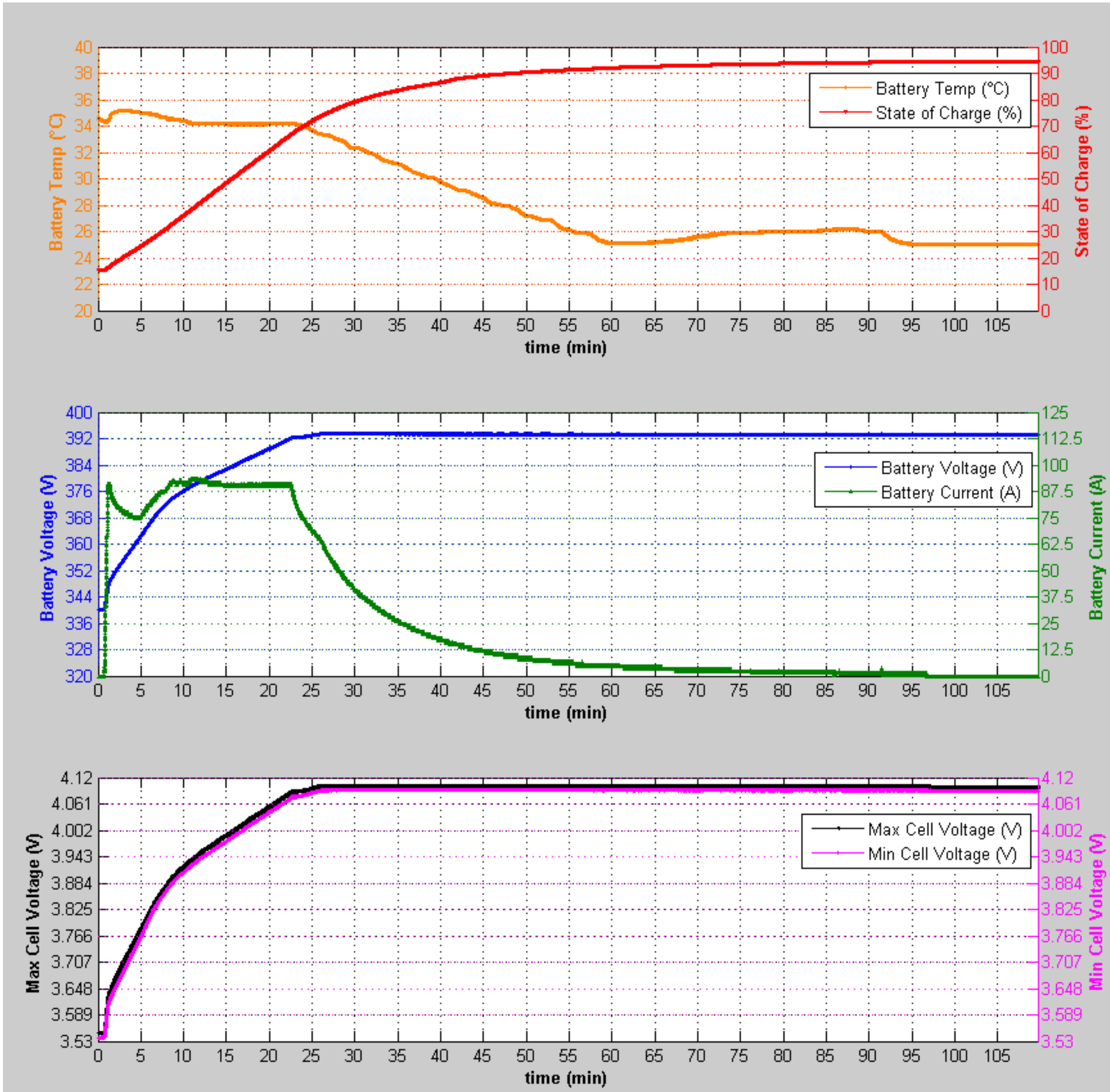

Figure 66: High Ambient Temperature (Coolant) Charge Data

4.15.2.2 Low Ambient Temperature Test

This test was not performed because ANL engineers have never witnessed the PEV heating the pack at any temperature the thermal chamber was capable of reaching. Additionally, the vehicle de-rating at cold temperatures was observed during validation of the parallel RESS protection procedure validation and thus is expected to be similar.

4.16 BMS Internal Fault Detection Test

4.16.1 Procedure Feedback and Revisions

This procedure focuses on specific RESS tests to determine how the BMS reacts and requires intimate knowledge of the RESS. This procedure would probably require the active support of the RESS manufacturer and although it is safety significant, the procedure may be a little too involved for these types of functional safety tests. This procedure may be best suited in the RESS Safety Evaluation Procedure document or in direct consultation with a vehicle/battery supplier.

4.16.1.1 Procedure Feedback

The procedures outlined in Section 6.17.5 of the original research documentation includes emulation of cell over-voltage, cell under-voltage and a cell temperature fault. Additional tests are allowed under this procedure to cover all BMS related internal fault detections.

The pass/fail criteria could be a little more specific and require for each emulated fault the DC charge session ends in a safe manner. However, without prior knowledge of the fault handling of the BMS and other CCS systems it is hard to determine how the system should operate (i.e., by emulating a cell under-voltage fault, is the PEV programmed to end a DC charging session?). While important, emulation of individual cell issues in even a laboratory setting requires intrusive instrumentation and new connections in order to apply current/voltage/etc. to a single cell connected within a battery pack. It is recommended that in lieu of an actual test, the procedure request information from the OEM/supplier regarding the individual cell limits used by the BMS and the associated battery system response (de-rate versus contactor open). These battery system responses can then be used to identify the subsequent charge system behaviors, again in consultation with the OEM/supplier of the vehicle's charging system.

4.17 Over-Charge Test

4.17.1 Procedure Feedback and Revisions

Although the name of the test is "over-charge" the rationale in the original documentation describes an "over-current" situation. The intent of this procedure is to try to "over-charge" the RESS by supplying more current to the battery near the end of a charge session to exceed its capacity rating. Providing an over-current for a long enough duration during charging, the battery's capacity may be exceeded.

4.17.1.1 Procedure Feedback

Section 6.18.5 of the draft project documentation outlines the steps to try to over-charge a RESS by applying a 10% higher charge current then the requested target current at a battery SOC of 90%. The original procedure falls short of defining a specified time or end SOC value to continue applying a 10% over-current. The revised procedure applies a 10% over-current @ 90% SOC until the PEV ends the charge session.

It should be pointed out that most PEV DC charge systems are monitoring the actual charge current and compare it to the requested charge current. Each OEM will have a tolerance and if that tolerance is exceeded the PEV will end the charge session. This tolerance is not specified in the SAE J1772 standard so it will be unknown for each PEV tested. Furthermore, individual batteries and vehicles may be more or less sensitive to overcharge, so again the actual current limit may vary significantly vehicle-to-vehicle. For example a 10% increase in the actual charge current from the requested current may exceed the tolerance for PEV A but not exceed the tolerance of PEV B. In this scenario PEV A will never get the chance to be over-charged because the charger current tolerance was exceeded and the session ended. In the case of PEV B, charging may be allowed to continue at a 10% increase from the target current request, however once the BMS detects the RESS has reached 100% SOC the PEV will end the charge session. There might not be a scenario in which the charger would be able to induce an over-charge hazard unless the PEV's system was modified.

Section 6.18.6 of the draft NHTSA document details the end of test procedure in which the PEV is stored in an open space for 72 hours to be monitored by a thermal imaging camera. After 72 hours the battery's SOC is to be discharged to 50% and then monitored for an additional 48 hours. It is believed this duration may be excessive and possibly not even required unless the RESS was actually significantly over-charged (SOC well above 100%). It is also recommended that this test conclude, regardless of current vehicle operating state, if the battery SOC is estimated to be above 130%. Only very specific cases, under direct consultation with an OEM/supplier, would merit charging a battery over 130% SOC under the guise of safety evaluation.

4.17.2 Validation Testing Results and Discussion

For this test the ABC-170 charge system was used and configured to apply 10% more current then requested once 90% SOC was reached. The data logging did not begin until after reaching a max current of ~120 A at ~60% SOC as shown in Figure 67. At ~ 90% useable SOC the PEV requested 15A and the ABC-170 charge system supplied 16.5 A to the PEV. The PEV did not stop charging and continued to the charge session until fully charged (applying 10% more current then requested). No DTCs were set for this test. Given that the PEV was fully charged with no issues, the PEV was not stored in an open space area and monitored for heat generation for 72 hours.

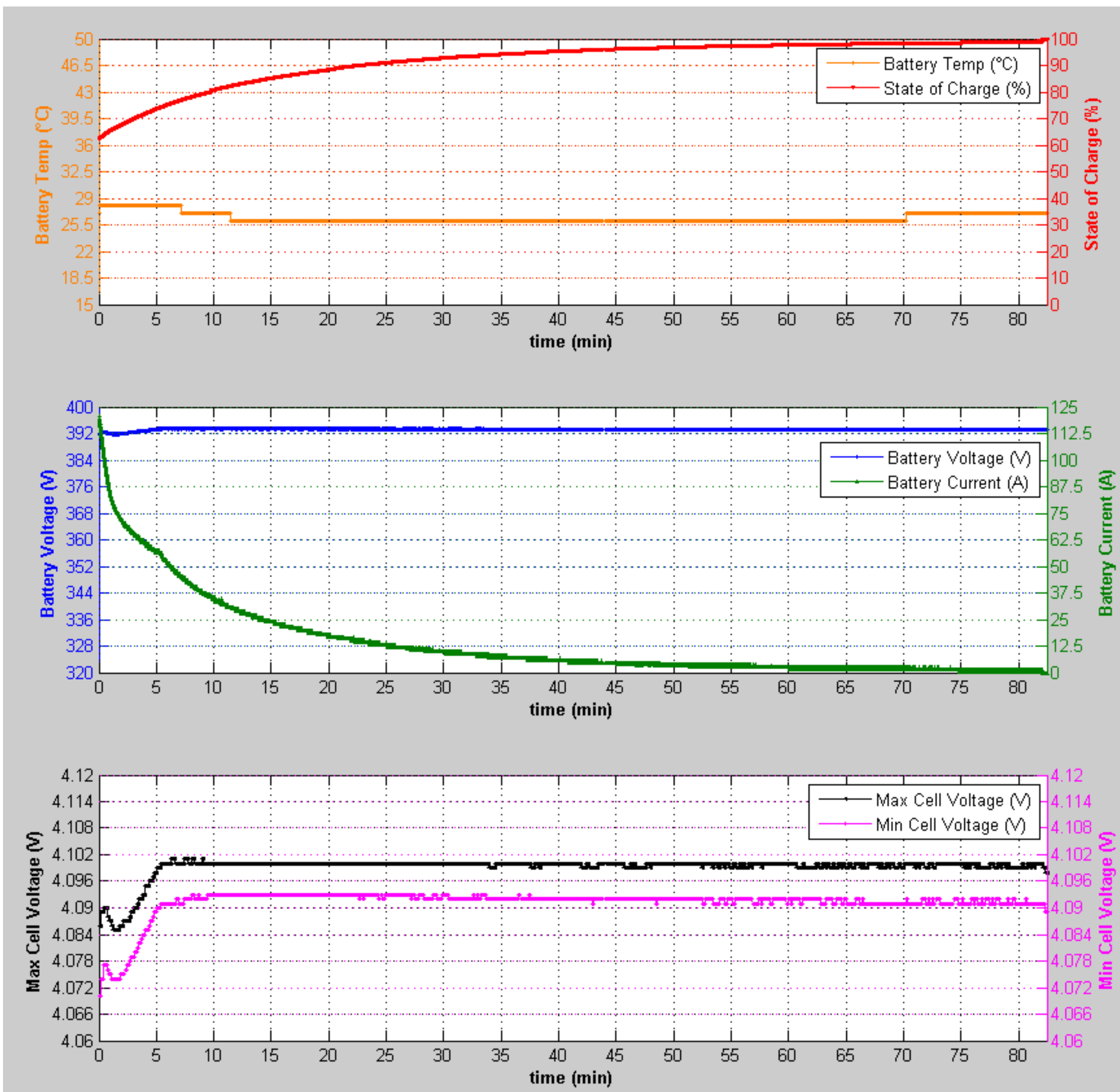

Figure 67: Over-Charge Test Charge Data

4.18 Over-Current Test

4.18.1 Validation Testing Results and Discussion

For this test the ABC-170 charge system was used and configured to apply an over current when the PEV requested current reached 100 A. The initial configuration for this test was setup in manner that once 100 A was requested by the PEV the output current applied by the ABC-170 charge system jumped to 110 A. Figure 68 shows that around ~55 seconds into the test, the jump to 110 A occurred and the PEV continued to charge with a charge current of +10 A greater than the actual requested current. This charge session was then ended by the test operator. Although the PEV continued to charge it was noted by the test operator that in the ABC-170 charge system logs the PEV sent the following error code when shutting down the session: "Charging Current Differential, charger cannot maintain an output current that fulfills the current request."

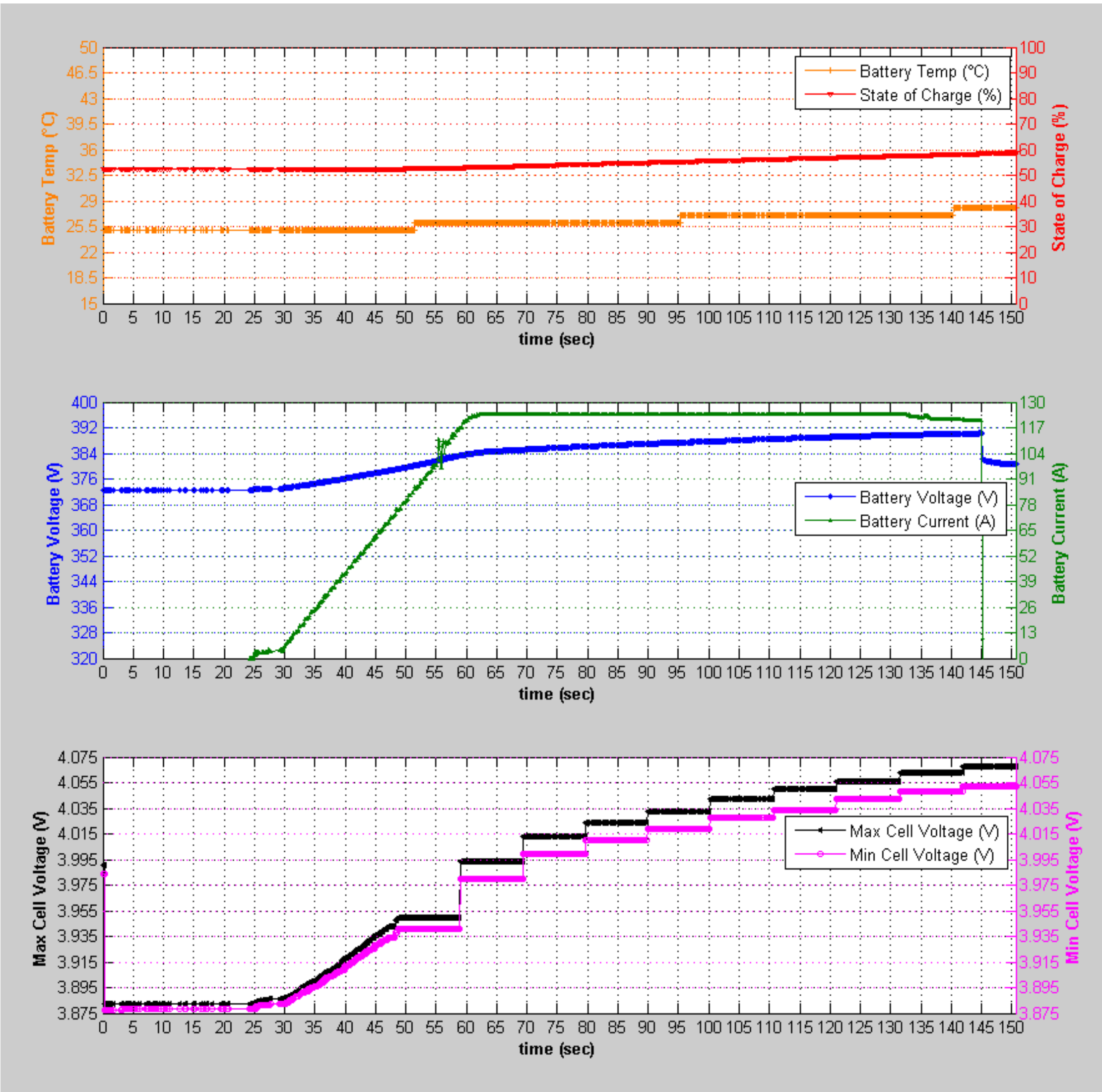

Figure 68: Over-Current Test Charge Data (10A Over)

Following the procedure guidance in the procedure to increase the current level until a fault is initiated, for the second test, the ABC-170 system was reconfigured to apply +20 A above the actual current request when the PEV's demand reached 100 A. Figure 69 shows that around ~54 seconds into the test, the jump to +120 A occurred and the PEV instantly shutdown the charge session.

Retrieved DTCs from the PEV (see "Over-Current.pdf"). The following DTC was set.

EME 222842 Charge management function: Fault during the charging procedure

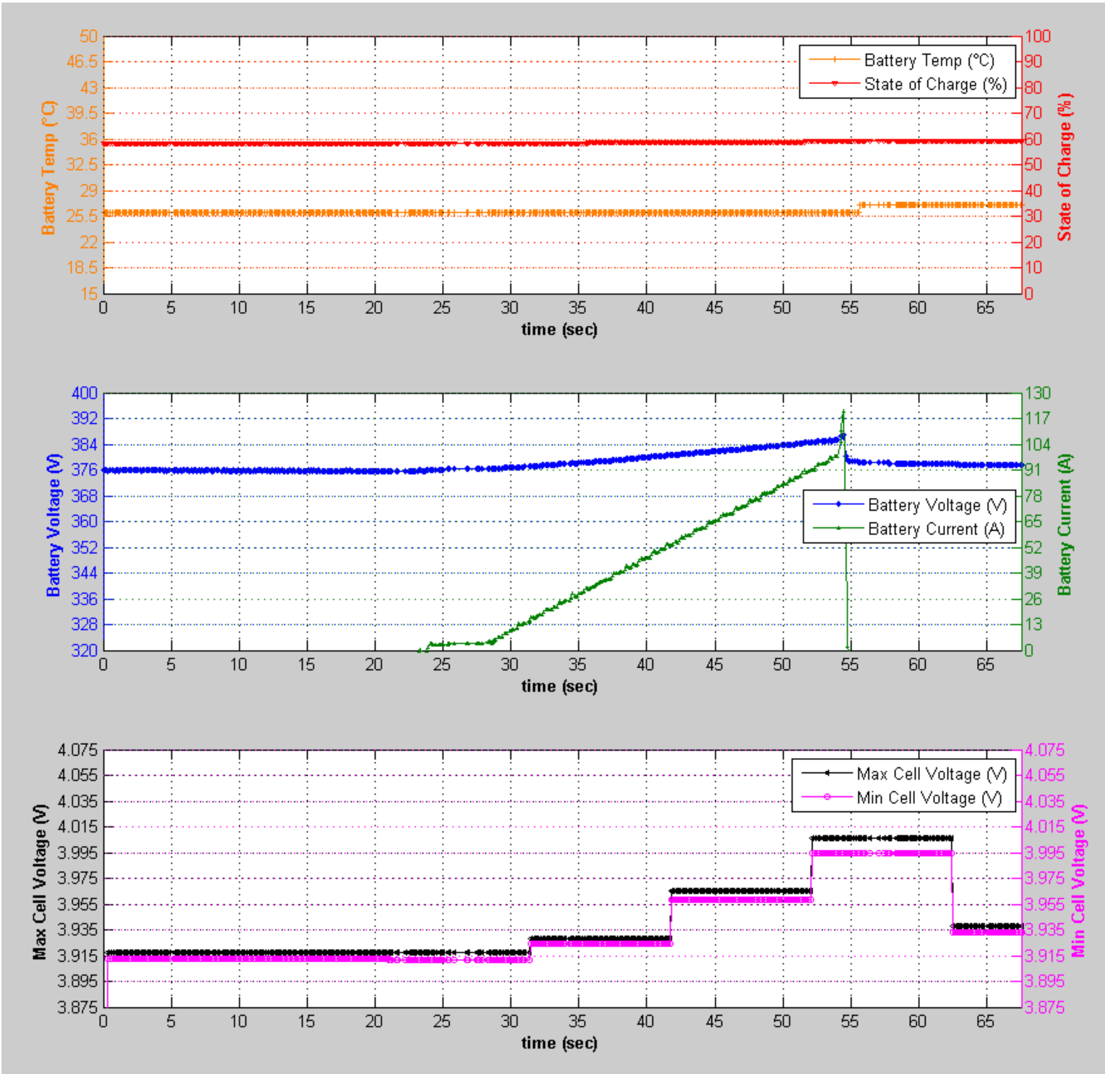

Figure 69: Over-Current Test Charge Data (20A Over)

4.19 Reverse Power Flow (Under-Voltage) Test

4.19.1 Validation Testing Results and Discussion

The ABC-170 charge system was used in this test and configured to sink instead of source the requested current from the PEV. The first current request from the PEV occurred around ~23 seconds into the test as shown Figure 70. The ABC-170 was able to sink a maximum of ~5A before the PEV opened its contactors, thus ending the charge session. The LED ring around the inlet blinked red and a message on the dashboard indicated the PEV was unable to charge.

The following DTCs were set.

EME 222834 Charge management function: Check Control message 804, unable to charge

EME 222842 Charge management function: Fault during the charging procedure

LIM 805519 Load: PLC data line, communication fault

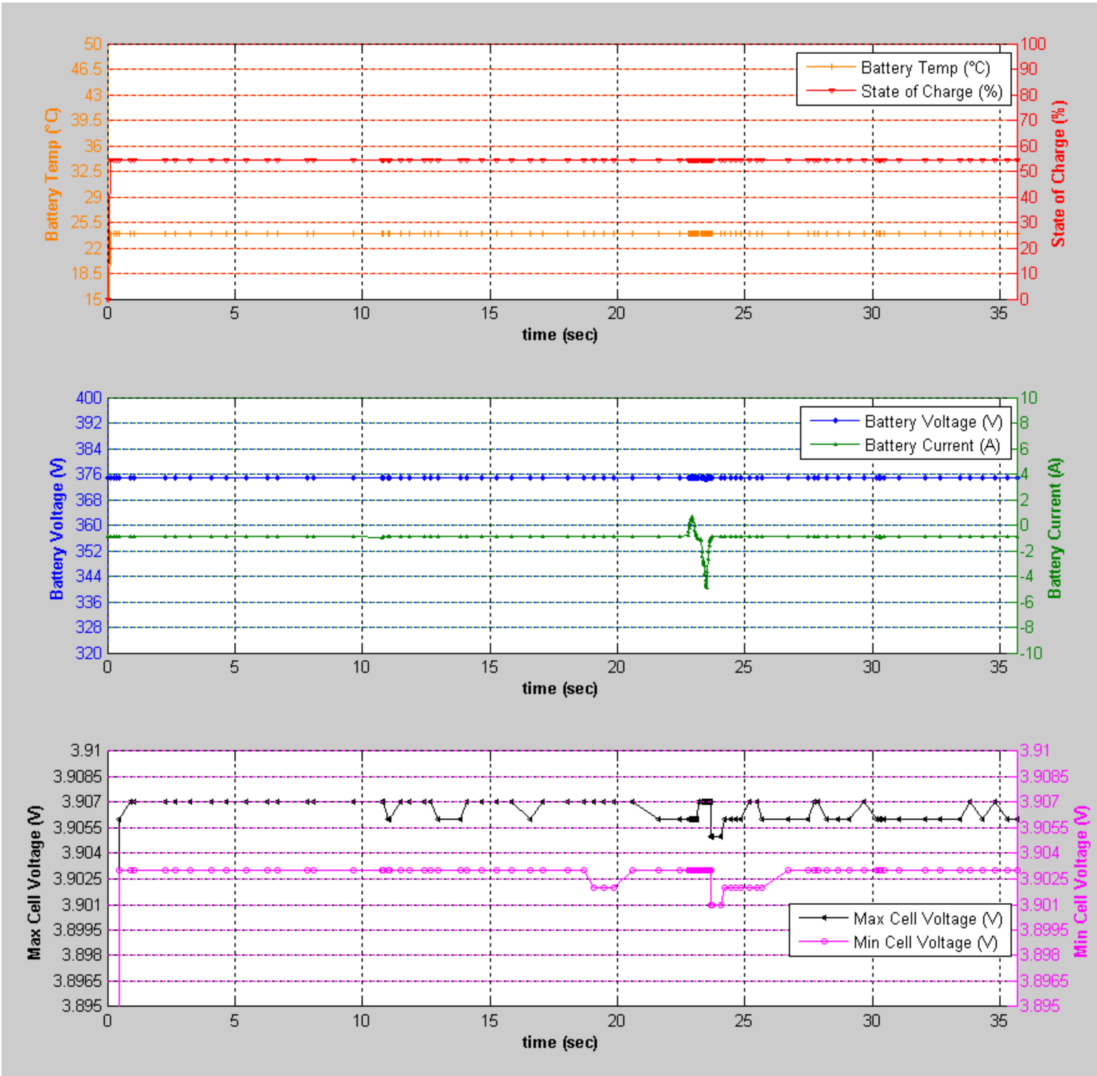

Figure 70: Reverse Power Flow Test Charge Data

4.20 Elevated PEV Inlet Temperature Test

4.20.1 Validation Testing Results and Discussion

The IES charger was used for this test with a 120 VAC heater tape. Using a thermocouple wrapped between the heater tape, the temperature of the heater tape was allowed to reach ~ 260° F and allowed to soak for ~ 5 min before a charge session was initiated. Figure 71 shows the charging data and the inlet temperature as reported by the IES charger. The internal temperature of the connector reached a maximum of ~43° C (109.4 ° F) before the test operator shutdown the charge session. The thermal resistance of the connector material caused a delay when heating up the internal air of the connector. However, from the data of Figure 71 it can be seen the inlet temperature was still rising when the charge session ended. It is unknown at what inlet temperature the IES charger is programmed to stop the charge session. It is also unknown whether the PEV monitors the temperature of the CCS inlet. As a proof-of-concept, these results validate the application of external heating to investigate a vehicle/charger's response to elevated inlet temperature. The specific temperature used for one of the pass/fail criteria of is well outside the scope of this work, but nonetheless the test appears achievable within the context of these procedures.

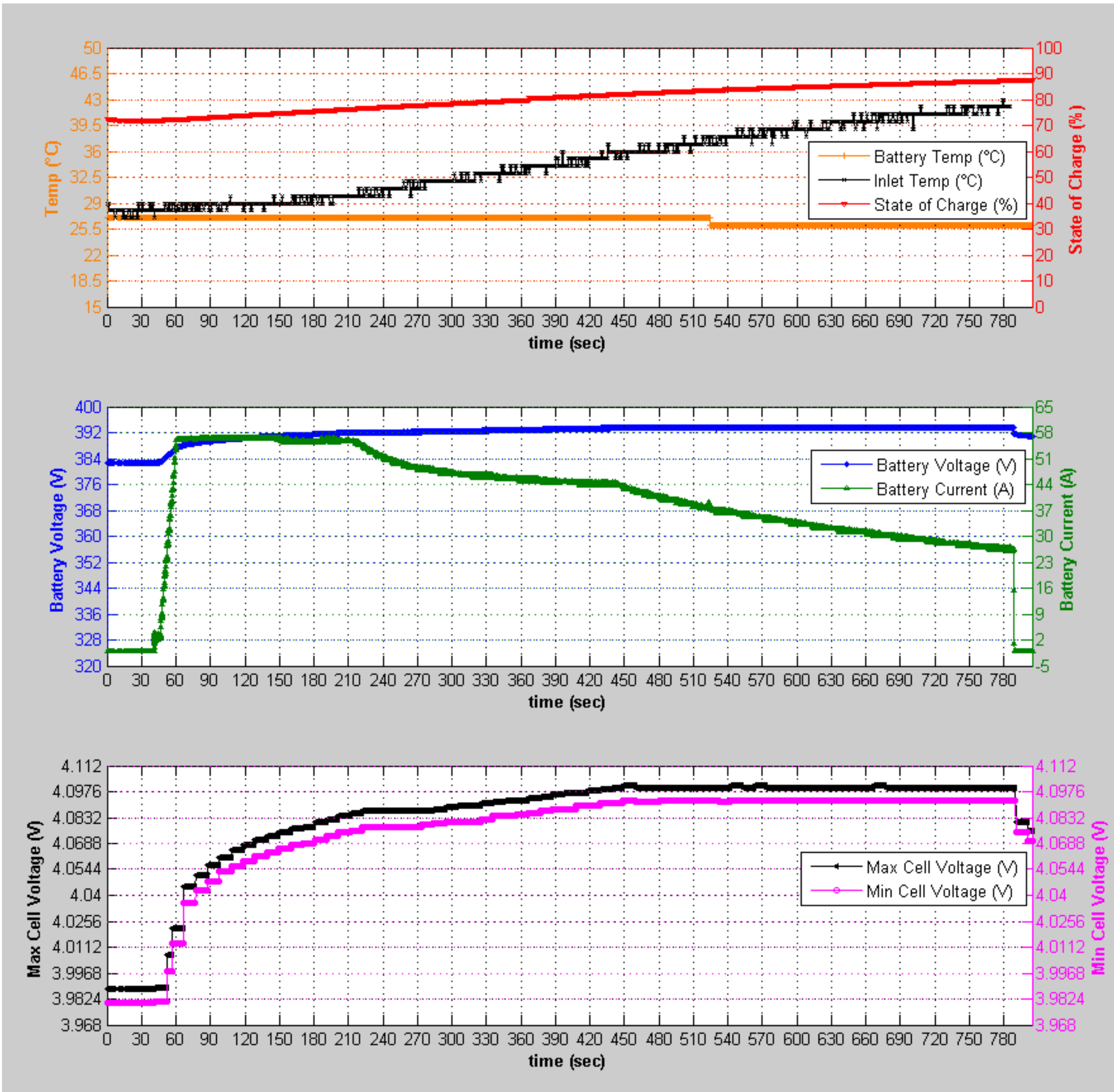

Figure 71: PEV Inlet Temperature Test Charge Data

No DTCs were set for this test.

5 AC Charging Test Procedure Discussion, Feedback, and Validation Testing

5.1 Chassis Ground Offset Test

5.1.1 Procedure Feedback and Revisions

5.1.1.1 Potentiometer versus fixed resistance values

Similar to the DC procedure, a 20 kΩ potentiometer is to be used in place of the four fixed resistors in the test breakout box. This will allow the technician to test a wider range of offset resistances and to capture the results and ensure that a range of acceptable and out-of-specification resistances can be evaluated for different vehicles. The logic and reasoning behind this revisions is similar to the points discussed in Section 4.2.1.1.

5.1.2 Validation Testing Results and Discussion

5.1.2.1 Chassis Ground Offset Before Charging

The figure below shows the results of the Chassis Ground Offset Before Charging Test for the BMW i3 DUT across a range of low-to-high resistance offset values. While the resistances to be used are allowed to be selected by the manufacturer or test operator, the initial values of 24, 47, 100, and 1,000 Ohm were found to provide enough variation for all vehicles tested. In the figure below, it can be clearly seen that and AC charge session does not initiate for either the 100 or 1,000 Ohm offset conditions, whereas the lower Ohm offset conditions lead to a normal charge session. In all cases, the vehicle was in a safe state throughput testing, whether simply staying in stand-by mode or running a charge session until the test operator ended testing manually.

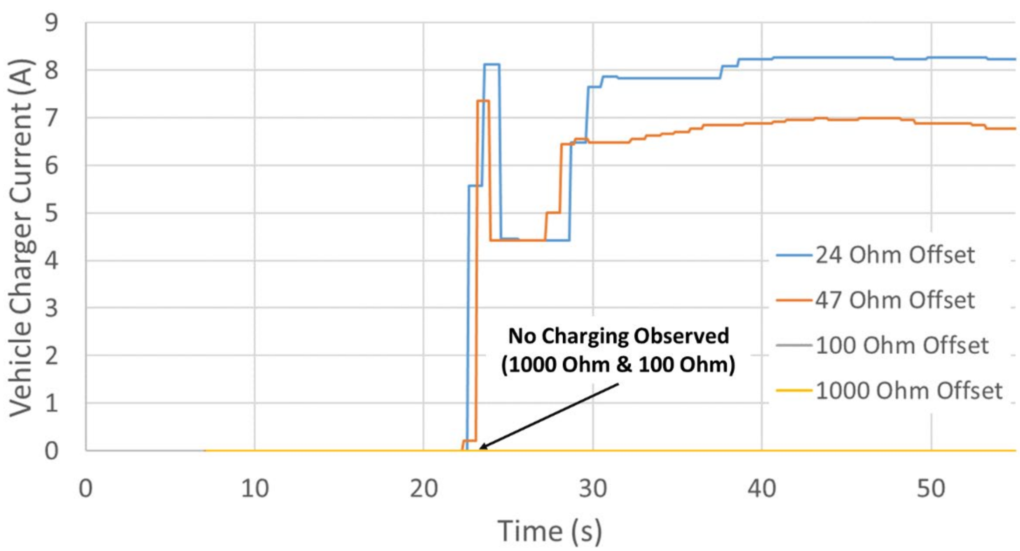

Figure 72: BMW i3 Chassis Ground Offset Test Before Charging Results (no charging observed at 100 and 1,000 Ohm)

In contrast to the BMW i3 results and in line with the discussion in section 4.2, the figure below shows offset testing results for the Toyota Prius Prime. In this case, the vehicle does allow charging for the 100 Ohm offset case as compared to the i3 that does not allow for charging. As with the i3 testing, the vehicle stated in an safe state throughout all test conditions.

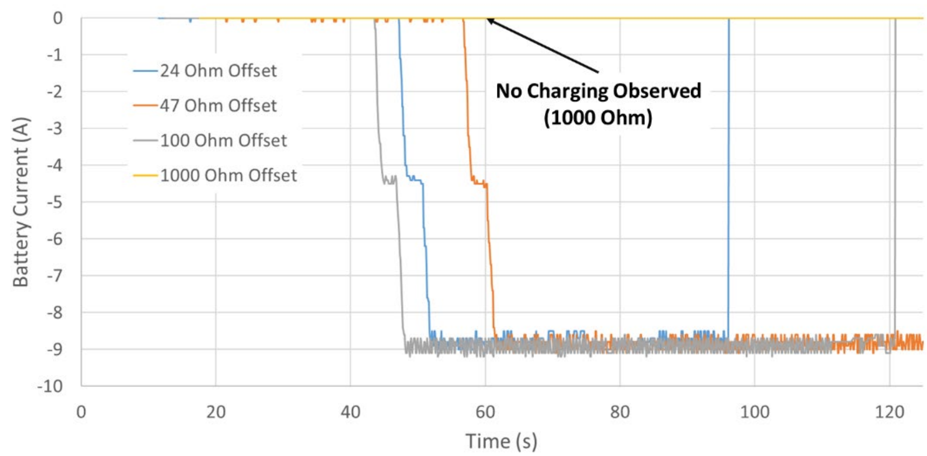

Figure 73: Toyota Prius Prime Chassis Ground Offset Test Before Charging Results (no charging observed at 1,000 Ohm)

5.1.2.2 Chassis Ground Offset During Charging

Figure 74 below shows the results for Chassis Ground Offset testing for the Honda Accord PHEV across the same range of offset resistances. At roughly 117 seconds, the ground offsets are introduced and in the 1,000 Ohm case, charging can be seen to rapidly halt as evidenced by the 0A battery current. For the lower resistance offset cases, the vehicle continued charging until testing was stopped manually. For this vehicle as well as all of those tested, the vehicle remained is a safe state during all test conditions.

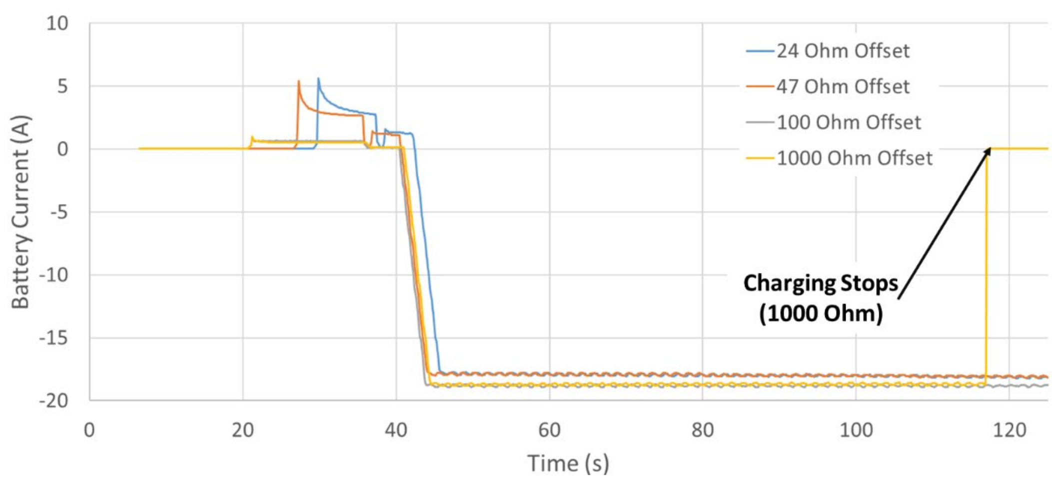

Figure 74: Honda Accord Chassis Ground Offset Test During Charging Results (no charging observed at 100 and 1,000 Ohm)

5.2 12 Volt System Undervoltage Test

5.2.1 Procedure Feedback and Revisions

5.2.1.1 Clarify Removal of All DC-DC Connection Points to 12V System

Certain vehicles within the validation fleet had two DC-DC converters, one connected to the HV battery and one connected to the charger assembly. Since the undervoltage test requires that all vehicle-provided DC-DC power connections be removed, a clarifying note has been added to the procedure that all DC-DC connections must be removed to ensure the actual 12V system voltage is within the desired test settings.

5.2.2 Validation Testing Results and Discussion

Figure 75 below shows an example results from the Honda Accord PHEV procedure validation testing. As indicated by a non-zero HV charge current, the vehicle charge session is active until between 8.4 and 7.7 volts. At this reduced voltage level, charging was immediately halted at evidenced by the zero HV charge current at roughly 710 seconds. For this and all other vehicles tested, the low voltage situation always lead to a halt in charging, although the actual voltage level at which charging was halted varied from vehicle to vehicle. All vehicle entered a safe state when testing was halted which no exposed high voltage or unexpected charging input to the RESS.

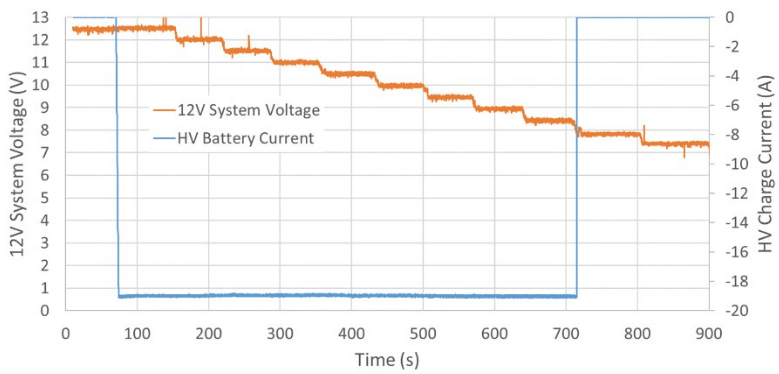

Figure 75: Honda Accord PHEV 12V Undervoltage Results (charging stopped between 8.4V and 7.7V)

Figure 76 below shows an example implementation for the DC-DC removal and subsequent connection to the offline 12V system needed to step through the voltage levels to exercise the low (and high) 12V system tests. The left figure shows the connection from the 12V system to the offline supply and the right figure shows the removal point for the connection between the HV battery connection and the DC-DC converter. While each vehicle was successfully validated using the described procedure, it should be mentioned that accessing the 12V system and DC-DC converter connection point varied in difficulty and sometimes required the removal of certain other vehicle parts.

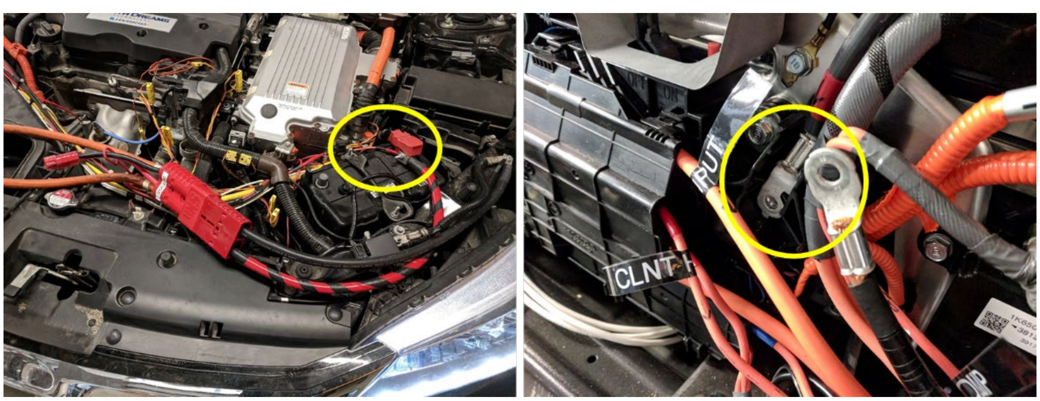

Figure 76: Honda Accord PHEV External 12V System Access Point (left) and DC-DC-to-12V System Disconnection Location (right)

Most vehicles tested also showed a vehicle diagnostic (fault) message attributed to the perceived low 12V system voltage, but not necessarily anything directly related to a charging fault, since this fault could occur at a different time as well. Shown in the figure below for the Honda Accord, several DC-DC converter errors were observed following the Undervoltage test and needed to be reset prior to additional testing.

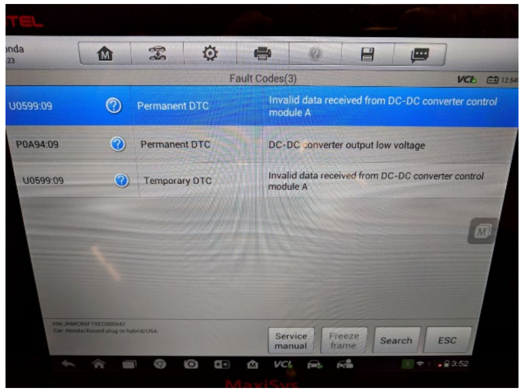

Figure 77: Honda Accord PHEV Diagnostic Tool Screenshot Showing DC-DC Faults

As mentioned above in the validation feedback, one of the test vehicles had a second DC-DC converter connected to the charger output. In this case, despite the removal of the main DC-DC connection, the vehicle still elevated the 12V system voltage above the desired level required to execute the Undervoltage test. Figure 78 highlights this observation where it can be seen that around 192 seconds the 12V system voltage increases as opposed to the desired decrease commanded by the offline system. To remedy this issue, the fuse for the secondary DC-DC converter was removed and testing was then repeated. Despite the removal of the DC-DC fuse, the system allowed for charging above the 12V system threshold and then halted charging when the 12V system voltage went below the threshold. As with other tests, all vehicles remained in a safe state for the entire duration of testing.

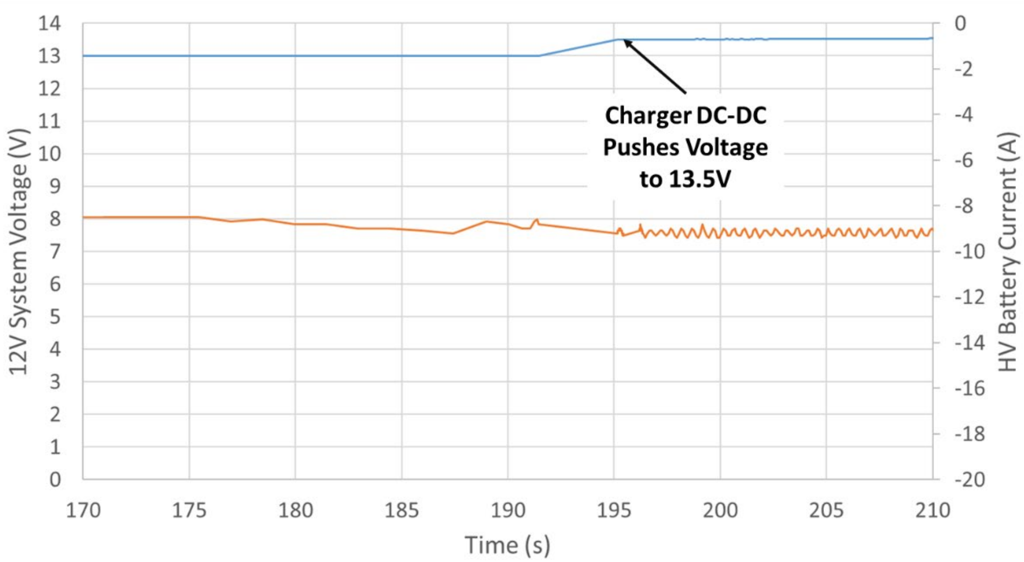

Figure 78: Toyota Prius Prime Charger Connected DC-DC Converter Increasing 12V System Voltage

5.3 12 Volt System Overvoltage Test

5.3.1 Procedure Feedback and Revisions

All vehicle were tested successfully using this procedure and all test vehicles remained in a safe state during the duration of testing. Interestingly, most vehicles halted charging above a particular 12V system voltage level, but similar to the Undervoltage testing, this was reported as a 12V system issue as opposed to anything related to a charging fault. Many error messages were shown by the vehicles related to the elevated 12V system voltage.

5.3.2 Validation Testing Results and Discussion

As shown in the figure below for the Honda Accord PHEV, once the system voltage crossed 18V charging was halted as evidenced by the 0A battery current. Similar results were observed for all other vehicles tested with varying error messages related to the expected fault.

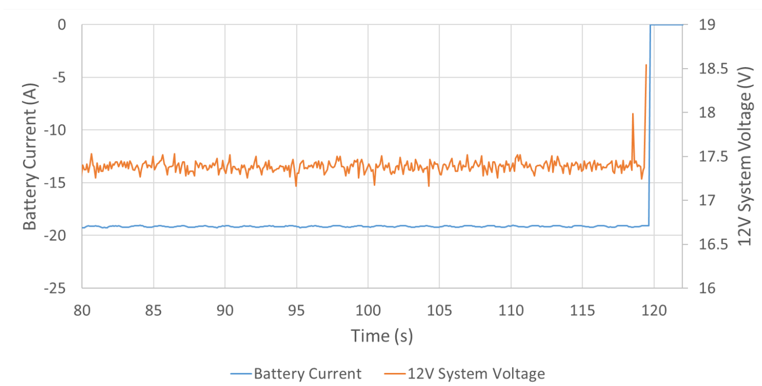

Figure 79: Honda Accord PHEV Overvoltage Test Results

Since an elevated 12V system fault could damage a range of vehicle components, not just items related to the charging system, this test produced a wide range of fault messages that varied from vehicle-to-vehicle. Show below for the Toyota Prius Prime, the elevated 12V system voltage produced errors related to the brake pressure solenoid pressure and the ignition voltage supply in addition to halting charging. While not specific to the charging related testing at hand, this is expected as the fault messages are diagnosing the elevated 12V condition for their individual components.

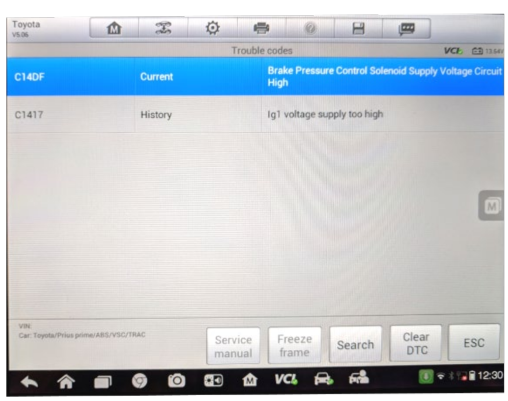

Figure 80: Highlighted Toyota Prius Error Messages Following Overvoltage Test

5.4 12 Volt System Disturbance Test

5.4.1 Procedure Feedback and Revisions

Similar to the DC procedure, this test seeks to establish that a vehicle's charging system and RESS stay in a safe state during charging despite 12V disturbances that could possibly interrupt ECU operation. Similarly, the aim of this test is to establish that the vehicle remains in a safe state and thus successful completion of the test can either end in a standard charge session (no inference) or the halting of charging and a continued safe state for the duration of testing.

5.4.2 Validation Testing Results and Discussion

Similar to the results in DC testing section, vehicle charging was not interrupted by the introduced 12V system disturbance. The vehicle continued to charge and was in a safe state throughout testing. Summarized in the figure below, the 12V system can be observed in the oscillating 12V system voltage, but charging continues as shown by the non-zero battery current.

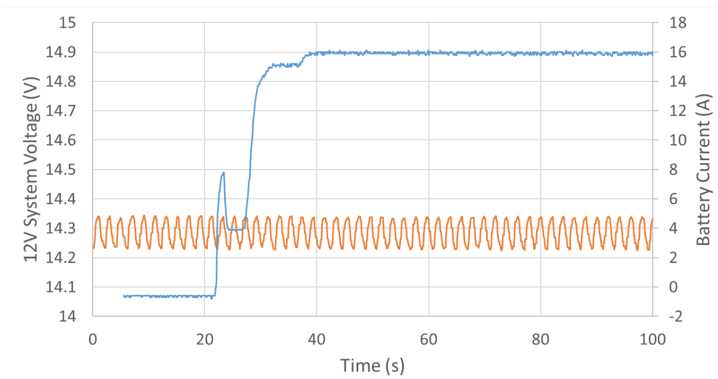

Figure 81: BMW i3 12V Disturbance Results

5.5 12 Volt System EMI/EMC Test

5.5.1 Procedure Feedback and Revisions

Guidance and feedback for this testing is similar to that contained in the DC charging section: Although the authors are not familiar with the SAE J1113-3,-4,-21,-24 test procedures (Electromagnetic Compatibility Measurement Procedures…) if each ECU that comprises the charging system and controls on the PEV complies with these SAE test procedures this test procedure could possibly be redundant in that the system components are all individually robust to interference.

The procedure of Section 6.8.5 of the original research documentation is basic and only requires the procedures SAE J1113-3,-4,-21,-24 to be performed while observing the behavior of the CCS system. Although it may be worthwhile to occasionally assess both component and system EMI issues, these tests may be redundant and could possibly be removed.

5.6 PEV Movement Test

5.6.1 Procedure Feedback and Revisions

Similar to the discussion in Section 4.9 for DC charging a PEV shall prevent operator initiated vehicle movement when the charge connector is mated to the vehicle inlet. In contrast to the DC procedures that seek to ensure a vehicle rollaway situation is also avoided while charging, the AC procedures focus on tests that evaluate the vehicle's ability to avoid operator initiated movement, namely: 1) powering a vehicle's traction system while charging or 2) shifting out of "park" and into a "drive" mode while charging. To this end the AC procedure differs from the DC procedure in that is only evaluates the responses to user initiated inputs and not the rollaway condition discussed in the DC section. All vehicles tested were unable to be moved by operator initiated requests and remained in a safe state throughout testing.

Although not required, recording a vehicles PRNDL state and power button status was particularly helpful for these tests and helps confirm that the vehicle is actively seeing and ignoring these requests while charging or attached to the charger (and not charging). Many of the vehicles tested during the PEV Movement Test also provided input to the user/driver that the requested actions were prohibited due to the current charging/connected status.

5.6.2 Validation Testing Results and Discussion

Figure 82 below highlight a typical response when connected to a charger while requesting the vehicle traction system become active. For all vehicles tested, the vehicle could be powered on to the "ignition on" state, but not to the "ready" state. While most vehicle allowed the parking brake to be released, vehicle movement was still not possible due to the lack of "ready" state. As con be confirmed in the figure below, the vehicle did "see" the request to power the vehicle, but did not act on the commands.

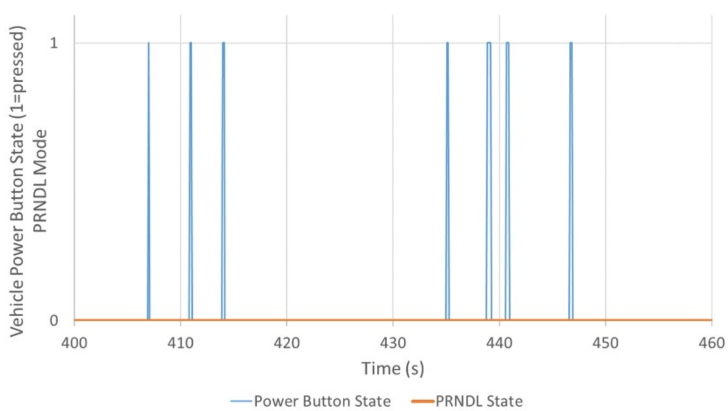

Figure 82: Toyota Prius Prime PEV Movement Test Results when Connected

In addition to not allowing a vehicle to enter "ready" mode, most vehicles also provided the operator with information on the dashboard related to the prohibited operation and the action required to complete the request (disconnection of the charging cord). Figure 83 shows some of the vehicle responses to the request to enter ready mode while the charging cable was connected.

Figure 83: Example Vehicle-to-Operator Feedback to Prohibited "Ready" State when Connected

Similar to the above testing, the vehicles were also evaluated during an active charge session to ensure that operator initiated movement was also prohibited. Again the user request can be seen on the vehicle communication bus, but the vehicle did not enter "ready" mode, nor did the PRNDL state change from its initial state.

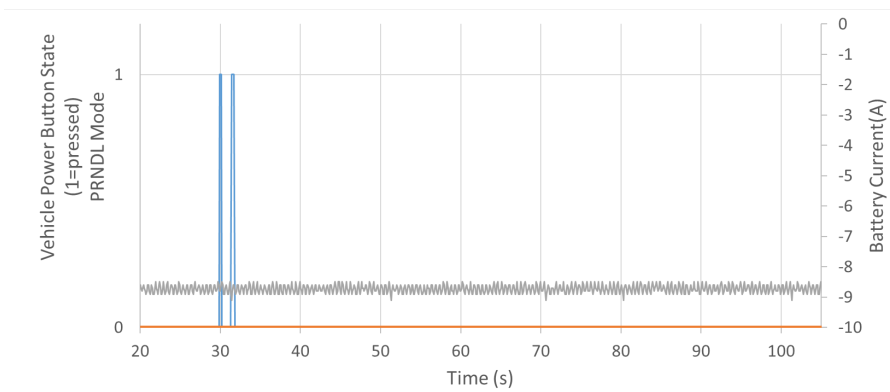

Figure 84: Prius Prime Example Vehicle Response to PRNDL/Ready Inputs During Active Charge Session

As with switching to "ready" mode while connected, most test vehicles also provide operator feedback relating to the prohibited shifting during charging (and a connected state). Several examples of these messages are show in the figure below.

Figure 85: Example Guidance Regarding Attempted PRNDL Shifting During Charge Session

5.7 Charge Connector Control Signal Disturbance Test

5.7.1 Procedure Feedback and Revisions

Giving the focus on AC testing issues for this subset of testing, the procedure was streamlined to evaluate four main conditions of interest. Namely, a vehicle's response to an interruption or short in the control pilot signal or proximity circuit during charging. These issues should be detected quickly and charging halted in a safe manner.

One noteworthy observation from this testing is that some signals related to proximity and/or control pilot state are broadcast over the vehicle communication bus at a slower rate that the actual system diagnostics and actions are taking place. This leads to the somewhat unexpected case of charging being halted before the observed change in state. Despite this fact it is somewhat easy to confirm that these conditions lead to halted charging, since they very closely follow the change in charging state. While the response time is left to the OEM in these procedures, it is worth highlighting that if one seeks to confirm the response time of these actions, an external check or direct connection to the control pilot and proximity state would be recommended, whereas the different communication rates a more than acceptable for this type of behavior confirmation testing.

Interestingly, most of these test cases did not lead to a vehicle or EVSE displayed error. This is likely due to some of the conditions mirroring or being relatively similar to regular stopping of charging and disconnection of the charge connector.

5.7.2 Validation Testing Results and Discussion

5.7.2.1 Control Pilot Interrupt or Short During Charging

Figure 86 and Figure 87 below show the vehicle response for a interrupt/short in the Control Pilot for the Chevrolet Bolt. Once the control pilot signal has been interrupted, as shown by the 0V Pilot voltage, charging quick halts for both cases. As discussed above, the charging actually stops prior to the communicated change in pilot state due to different communication rates for different signals within the vehicle.

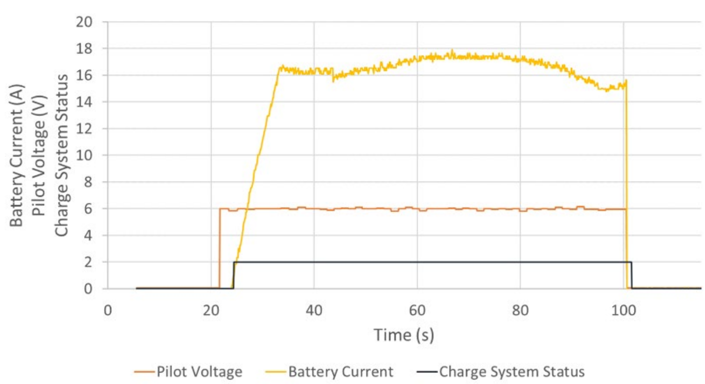

Figure 86: Chevrolet Bolt Control Pilot Interrupt Results

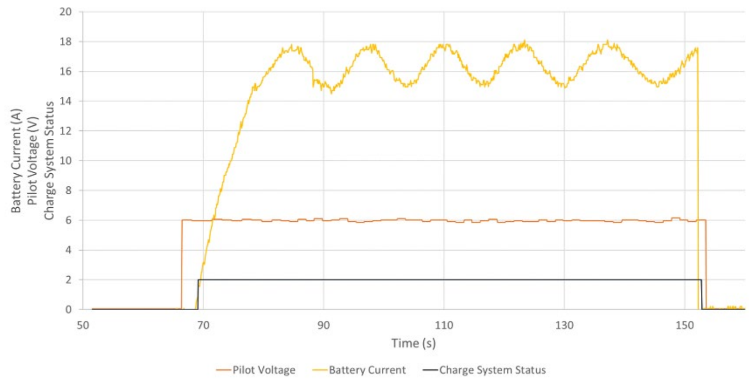

Figure 87: Chevrolet Bolt Control Pilot Short to Ground Results

5.7.2.2 Proximity Circuit Interrupt or Short During Charging

Figure 88 and Figure 89 show the Chevrolet Volt response to an interruption of the proximity circuit in a similar fashion to the above control pilot testing. As with the pilot interruption, vehicle charging is halted immediately and the vehicle stops charging while remaining in a safe state. Unlike the pilot disturbance testing, the proximity interruption can be observed when the control pilot voltage state rise to 9V versus 0V in the pilot interruption test. Again, the small lag between observed state change and the halting of charging as evidenced by a change in system state and 0A battery current is due to communication rate differences.

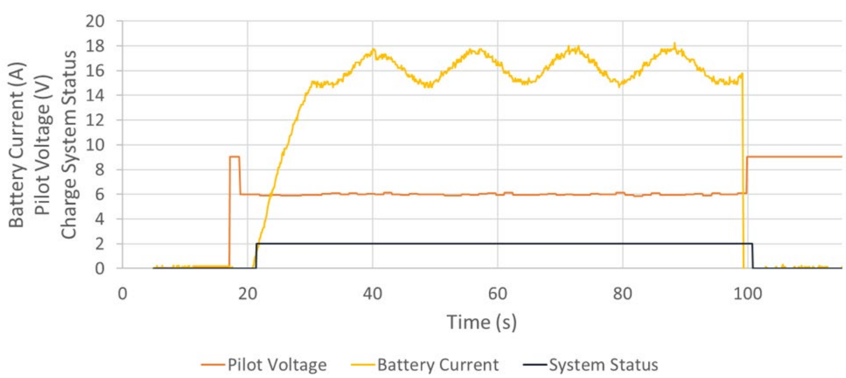

Figure 88: Chevrolet Bolt Proximity Interrupt Results

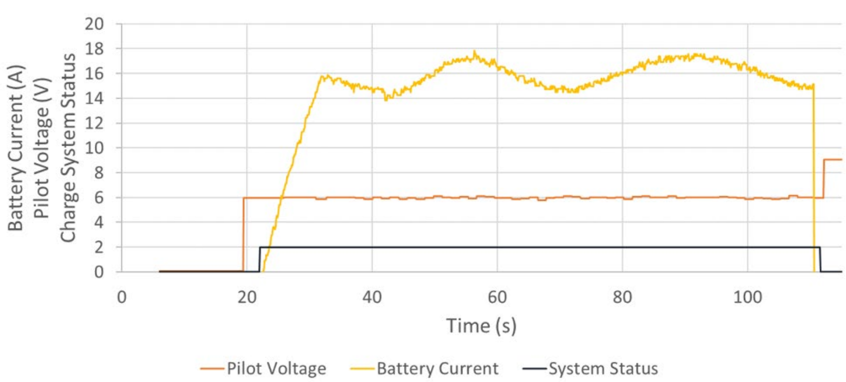

Figure 89: Chevrolet Bolt Proximity Short to Ground Results

5.8 Charge Connector Field Ground Disturbance Test

5.8.1 Procedure Feedback and Revisions

Similar to DC charging a disturbance related to the ground connection between the PEV chassis ground and charger earth ground can have a detrimental impact on the control pilot and proximity circuit voltages and thus lead to an undesirable condition. A vehicle should be able to detect unexpected (out of specification) control inputs and accordingly request charging be halted. During this condition as well as after charging has been halted the vehicle must remain in a safe state.

As with other tests in this section, having vehicle reported information (specifically the control pilot voltage) is helpful, but not required to understand a vehicle's response (and observation) of these unexpected inputs due to a loss of grounding connection between the vehicle and charge earth ground.

5.8.2 Validation Testing Results and Discussion

For all vehicles evaluated, the removal of the ground connection was observed immediately and charging was halted. During and following this test, all vehicles remained in a safe state. Figure 90 shows the test results for the Chevrolet Bolt. At roughly 195 seconds, the ground connection was removed and shortly thereafter, the control pilot voltage rises to about 7.5 volts, which is out of specifications for an active AC charge session. The vehicle observes this out of specification value and quickly halts charging as can be observed by the 0A battery current. As with previous tests, the actions are slightly out of sequence due to different communications rates within the vehicle. Following the out-of-specification voltage reading, the pilot state increases to roughly 11.2V, which is also outside of specification for J1772 based charging (and due to the ground offset). Although charging was halted immediately during for this test neither the vehicle nor the EVSE showed a fault despite the stopping of the charge session.

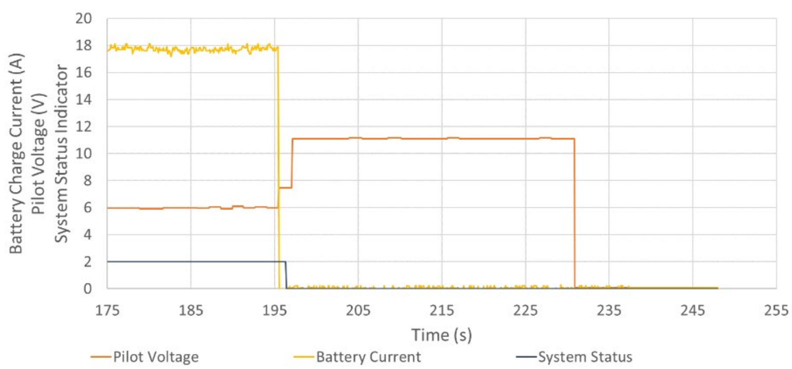

Figure 90: Chevrolet Volt Connector Field Ground Disturbance Results

5.9 Draft Procedures Removed From Final AC Testing Procedures

In addition to the procedures contained above, several procedures were originally included in the draft of the procedure document and evaluated within the validation set discussed in this work. An Elevated PEV Inlet Temperature Test was tested and ultimately removed from the testing since it is very subjective in terms of identifying a condition that would lead to a safety hazard and thus testing condition. While the author feel that elevated inlet temperatures could be an issue for certain AC charging systems, and have seen in-field examples of these issues, it was difficult to identify a procedure or test condition that could robustly execute this situation for an AC vehicle. Unlike DC charging where the interface between the vehicle and charger is sensed due to the higher current levels observed during charging, conditions that would lead to a hazardous condition for AC charging are not particularly clear and thus it is difficult (and not recommended) to provide guidance as a test procedure. While a procedure is not suggested in this document, it is useful to consider how certain unexpected AC charging situations might lead to elevated temperatures at the vehicle/charger interface and what, if any, mitigation strategies might be needed to protect for these issues.

A Power Quality Test was also included in the original version of the AC test procedures but removed following validation testing. Not only was this test difficult to set up and initiate due to the requirement for a custom AC power supply into the AC EVSE, it also appears redundant to other tests evaluating similar conditions relative to the interruption of charging discussed in earlier section. More specifically, the event either appears as an interruption or the vehicle continues charging normally, thus no additional information is gained despite the complex setup process.

6 Conclusions

As discussed in the introduction, this report expands on a NHTSA provided research DC Fast Charging test procedure document written for NHTSA under a research contract with the Society of Automotive Engineers (SAE). The expanded test procedures within this report are based on a range of industry best-practices, strongly using information from several electric vehicle interoperability recommended practice documents. The suite of tests is built around evaluating vehicle-level responses to a range of hazards associated with DC and AC charging as summarized below in Table 13.

Table 13: Safety Hazards and Potential Risks of PEV DC Charging

Safety Hazard	Potential Risk
Over Current	Melted Wires, Fire, Burns, etc.
Over Charge	RESS Thermal Runaway Leading to Fire or Explosion
Exposed HV	Shock/Electrocution, Short Leading to Thermal Runaway
Increased Resistance	Fire, Burns, etc.

Specific sub-procedures were then developed to evaluate a PEV's ability to mitigate the hazards associated with specific failure modes associated with DC and AC charging. The developed procedures include:

- Ground Fault Test (DC Only)
- Chassis Ground Offset Test (DC and AC)
- DC or AC Bus Short Test (DC and AC)
- DC Bus Held High Test (DC Only)
- 12V System Over-Voltage Test (DC and AC)
- 12V System Under-Voltage Test (DC and AC)
- 12V System Disturbance Test (DC and AC)
- 12V System EMI/EMC Test (DC and AC)
- Vehicle Movement Test (DC and AC)
- Vehicle Crash or Bump Test (DC Only)
- Charge Operation Disturbance Test (DC only)
- Charge Connector Control Signal Disturbance Test (DC and AC)
- Charge Connector Field Ground Connection Disturbance Test (DC and AC)
- Charge Connector HV Connection Disturbance (DC Only)
- Failed Battery Cooling/Heating System Test (DC Only)
- BMS Internal Fault Detection Test (DC Only)
- Over-Charge Test (DC Only)
- Over-Current Test (DC Only)
- Reverse Power Flow (Under-Voltage) Test (DC Only)
- PEV Inlet Temperature Test (AC or DC When Applicable)

The refined DC test procedures were successfully validated using a BMW i3 vehicle enabled with a SAE CCS DC charging port capable of roughly 50kW charging. Procedure clarifications and refinements were developed during the validation testing and are detailed within this report. With minor adaptation to handle various DC charging connectors, the developed procedures should be applicable for a range of current and future DC protocols and connections. Building on the developed and validated DC testing procedures, a set of applicable AC charging procedures were also developed and are included in this report. These procedures were validated across several PEV vehicles. The developed procedures offer a set of robust and repeatable test procedures to evaluate a vehicle's response to a variety of charging-safety relevant scenarios and will hopefully allow a greater range of stakeholders the ability to understand and test behavior leading to safer PEV charging.

7 References

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Appendix A: Test Procedure Recommendations

Table A-1: Recommendations for CCS Test Procedures

NHTSA Document Section	**Original DC Test Type List**	**Recommendations** **(*rationale in italics as needed*)**
6.1	Ground Fault	Edit procedures to disconnect the DC charger from the breakout box/PEV before the S1_short and S2_short switches are closed
		Assuming the worst case PEV isolation threshold of 100Ω/V and the maximum HV+/HV- to earth GND voltage, voltage measurements should be used to determine the correct resistance value and power requirement for the ground fault resistor to induce a PEV isolation fault. This resistor will be DC charger/PEV dependent.
		It would be advantageous to disable the ground fault monitoring of the charger for these tests in order to ensure the PEV detects the ground fault. *This would focus the testing on a PEV's ability to detect the isolation loss as opposed to either the vehicle or charger detecting the issue*
		Remove the two, "Fault – ground connection between station and vehicle removed," procedures from this section since it is redundant to the procedures of Section 6.13
6.2	Chassis Ground Offset	It is recommended that a 20 kΩ potentiometer be used in place of the four fixed resistors in the test breakout box. *Additional test flexibility and compatibility*
		Pass/fail criteria should be changed to only fail a PEV if by adding additional ground offset resistance an unsafe condition occurs. If an unsafe condition does occur the offending device (PEV or DC charger) should be determined.
6.3	DC Bus Short	There are 3 fuses between TP1-TP2 on the breakout box schematic. Update the text. These HV fuses should also be rated for the maximum output current of the CCS charger.
		Define "charge session start" in procedure text.
		A compliant CCS charger should never get past the Cable Check phases of a CCS session when a short is present between the DC+ and DC- bus. However, if for some reason the CCS charger is not compliant and allows the charge session to reach the Energy

NHTSA Document Section	Original DC Test Type List	Recommendations (***rationale in italics as needed***)
		Transfer phase the system can still enter a safe state and be considered passing.
6.4	DC Bus Held High	The high voltage setting for all DC Bus Held High tests should be set at 60 V DC. *Common to other charging and HV safety documents*
		Step 3 of the "DC bus held high before a charge session" test needs a more defined procedure with regards to when or what connector is plugged in when enabling the HV in the previous step. It is suggested that two tests are performed: one in which the HV is enabled while plugged in before a charge session and one in which the HV is enabled before being plugged in.
6.5	System Overvoltage (12V Board Net)	In addition to applying the 12V system overvoltage before a charge session and then starting a charge session, the conditions could be applied during a CCS charge session.
		The pass/fail criteria for this test needs to be better defined. If a DC charge session is allowed to start or continue during a 12 V system over voltage, the CCS system should not end or result in an unsafe condition.
6.6	12V System Undervoltage	No recommendations
6.7	12V System Disturbance	The pass/fail criteria for this procedure states that the test shall be considered a pass if the vehicle or charger does not react to the load switching and the DC charge session is not interrupted. It is believed that even if the DC charge session was interrupted as long as the session ended in a safe condition the test should be considered passed.
6.8	12V System EMI/EMC	These tests may be redundant and could possibly be removed if the ECU's comprising the CCS on the PEV complies with the SAE J1113-3,-4,-21,-24 test procedures.
6.9	Vehicle Movement	Add a test to the first procedure that also checks if the power train is disabled when not charging but connected.
		The second procedure simulates vehicle movement during a DC charge session by attempting to rotate the PEV's wheels. The procedure should require that all 4 wheels be rotated to ensure that both the front and rear wheel sensors are tested. In the current form of this procedure the steps do not specify what wheel to be rotated.

NHTSA Document Section	Original DC Test Type List	Recommendations (*rationale in italics as needed*)
		The pass/fail criteria should be edited to fail any PEV that allows vehicle movement while the connector is mated to the vehicle inlet. For the simulated vehicle movement test, it is not known whether simply turning a wheel is enough to "trick" the PEV into believing the PEV is actually moving and therefore initiate a charge session shutdown. See Section 3.9.2.2 of this document.
6.10	Vehicle Crash or Bump	No recommendations
6.11	Charge Operation Disturbance	Each procedure outlined in Section 6.11.5 of the Original Research Documentation should have pass/fail criterion.
6.12	Charge Connector Control Signal Disturbance	Since the CCS communication protocol does not use CAN but rather PLC the 4 CAN disturbance tests could be eliminated since they are not a true "Charge Connector Control Signal." In the place of the CAN disturbance tests, PLC disturbance tests could be performed.
		Remove the following four procedures since it was shown the same results occur when performing the procedures of Section 6.2 (Chassis Ground Offset Test) of the NHTSA document. • Introduce high resistance on the control pilot before a charge session • Introduce high resistance on the control pilot during a charge session • Introduce high resistance on the proximity signal before a charge session • Introduce high resistance on the proximity signal during a charge session
6.13	Charge Connector Field Ground Connection Disturbance	The first procedure needs to be updated with what switch to use (S1_GND) to perform this action.
		Table 6 (initial conditions) of this section also needs updated.
		Remove the test "removing the field ground connection, but maintain earth ground using external ground straps" because it is redundant to the chassis ground offset test. See Section 3.13.2.2 of this document.
6.14	Charge Connector HV Connection Disturbance	Section 6.14.5 of the NHTSA document details the procedure for the charge connector HV connection disturbance test. Step 4 allows the procedure operator the choice of opening either the DC+ or DC- lines. This test should be performed three times. The first test should open the DC+ line and the second test should open

NHTSA Document Section	Original DC Test Type List	Recommendations **(*rationale in italics as needed*)**
		the DC- line. The third test would be to open both the DC+ and DC- lines at the same time.
6.15	Visual Inspection of Charge Port	This test involves a visual inspection of the PEV inlet. This test procedure should be removed from the NHTSA document and replaced as a prerequisite check in Section 5 of the NHTSA document.
6.16	Cooling Heating System	Recommend contacting the OEM manufacturer to gather their feedback on the sample preparation and procedures before performing this test.
6.17	BMS Internal Fault Detection	The pass/fail criteria could be a little more specific and require for each emulated fault the DC charge session ends in a safe manner. However, without prior knowledge of the fault handling of the BMS and other CCS systems it is hard to determine how the system should operate (i.e., by emulating a cell under-voltage fault, is the PEV programmed to end a DC charging session?).
		Recommend removing this procedure and including it in the RESS Safety Evaluation Procedure document.
6.18	Overcharge	Suggest editing test to applying a 10% over-current @ 90% SOC until the PEV ends the charge session. Previous document did not specify the required duration for the over-current event. Since the goal is to observed over-charge protection, over-current should applied to the end of the charge session.
		Section 6.18.6 of the NHTSA document details the end of test procedure in which the PEV is stored in an open space for 72 hours to be monitored by a thermal imaging camera. After 72 hours the battery's SOC is to be discharged to 50% and then monitored for an additional 48 hours. It is believed this duration may be excessive and possibly not even required unless the RESS was actually over-charged (SOC > 100%)

Appendix B: SAE CCS Background

The following is an excerpt from the 2013 paper titled *Development and Implementation of SAE DC Charging Digital Communication for Plug-in Electric Vehicle DC Charging* written by Harper [3].

> *The SAE J1772 standard defines the electrical and physical interfaces between a PEV and Electric Vehicle Supply Equipment (EVSE) for both AC level 1 and AC level 2, as well as DC level 1 and DC level 2. The SAE J1772 standard also defines functional and performance requirements for the PEV and EVSE.*
>
> *The SAE J1772 coupler consists of 5 core pins: AC Power (L1) or DC +, AC Power (L2/N) or DC -, Equipment Ground, Control Pilot, and Proximity Detection. With this coupler it is possible to charge a PEV at AC level 1 (120 V_{rms}, ≤ 16 A_{rms}) AC level 2 (240 V_{rms}, ≤ 80 A_{rms}) or DC level 1 (500 VDC, ≤ 80 ADC), depending on the EVSE and PEV's configuration. The SAE J1772 combo coupler consists of the 5 core pins and 2 additional extended pins below these core pins. The two additional extended pins are DC + and DC – and allow DC level 2 (500 VDC, ≤ 200 ADC) charging.*
>
> *Communication between an AC level 1 or AC level 2 EVSE and PEV occurs by measuring the physical parameters of a pulse width modulated (PWM) square wave induced on the control pilot by the AC EVSE. Information such as the EVSE's state, PEV's state and the EVSE supply current capacity, are all conveyed by measuring the presence of a PWM signal (EVSE state), the PWM's peak voltage (PEV state) and its duty cycle (supply current capacity).*
>
> *For AC level 1 and AC level 2 charging, rectification of the AC power occurs via the PEV's onboard charger. The AC EVSE's supply current capacity is conveyed to the onboard charger, which communicates with the On-board Charge Module (OBCM) to control the RESS charge profile and stay within the limits of the AC EVSE's supply current capacity and the onboard charger's power rating. The greater of the AC EVSE supply current capacity or the onboard charger's power rating, sets the RESS maximum charge rate for AC level 1 and AC level 2 charging. Typical onboard charger power ratings range from 3.3 kW to 6.6 kW, which depending on the PEV's RESS energy capacity and state of charge (SOC) can result in hours of recharging. To facilitate faster recharge rates, the PEV's onboard charger is bypassed and an off-board charger (DC EVSE) is used.*
>
> *Using an off-board charger requires establishing a digital communication link between the Battery Energy Control Module (BECM) and off-board charger. An obvious candidate for this type of communication is a controller area network (CAN) bus. However, CAN requires a differential pair (CANH & CANL) to implement, which would require an additional two pins to be added to the J1772 coupler. To overcome this physical impediment, the SAE Hybrid Communication Task Force has decided to implement power line communication (PLC) over the control pilot. The specific PLC technology chosen for PEV/EVSE communication is HomePlug Green PHY (HPGP). HomePlug Green PHY is a broadband PLC (BB PLC) technology in which digital data is modulated onto multiple carrier frequencies via orthogonal frequency-division multiplexing (OFDM). Digital communication between the BECM and off-board charger is performed by coupling the HPGP signal onto the PWM square wave on the control pilot. Thus one pin is used for communication for both AC level 1 and AC level 2 charging (PWM) and DC level 1 and DC level 2 charging (BB PLC).*

It should be pointed out that the CHAdeMO DC charging standards and protocol greatly differ from the SAE DC charging standards and protocol. The CHAdeMO communication protocol uses a CAN bus via a dedicated set of pins in the Japan Automobile Research Institute (JARI) coupler to communicate and transfer DC power. The JARI coupler can only be used for DC fast charging and a PEV would require an SAE J1772 coupler for AC level 1 or AC level 2 charging. The SAE combo connector alleviates this issue by providing both AC and DC charging with one coupler. Therefore, the SAE DC charging standards and protocols are not compatible with the JARI and CHAdeMO DC charging standards and protocols.

The SAE J2931/4 standard establishes the specifications for the physical (PHY) and data-link layer (DLL) communications of HomePlug Green PHY, while SAE J2931/1 establishes the specification and requirements for the upper layers of the communication stack, excluding the application layer. The SAE J2847/2 standard establishes the application layer specifications and requirements for DC charging. The SAE J2847/2, SAE J2931/1, and SAE J2931/4 specifications have been harmonized with the DIN SPEC 70121 ISO/IEC DIS 15118-2, and ISO/IEC DIS 15118-3 DC communication standards to ensure interoperability.

Appendix C: Applicable Publications

The following publications form part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of the publication shall apply.

SAE Publications - Available from SAE International, Warrendale, PA www.sae.org

1. SAE J1113 Electromagnetic Compatibility Measurement Procedures and Limits
2. SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology,
3. SAE J1739 Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)
4. SAE J1766 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
5. SAE J1772 Recommended Practice for SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler
6. SAE J1797 Recommended Practice for Packaging of Electric Vehicle Battery Modules
7. SAE J1908 Electrical Grounding Practice
8. SAE J2293 Energy Transfer System for Electric Vehicles—Part 2: Communication Requirements and Network Architecture
9. SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
10. SAE J2847 Communication Between Plug-in Vehicles and Off-Board DC Chargers
11. SAE J2929 Electric and Hybrid Vehicle Propulsion Battery System Safety Standard -Lithium-based Rechargeable Cells
12. SAE J2931/3 PLC Communication for Plug-in Electric Vehicles
13. SAE J2950 Recommended Practices (RP) for Transportation and Handling of Automotive-type Rechargeable Energy Storage Systems (RESS).
14. SAE J2953 Plug-In Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE).

IEC Publications - Available from IEC Central Office; Geneva, Switzerland webstore.iec.ch

1. IEC 62660-2 Reliability and abuse testing for lithium-ion cells
2. IEC 61010 Safety requirements for electrical equipment for measurement, control and laboratory use

ISO Publications - Available from ISO Central Secretariat; Geneva, Switzerland www.iso.org

1. ISO 6469-1 Electric road vehicles – Safety specifications – Part 1: On-board rechargeable energy storage system (RESS)
2. ISO 6469-3 Electric road vehicles — Safety specifications — Part 3: Protection of persons against electric hazards
3. ISO 12405-1Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems – Part 1: High-power applications
4. ISO 12405-2 Electrically propelled road vehicles – Test specification for lithium-ion traction battery packs and systems – Part 2: High-energy applications

5. ISO 16750-2 Road vehicles — Environmental conditions and testing for electrical and electronic equipment

UL Publications - Available from UL Corporate Headquarters; Northbrook, IL www.ul.com

1. UL 2580 Batteries for Use in Electric Vehicles

FMVSS Publications - Available from NHTSA Washington, DC, www.nhtsa.gov

1. FMVSS 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection
2. Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High Voltage Batteries
3. NHTSA Test Procedure TP-581-01 – Standard regulation on bumper standard, (https://one.nhtsa.gov/Vehicle-Safety/Test-Procedures)

IEEE Publications - Available from IEEE, New York, standards.ieee.org.

1. IEEE Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles, IEEE Std 2030.1.1-2015

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