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EFFECT OF SOLID-STATE POWER-CONVERTER HARMONICS ON ELECTRIC-POWER-SUPPLY SYSTEMS

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MARCH 1973

FINAL REPORT

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16. Abstract

The United States utility industry has not set suitable standards other than TIF (Telephone Interference Factor),for controlling the design of solid-state wayside and on-board power-conversion equipment, to limit the harmonic currents and voltages in both the transit and electric-power-supply systems. To reduce interference with telecommunications and control equipment, and to insure reliable operation of power equipment, the manufacturers can attenuate the power harmonics by selecting the converter pulse number and by the use of filters. Techniques for calculating the harmonic voltages have been developed and can be applied to transit systems. We propose a standard of 10 percent of fundamental amplitude for each harmonic voltage at the connection point to the utility and 3 percent for each harmonic voltage within the transit system such as the power rails.

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PREFACE

The work described in this report was performed in the Power and Propulsion Branch at the Transportation Systems Center under the sponsorship of the Advanced System Division of the Office of Research and Demonstrations, Federal Railroad Administration, and the Special Projects Office of the Urban Mass Transportation Administration.

The objective of this work was to determine the effects of power harmonics generated by the solid state propulsion control equipment on the electric power supply and the electric utility loads. The work was performed by Alexander Kusko Inc. under contract DOT-TSC-203, Task Directives 20 and 46.

The author wishes to acknowledge the cooperation and assistance of Mr. Conrad F. De Sieno and his staff of the American Electric Power Service Corporation in the meetings held to discuss the problems relating to the interface between transportation systems and the electric utilities which supply power to them.

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ILLUSTRATIONS

1. INTRODUCTION

The objectives of this work are (a) to develop techniques for calculating the harmonic voltages, and (b) to propose standards for the allowable harmonic magnitudes.

On-board and wayside solid-state power-conversion equipment for surface transportation (transit) systems distort the waveforms of the currents which carry the power from the AC electric supply systems to the transit systems. These distortions, which are described as harmonics of the basic power frequency (60 Hz), can directly produce electromagnetic interference with telecommunications and electronic equipment, and through their impedances produce harmonic voltages within the transit and supply systems as well. The consequences can be faulty operation of electronic equipment, deteriorated performance of power equipment, and reduced life of AC capacitors, cables, and motors.

The magnitudes of the harmonic currents can be attenuated in the design of the solid-state conversion equipment using well-known principles, and by the use of harmonic power filters to confine the circulation of the harmonic currents as close to their sources as possible. The least expensive method for handling harmonics is in the selection of the initial design of power conversion equipment, rather than in making field fixes on operating systems. The higher the rating of the power conversion equipment with respect to the supply system, the greater will be the impact of the harmonic currents. The American electric utility industry has practices, but not standards, for regulating the harmonic levels for customers. Model standards for harmonic current and voltage levels must be developed to control the design and operation of solid-state transit power conversion equipment.

2. SOURCES OF HARMONICS

The transit system harmonic currents, which ultimately reach the electric power systems via the power rails and feeders, are generated in the solid-state power conversion equipment either in wayside substations or on board the vehicles. The technology for minimizing the impact of harmonics of large rectifiers, typically as used in the electrochemical industry, in large motor drives, and in urban DC transportation systems, is well known; it is accomplished by increasing the number of rectifier phases, by using independent feeders, by using AC power harmonic filters, and by properly orienting offending power lines with respect to telecommunications circuits. The same measures cannot be taken as easily for vehicles. Transformers for phase multiplication and filters for harmonic suppression are bulky and heavy; multiple vehicles must operate on a common wayside facility so that their individual power supplies cannot be independent; and all power enters a vehicle through a common current collector, so that interaction will occur between converters and other on-board equipment.

The AC line current waveform for an ideal six-element rectifier is shown in Figure 2-1. For the ideal case of zero AC system reactance, the rectifier elements transfer the load current with no overlap and zero commutation period; the flat-top current pulses have vertical sides and 120° length. The AC supply system voltages remain sinusoidal and undistorted. The impact of AC system reactance, which must always be present to some degree, is to cause the sides of the current pulses to slope as shown in Figure 2-2, but the average length is still 120°. The current waveform of Figure 2-1 can be resolved into a Fourier series which contains in addition to a fundamental frequency component, odd harmonic components of order 5, 7, 11, 13,......; the tripled harmonics, 3, 9, 15,......, are missing. The amplitudes of the harmonic components of order n are 1/n of the fundamental amplitude. If the current is supplied through a Δ-Y transformer bank, then the waveform changes to the shape shown in Figure 2-3, but still retains the same order and relative amplitude of harmonic components.

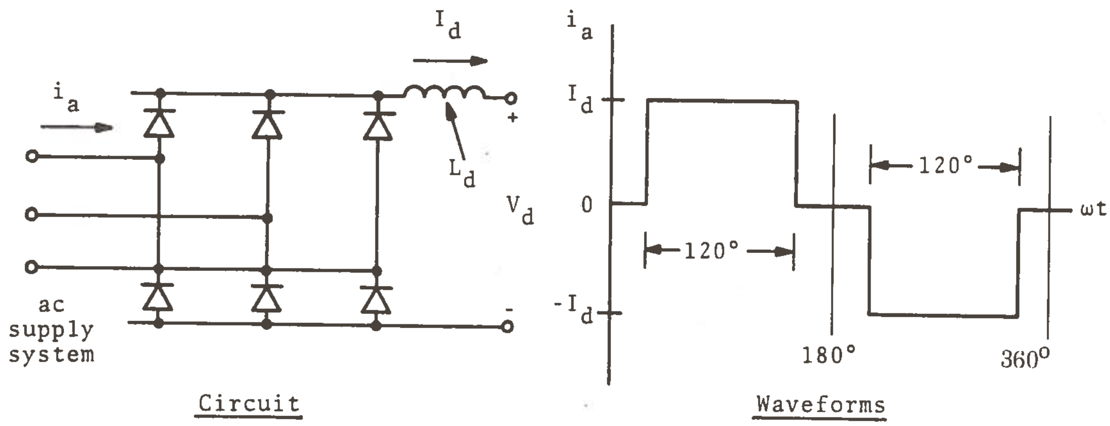


Fig. 2-1. Waveform of AC Supply Current to Six Pulse Bridge Rectifier. Zero Supply Reactance

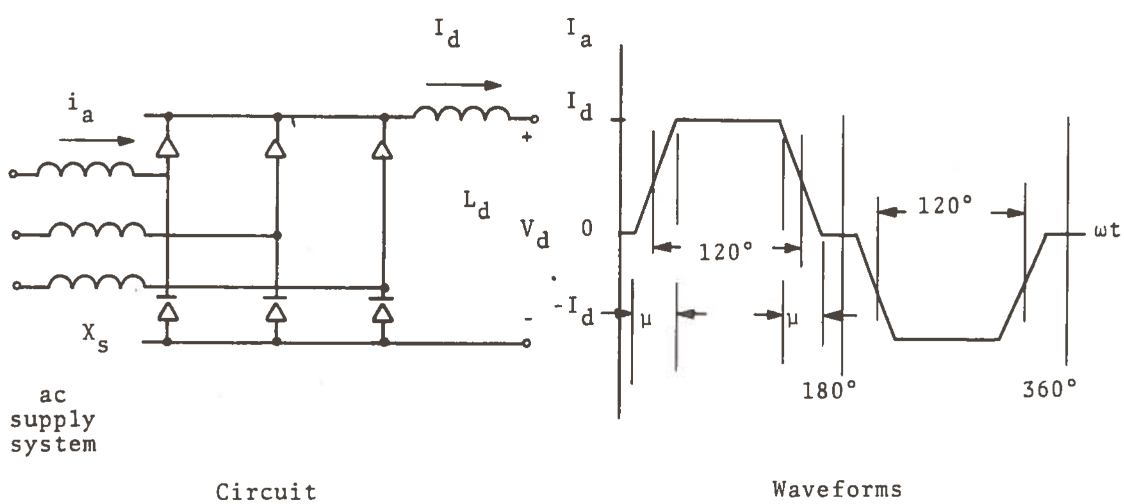


Fig. 2-2. Waveforms of AC Supply Current to Six Pulse Rectifier With Supply Reactance X_s per Phase. Overlap Angle μ

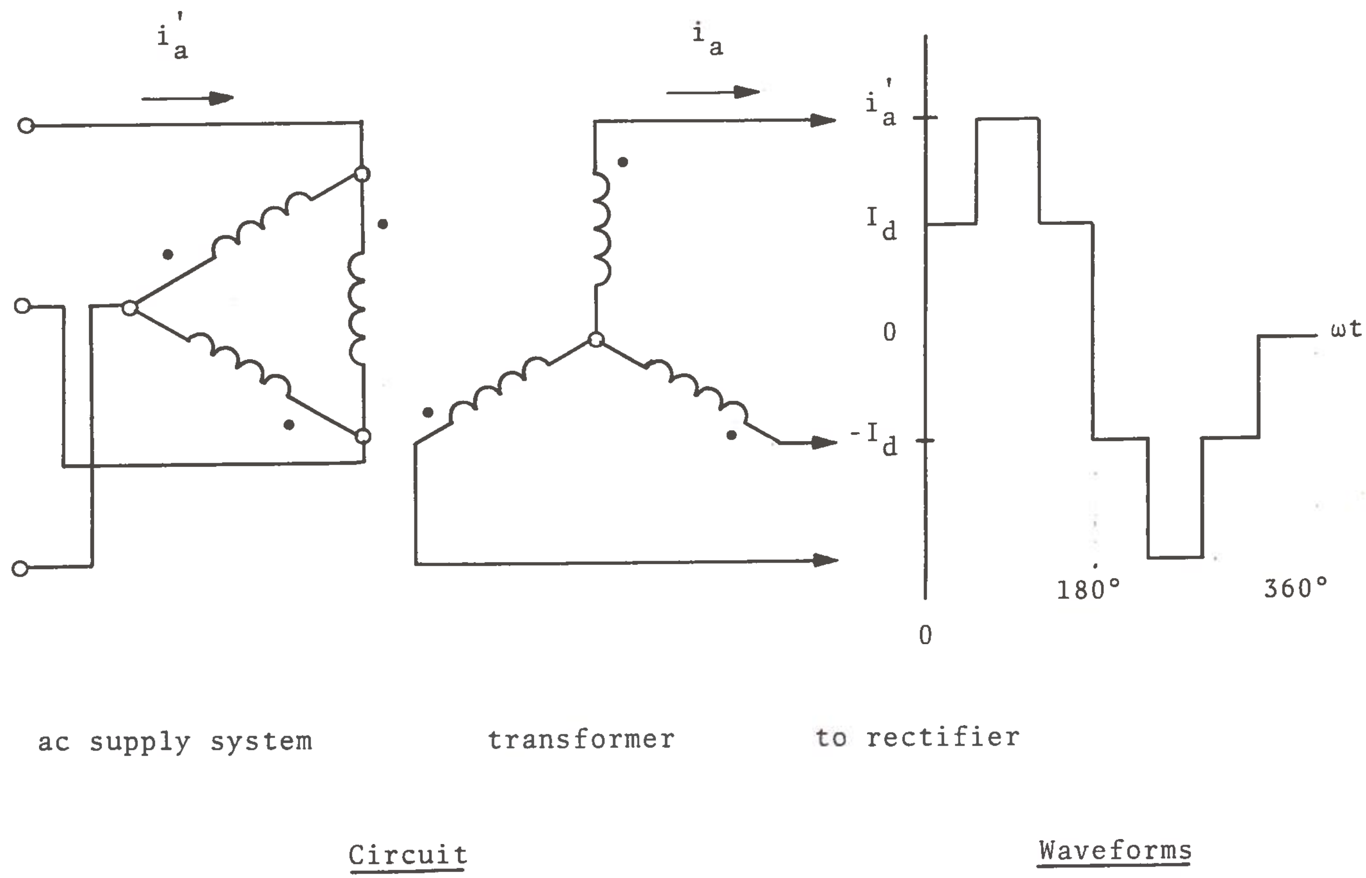


Figure 2-3. Waveforms of AC Supply Current to Six Pulse Rectifier Through Delta-Wye Transformer Bank. Zero Supply Reactance

The relative phase of the harmonic components changes to account for the difference between the waveforms of Figure 2-3 and Figure 2-1. The flat top of the current waveform is idealized; it is caused by inductance in the DC side of the rectifier as shown in Figure 2-1, either in a filter choke, in the DC lines feeding the load, or in the DC load itself. For resistance load only, the flat top is replaced by two cusps of 60° each. In rectifier analysis, the assumption is usually made that the waveform is flat top and the harmonic components are given above.

Two effects of the rectifier will alter the ideal waveform shown in Figure 2-1 and its harmonic components. The first effect comes from an increase by design in rectifier phases or pulse number. A three-phase bridge rectifier, also termed a double-way rectifier, produces six pulses of DC ripple per cycle (period) of line frequency, hence is referred to as a 6-pulse rectifier. When two rectifier bridges are supplied from AC voltage sources which are phase displaced 30° from each other as shown in Figure 2-4, then the resulting DC ripple is 12-pulse and the harmonic orders, 5, 7, 17, 19,......, are eliminated from the AC line current resulting in the waveform shown in Figure 2-5. The order of the AC harmonics in a multipulse rectifier is given by the expression, $kn \pm 1$; k takes on the values, 1, 2, 3,......; n is the pulse number of the rectifier. For example, for n = 6, the harmonic orders are 5, 7, 11, 13,......, and the largest 5th harmonic has an amplitude of 1/5th of the fundamental. When the pulse number is increased to 12, as described above, the surviving harmonics of order n, namely, 11, 13, 23, 25,......, still have the amplitude 1/n of the fundamental, but the largest 11th harmonic is now 1/11th of the fundamental.

The second factor that affects the waveform and harmonics of the AC current is the rectifier overlap produced by the AC system reactance. The effect is shown in Figure 2-2, where the sloping sides of the AC current pulses occur during the commutation period when two rectifier elements are conducting simultaneously as the load current is transferred from one to the other. The period is

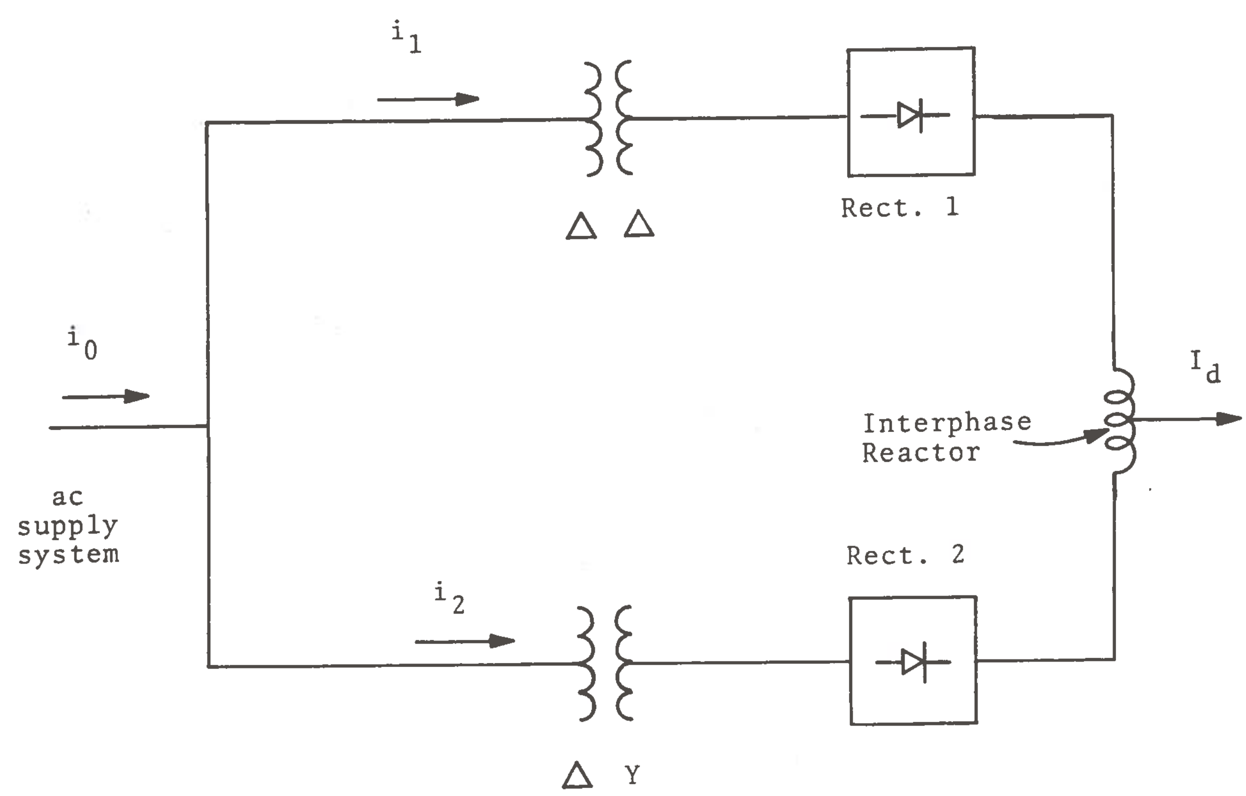


Figure 2-4. Single-Line Diagram of 12-Pulse Rectifier

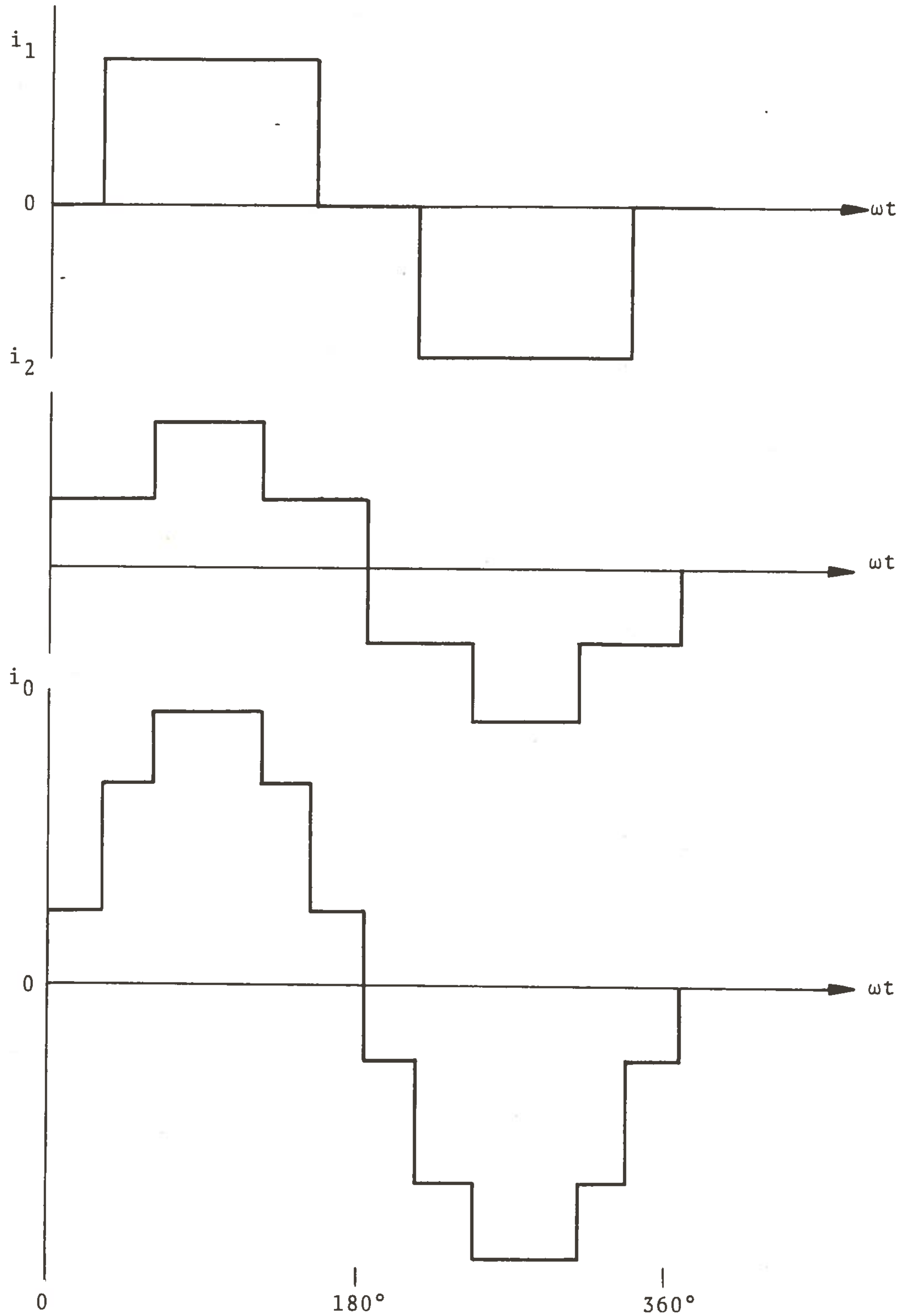


Figure 2-5 Waveforms for AC Supply Currents for Each Rectifier and the Total Supply Current for 12-Pulse Operation.

defined by the overlap angle μ and is a function of the total reactance, including the system reactance, feeder reactance and rectifier transformer reactance. The AC reactance has three consequences on the rectifier. First, it reduces the maximum DC voltage so that the rectifier must be overbuilt in order to supply the required load power. Second, it reduces the amplitude of the highest order harmonics as shown in Figure 2-6. Third, the line voltage at the rectifier is forced to zero during the overlap periods, thereby distorting the voltage for other AC loads connected anywhere on the AC system, as shown in Figure 2-7.

Primary voltage control of induction and linear motors (LIM'S) by the thyristors produces harmonics directly in the line current. A typical waveform of induction motor current with such control is shown in Figure 2-8.[2] The current pulses are 120° in length and consist of multiple cusps, depending upon the firing angles of the thyristors and the motor speed. As the firing angle is changed to adjust the motor voltage, the currents shift in phase, retain their general shape and duration, but change in amplitude. The harmonic orders are basically the same as for 6-pulse rectifier AC supply harmonics, but the amplitudes decline more rapidly than 1/n. Measured harmonic amplitudes for a primary voltage control system are shown in Figure 2-9.[2]

The chopper, which is used for controlling DC traction motors, is another potential source of harmonics. An on-board inductance-capacitance (LC) power filter between the power collector and the solid-state chopper tends to decouple the chopper from the DC wayside system. The chopper produces electrical noise both on-board and in the power rail system, the rectifier substations which supply the wayside DC power rail produce harmonic currents in the AC supply system.[3]

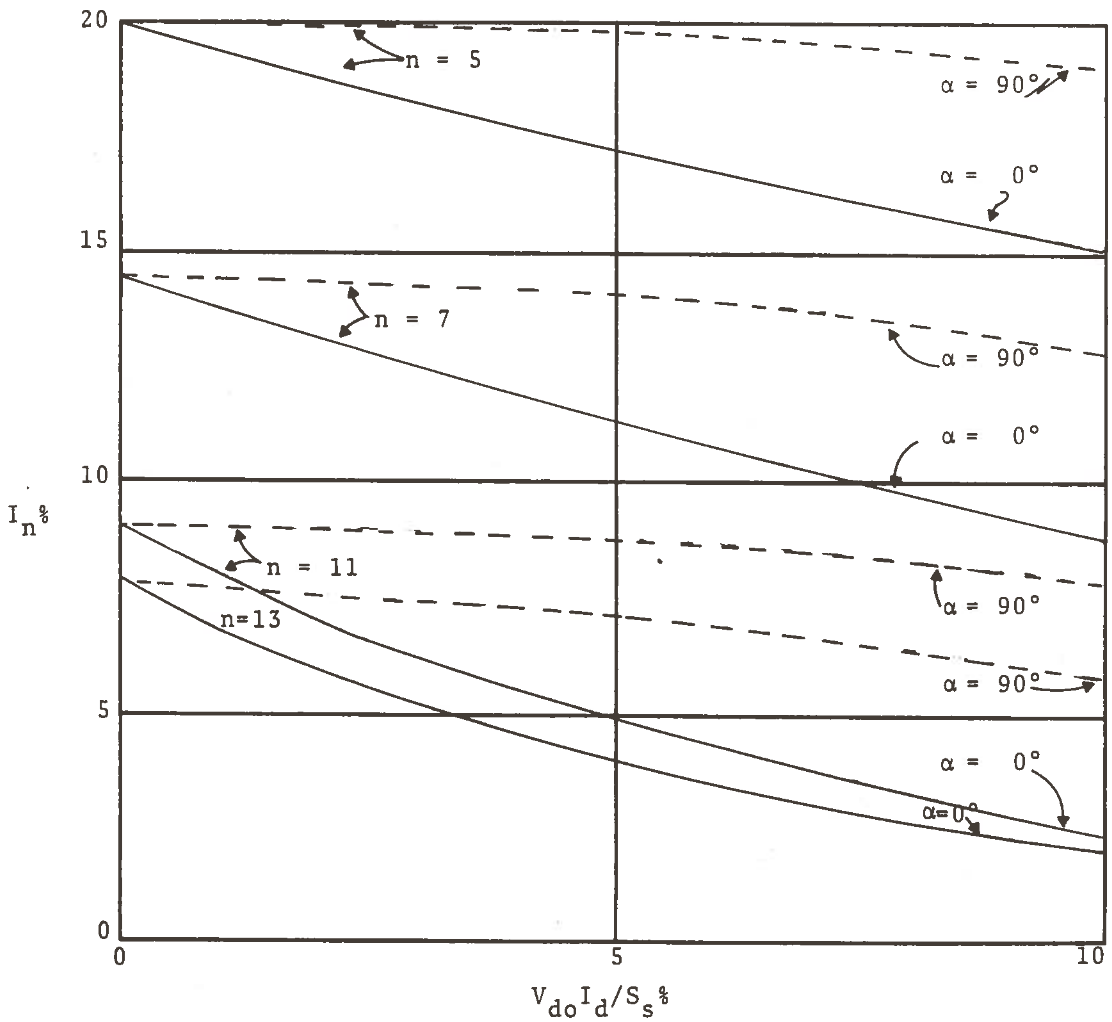


Figure 2-6 Effect of Supply Reactance on Harmonic Levels for 6-Pulse Rectifiers.[1] (V_{do}= No Load DC Voltage, I_d= Rated DC Current, S_s= Three-Phase System Fault Volt Amperes.

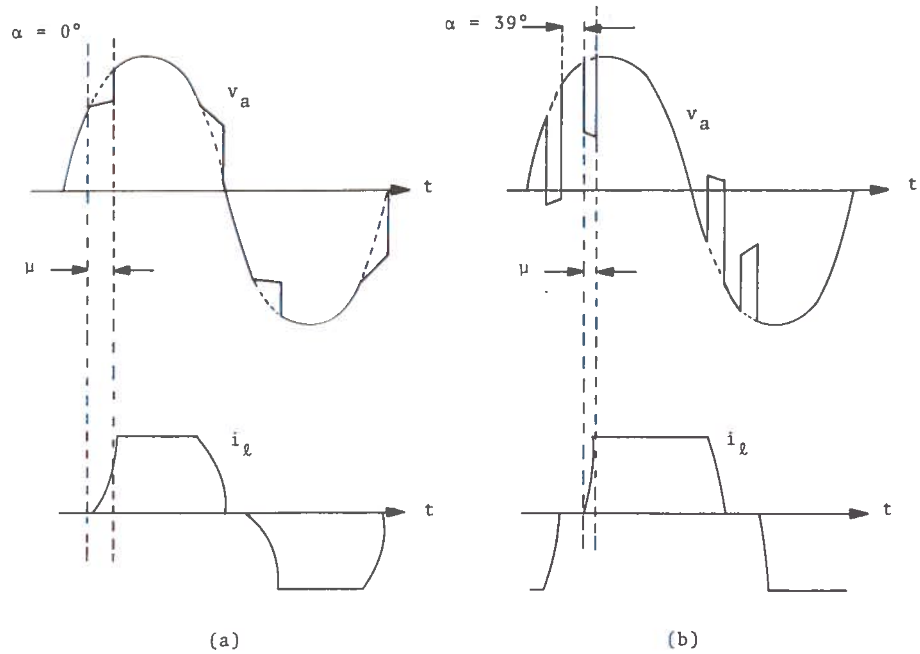


Figure 2-7 Waveforms of Line Current and Primary Bus Voltage for a Six-Pulse Rectifier Supplied from a System of j0.09 pu Impedance and Rectifier Transformer of j0.045 pμ. (a) Maximum DC Output, α=0°; (b) Reduced DC Output α=39°

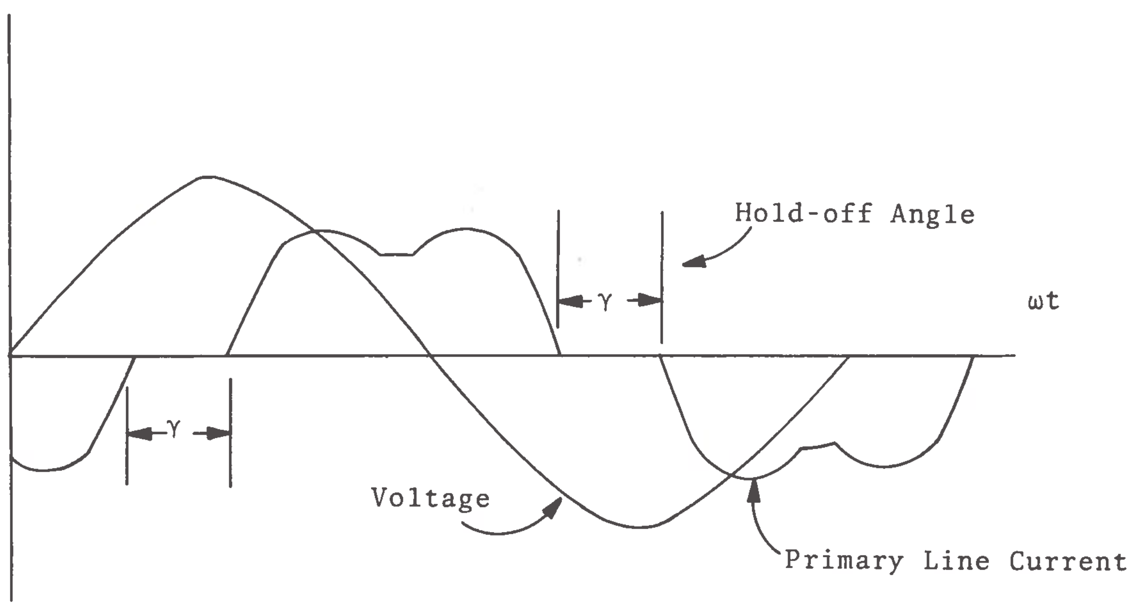


Figure 2-8 Current Waveform in Primary Thyristor-Controlled Induction Motor

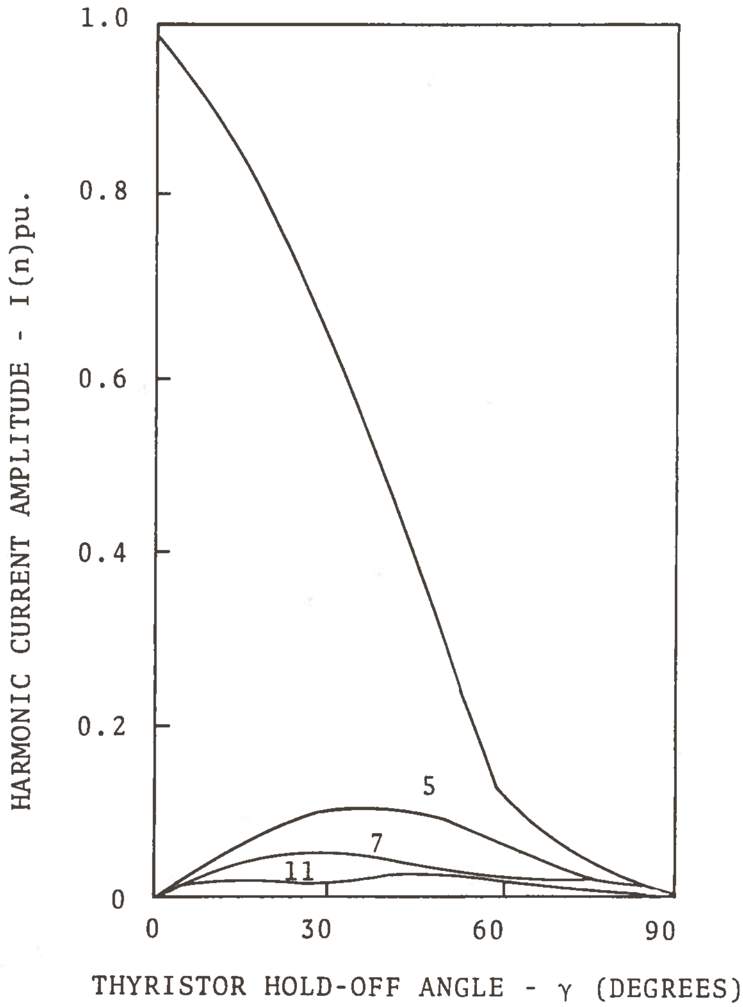


Figure 2-9 Harmonic Components of Line Current for Thyristor-Controlled Induction Motor.

3. EFFECT ON ELECTRIC-POWER SYSTEM

The solid-state power conversion equipment, either at the wayside or in the vehicle, can be considered as a generator of harmonic currents which are injected from the conversion equipment into the electric power system supplying the particular transit complex. The harmonic currents can produce interference directly by induction in nearby exposed telecommunications circuits, but the most serious effects are the harmonic voltages produced at various points in the supply system and in the transit-system network.

An electric power system is basically a linear electric circuit; each harmonic voltage is the independent response of each harmonic current and can be calculated separately. For each harmonic, the conversion unit is replaced by a current harmonic generator (source) of the particular order and amplitude; for example, a 200A, 5th harmonic component in the line current is represented as a 300 Hz, 200A current source. The impedance of the complete electrical network facing the current source is then calculated at the harmonic frequency and connected as a load circuit to the current source. From this source and circuit representation at each harmonic order the voltages at all points in the connected network at each harmonic order can be calculated.

As increasing harmonic orders are calculated, the impedance seen by the harmonic current source looking into the electric power system varies in a complex manner. For the purpose of preliminary calculations, a relatively simple model of the electric power system can be used. The system can be represented by a Thévènin equivalent consisting of an internal 60 Hz (n = 1) voltage generator and a series reactance X_s, whose value is given by the three-phase short circuit rating of the system at the point of converter connection. At each harmonic order above n = 1, the internal generator voltage is zero and the series reactance becomes nX_s. The significance of the simple model is that the capacitances and resistances of the electric power system are neglected and the system is considered to consist only of inductive reactance; in addition, the system is assumed to have no other harmonic sources than the converter. For systems having relatively short connections between major generating plants or high voltage buses and the power conversion equipment, for example, connections up to 50 miles, the simple reactance model is suitable to a high harmonic order. The model used for calculating the effect of the 5th harmonic currents from the Tracked Air Cushion Research Vehicle (TACRV) for the DOT Pueblo Test Site is shown in Figure 3-1.

A more accurate model of an electric power system requires that the resistances and capacitances be taken into account.[4] A polar diagram of the impedance as a function of frequency for a 225 kV electric-power system is illustrated in Figure 3-2a. The magnitude of the impedance versus frequency is shown in Figure 3-2b. The impedance has both real and reactive components and passes through poles and zeroes of impedance as a function of frequency. The poles occur at parallel resonances and the zeroes occur at series resonances. The parallel resonances (poles) are particularly critical because they result in amplified harmonic voltages and currents at various points in the power system. The series resonances (zeroes) tend to reduce the effectiveness of power harmonic filters.

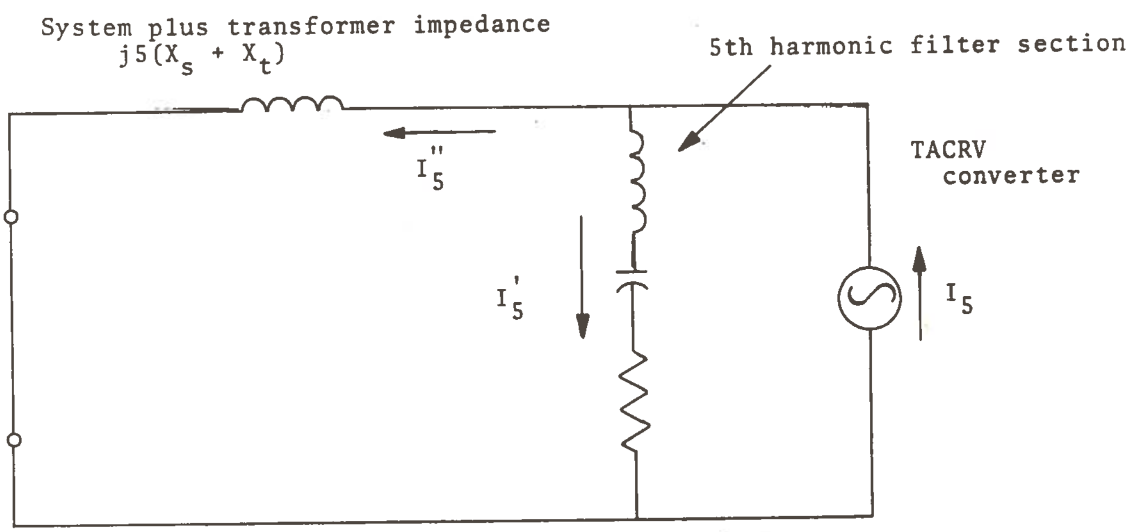
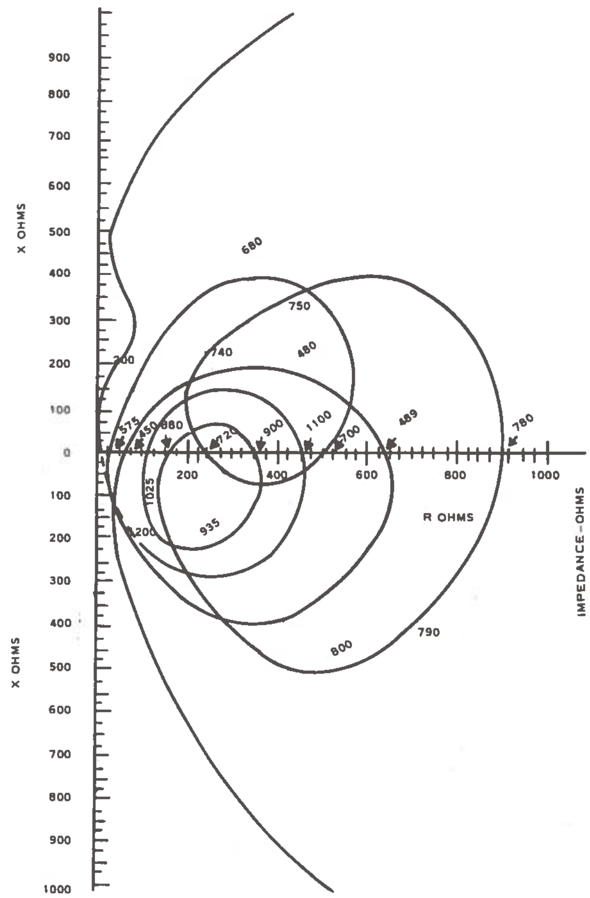


Figure 3-1. Equivalent Circuit for Pueblo Filter Design



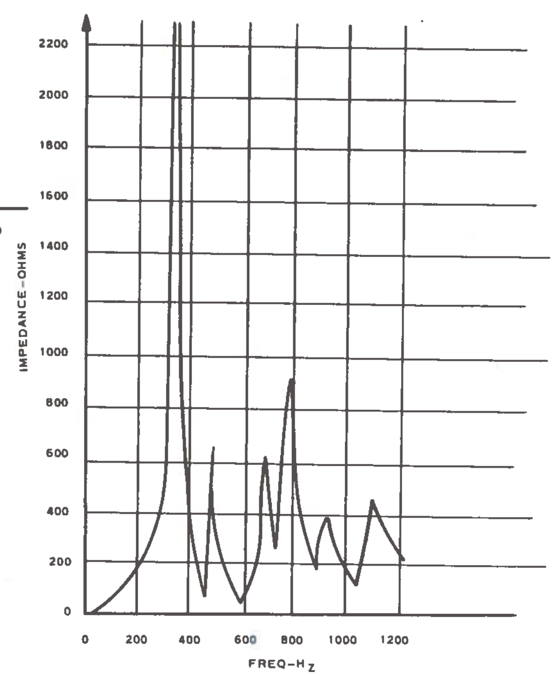


Figure 3-2a. Typical Impedance-Frequency Polar Diagram of a 225 KV, 50 H_z Electrical Power System.

Figure 3-2b. Impedance-Frequency Amplitude Diagram for Figure 3-2a.

The impedance in Figure 3-2a is seen to be nearly reactive up to 300 Hz, before the resonance at about 500 Hz is reached. The diagram is for a 50 Hz system so that a reactance model is valid to the sixth harmonic, n = 6. Lower voltage systems, where the converter is coupled to the supply system through transformers, and with the damping effects of load, tend to be representable by an impedance of the form nX_s up to the 25th harmonic. The impedance as a function of frequency is difficult to measure on an actual electric power system. It can be measured on a network analyzer model or calculated from an equivalent circuit representation of the system.[4] For transit applications, it appears suitable to employ the simple model of the reactance determined by the short-circuit rating.

The series impedance element described above is sufficient for calculating the harmonic effect of the power converter on the electric power system at the connection point. However, within the electric power system itself, the harmonic currents will penetrate to an extent determined primarily by the system capacitances. Harmonic currents will be dissipated in AC capacitor banks, in transmission line capacitance, and in the capacitance of cables. The admittances (Y = 1/Z) of these paths increase with harmonic order n, so that the higher frequency harmonic currents become dissipated more quickly. The effects of the harmonic current in producing telecommunications interference and serious voltage distortion is greatest in the vicinity of the conversion equipment and then generally decreases as the current penetrates into the system.[5] AC capacitors located close to power conversion units will carry nearly all of the harmonic currents producing excess heating, possible harmonic resonances, and may require special attention.

4. UTILITY HARMONIC PRACTICE

The American utility industry appears to have no uniform criteria for the allowable levels and orders of harmonic currents produced by customers. Criteria exist for interference between voltage and current harmonics on power lines and communications circuits. These criteria, termed TIF (Telephone Interference Factor), were worked out between the Bell Systems and the Edison Electric Institute representing the utility industry. However, for the new area of solid-state power converter load, such as for the transit industry, we can assume that the utility industry has no standards other than TIF for harmonic currents and voltages produced by customers.

One reason for the absence of criteria for harmonics on power systems is that customers purchasing large rectifier sets generally increase the specified pulse number as the rectifier rating increases with respect to the supply system. By this means and the use of filters the magnitude and order of the harmonic currents are kept under control. Large rectifier installations are not particularly common on power systems. Traction rectifier sets are generally located in urban areas, and are usually supplied with independent cable feeders, which tend to attenuate harmonic currents. Furthermore, at the connection point of large rectifier sets, the waveshape of the line voltage is generally of no great concern. That is, there are no laboratories, computers, communications equipment, or other equipment supplied from the same feeder which might be sensitive to the voltage distortion produced by the harmonic currents.

Another factor that has tended to reduce the concern of the utility industry with power converter harmonics is that the effect is proportional to the ratio of the converter rating to the short circuit rating of the system. For example, if a converter rated at 10 MVA is connected to a system having a short circuit rating of 1000 MVA, then the system reactance is only 0.01 per unit on the converter base. Harmonic voltages produced by even a 6-pulse converter will be less than 1 percent of the system voltage at the connection point, and less as the currents penetrate into the system. It is only when the converter reaches 3 to 5 percent of the short circuit rating of the system that series interactions commence.

Some clue to utility tolerance of converter harmonics is provided by a table prepared by English Electric Hewittic Rectifiers Ltd,[6] and modified as Table 4-1. The table shows the maximum recommended ratings of 6-pulse and 12-pulse rectifiers as a function of network voltage. We have assigned typical short-circuit MVA ratings to each voltage class and calculated the amplitude of the dominant harmonic voltage. The value appears to be about 0.5 percent for the 5th harmonic and about 1.0 percent for the 11th harmonic voltage at the connection point. American manufacturing practice with 460 V solid-state rectifier DC motor drives is to shift from 6-pulse to 12-pulse circuits at between 300 and 500 hp, corresponding to about 250 to 400 kW.[7] The requirement is determined by module size and armature current ripple, rather than utility criteria.

TABLE 4-1 RECOMMENDED RECTIFIER CONFIGURATION AND RATING AS A FUNCTION OF NETWORK VOLTAGE[6]

Network Voltage	Substation Rating	Three-Phase Short Circuit	System Impedance	Maximum Rectifier Rating 6-pulse	5th har. volt.*	12-pulse	11th har. volt.*
kV	MVA	MVA	pu	kW	per cent	kW	per cent
0.42	2.5	25	j0.10	250	1.0	750	3.0
6.6	15	150	j0.10	600	0.4	1800	1.2
11	25	230	j0.11	1000	0.44	3000	1.3
33/66	100	710	j0.14	3000	0.42	7000	1.0
132	225	1500	j0.15	--	--	14000	0.93

*Assume that system impedance at nth harmonic is n times impedance at fundamental frequency.

The utility industry is concerned with power harmonics at the converters of DC transmission systems. The power converters operate in either the 6-pulse or 12-pulse mode; since their rating can be up to one-third of the short circuit rating of the connected power system, both the harmonic currents and the harmonic voltages are severe. In practically all DC transmission system converters, tuned AC power filters are employed for the control of harmonic currents.[8, 9]

The harmonic criteria for the Kingsnorth DC system at the 132 kV London end is essentially, (a) no harmonic voltage greater than 1 percent, and (b) arithmetic sum of 5th to 25th harmonic not to exceed 2.5 percent for the given system impedance characteristic.[8] On the New Zealand DC system, the harmonic criteria at the 110 kV terminals is for the individual harmonic voltages to be less than 0.7 percent. We can conclude that 1 percent represents a typical maximum harmonic component voltage for a high-voltage system.

A comprehensive treatment of the impact of power harmonics on electric power systems is given in CIGRE paper 405, 1964.[11] The authors deal primarily with power harmonics resulting from DC transmission systems and power filter designs, but the treatment and standards are suitable for power harmonics no matter what their source. A single parameter is defined called the "maximum theoretical deviation", or D factor, which is a ratio of the summation of the harmonic voltage amplitudes to the fundamental voltage amplitude, or

$$D = \sum_n \frac{(V_n)}{(V_1)} \times 100 \text{ percent}$$

Note that the factor is calculated on the basis of an arithmetic sum of harmonic voltages, rather than an rms sum. The authors recommend a maximum value of $D \approx 5$ percent for a high-voltage power system. Higher value of D, 10 percent or more, have been measured for traction and large industrial rectifiers without disturbance having been reported.

Several other indications of the tolerance of electric power systems to harmonics can be reviewed. The NEMA Std. MG1-22.43 limits the maximum deviation factor of large synchronous generators to 10 percent.[12] This deviation factor is defined as the percentage deviation of the actual open-circuit, line-to-line, voltage waveform from a sine wave drawn so as to minimize its value. The Federal Aviation Administration Specification FAA-E-2473[13] for large rectifier-inverter systems (UPS), in paragraph 3.1.5.1.3 limits the total rms harmonic current fed back into the AC supply system (460 V) to 5 percent of the rms full load current. Paragraph 3.2.10.1 limits the rms harmonic voltage at the output to 5 percent of the rated voltage. It is apparent that the effect of harmonic currents from power converters on the supply system can be specified in terms of rms harmonic current, rms harmonic voltage, amplitude of individual harmonic components, and deviation factor. The voltage specifications require knowledge of the supply system impedance characteristics.

5. EFFECT ON EQUIPMENT

Power converter operation does not usually produce smooth voltage waveforms at the connection point; the waveforms become smoother within the supply system. The line voltage waveforms for a six-pulse controlled rectifier are shown in Figure 5-1 at two values of DC output voltage and firing angle ($\alpha = 0°$, $\alpha = 39°$).[14] The rectifier is operating from a relatively soft supply system of 9 percent short-circuit impedance and 4.5 percent transformer reactance. During the commutation intervals denoted by the angle μ, the line voltage v_a at the supply bus is sharply distorted, and at the rectifier itself, even more so. The actual line voltage observed at the controlled rectifier terminals of a 100 hp DC motor drive system operating with 3 percent line reactance from a 480 V industrial system is shown in Figure 5-2.

Distorted voltage waveforms, which contain electrical noise, when applied to computer, data processing, communications, and measuring equipment on a common circuit will produce disturbances to that equipment. Operation of power converters on isolated feeders will tend to reduce the coupling of electrical noise to critical equipment. On the other hand, modern transportation systems would utilize computer and other electronic equipment as part of the wayside control system and also on-board the vehicle, and so be fully exposed to electrical noise. The electric supply to the power converter and to the on-board electronic equipment must be carefully decoupled. Severely distorted AC voltages will interfere with the normal operation of converters. The distorted waves can produce false firing of thyristors, interfere with the commutation process between rectifier elements, and can produce hazardous misfires when a converter is in the inverter mode during regenerative braking. When the voltage distortion causes jitter of the firing angles of the individual thyristors, the converter will draw harmonic currents of practically every order from the supply system and may become fully unstable.[15]

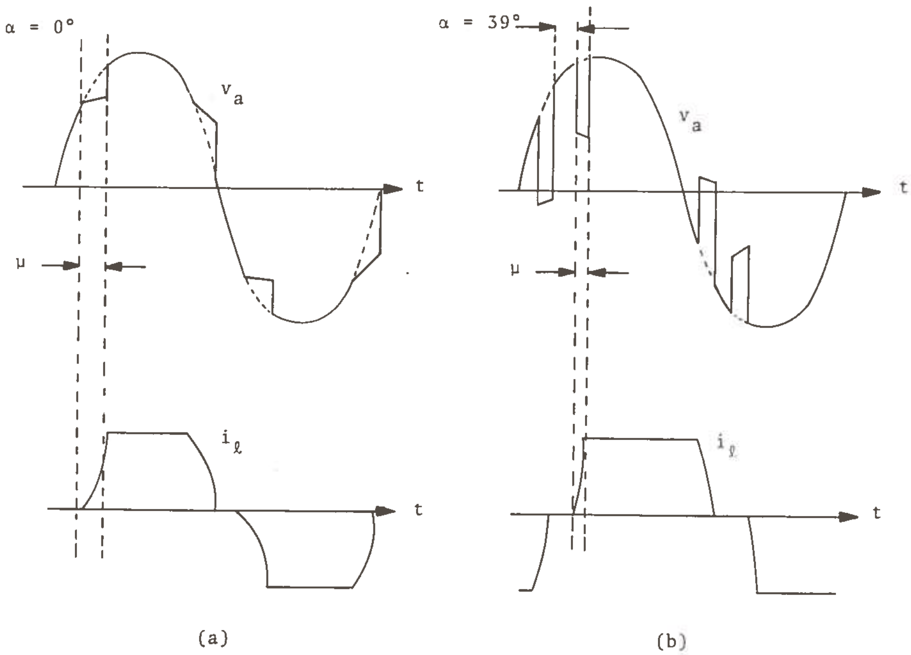


Figure 5-1. Waveforms of Line Current and Primary Bus Voltage For a Six-Pulse Rectifier Supplied from a System of j0.09 pu Impedance and Rectifier Transformer of j0.045 pu. (a) Maximum DC Output, α = 0°; (b) Reduced DC Output, α = 39°

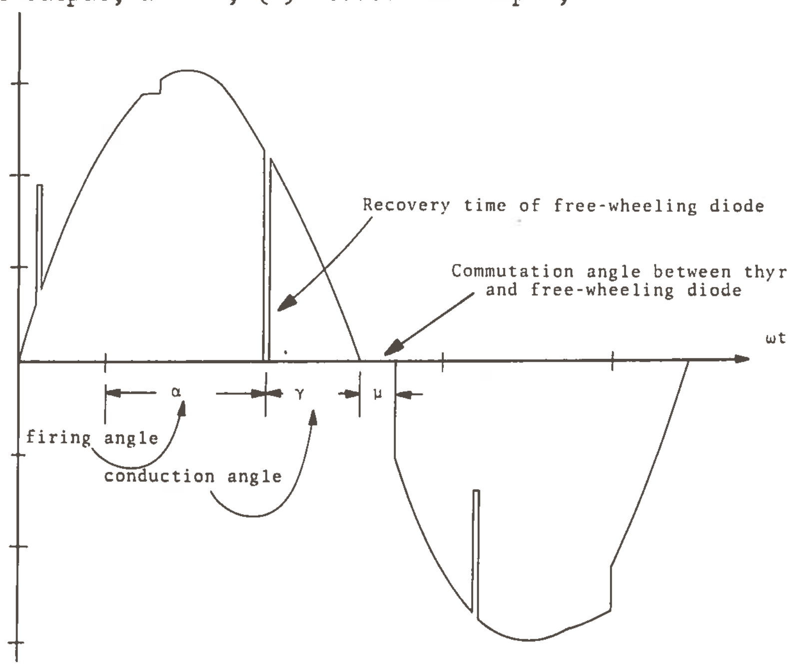


Figure 5-2. Line Voltage Waveform at Terminals of Three-Phase Incomplete Bridge Rectifier for 100-hp DC Motor Drive System Operating at Low Speed, Nearly Full Load Torque. Line Impedance is j0.03 pu Drive System Base.

Harmonic voltage generated by power harmonic currents produce additional dielectric losses and heating in AC power capacitors and in cables. Dielectric loss is proportional to voltage squared and frequency (V^2f); dielectric stress is proportional to peak voltage. A measure of harmonic voltage effect on the loading of dielectric materials is the total fundamental and harmonic-frequency kilovars, expressed as

$$\text{kvars} = \sum_n \frac{V_n{}^2 n}{X_1} \times 10^{-3}$$

where V_n is the harmonic voltage, X_1 is the reactance at fundamental frequency, and n is of the harmonic order. For example, a fifth harmonic voltage of 0.20 pu will contribute $(0.20)^2 \times 5 =$ 0.20 pu to the kvar loading of the capacitor. The NEMA specification for capacitors limits the loading to 1.35 pu kvar, including the effect of overvoltage and harmonics. Parallel resonance at a harmonic frequency can produce excessive voltage, loading, losses and excess temperature rise. A cure used by the utility industry is to insert reactors in series with the capacitors to shift the resonance points. With diode rectifiers, in which the power factor of the rectifier set is determined largely by the overlap angle, capacitors have not been needed nor extensively employed for power factor correction. However, with the advent of controlled rectifiers using saturable reactors or thyristors, in which the power factor decreases as the DC output of the rectifier set is adjusted downward, capacitor banks have been installed for power factor correction and resonance conditions have ensued.

Harmonic voltages applied to induction motors produce travelling air gap magnetic fields at speeds in the same order as the harmonics, that is, the 5th harmonic produces a magnetic field travelling at five times synchronous speed. The harmonic fields produce rotor losses and may produce parasitic torques if they travel backwards, so-called negative sequence harmonics. The 5th harmonic, the 11th harmonic, and so forth, are negative sequence harmonics and will produce parasitic torques. These added losses and torques can limit the performance of propulsion and auxiliary rotary and linear motors on vehicles.

The utility industry has been concerned with the effects of harmonic current on synchronous machines, which produce the same types of losses in the field structures and parasitic torques as they produce in induction motors. The criterion for harmonic currents in large synchronous machines is 6 percent of the rating. Where substantial transmission facilities exist between power plants and connection points of large potential harmonic loads, the transmission line capacitance generally attenuates the harmonic currents below the criteria level. Synchronous condensers located close to such loads must be specially designed to handle the harmonics, or be derated. However, if the power converters of a transit system were operated coupled closely to generating plants, then the harmonic currents, unless corrected, could limit the operation of the synchronous machines.

6. HARMONIC SUPPRESSION

Every future transit system employing solid-state power converters on the wayside or in the vehicles will require some measures for harmonic suppression. The extent of the measures will be determined by the short circuit MVA of the electric power system at the point of connection of the converter. A first-order threshold at which measures for harmonic suppression should be considered is when the rating of the power converter exceeds 1 percent of the short-circuit rating of the power system at the point of connection. Since the short-circuit rating of the system increases with voltage level, the power converter should be supplied from the highest feasible system voltage level to minimize the measures required. Under this criterion, it is not practical to supply power converters from distribution circuits already available, but to use feeders from nearby substations at highest available voltage.

Tuned filters connected on the AC side of converters are the standard method of suppressing the effects of harmonic currents. The largest cost of such filters are for the capacitors. Since most transit equipment will require capacitors for power factor correction, the cost of the filters can be reduced by combining them with the capacitors already required for power factor correction. In the specification for each power conversion unit a harmonic standard must be incorporated and the recommendation made that the filter be combined with the power factor correction means.

The effect of harmonic currents can also be reduced by employing the largest pulse number in power converters for transit systems. For the maximum power levels contemplated, the best economical and technical compromise is 12-pulse equipment, which means rectifier sets with two 6-element bridges supplied from phase-shifted transformers to obtain the 12-pulse operation. The 11th harmonic will be the lowest normal level in the AC line current to the converter. Six-pulse rectifiers should only be allowed at power levels up to 500 kW.

Whereas harmonic filters and high-pulse number rectifiers are easily employed on wayside equipment, they are difficult to employ for on-board vehicle power converters. Filters are heavy and bulky and should only be used if necessary.[16] Twelve-pulse rectifiers require some means for phase-shifting the AC voltages. To minimize the weight of full-rating transformers, lighter auto-transformers for phase shifting alone can be used. Practically all on-board power converters used to date have been single-phase, where harmonic cancellation by pulse number has not been possible.[16] Experimental vehicles, such as the TACRV, have employed three-phase systems, and the trend will certainly grow in that direction.

Harmonic standards for electric power systems and within transit systems must take into account the ambient harmonic levels resulting from inherent system resonances, transformer magnetizing current, gaseous discharge lighting load, and other effects, which may produce ambient levels of 1 percent before transit load is connected. The standards for the harmonic effects of transit systems should be commensurate with the ambient harmonic levels.

7. RECOMMENDED STANDARDS

The standards for harmonic levels will be different for vehicles and for wayside stations. The application of standards is more manageable for wayside stations, because the supply system impedance is better known. The impedance seen from a vehicle looking into the wayside power rail and the whole supply system is a function of the position of the vehicle and the operation of other vehicles on the same power rail and system. In addition, the vehicles might carry on-board AC capacitors, which could resonate or at least sharply change the impedance of the system as the vehicle travels.

A severe standard for all power converters whether on-board or at wayside stations is a limit of AC current harmonics to 5 percent rms of the fundamental current. The rms harmonic current is defined as $I_h = \sum_{n, n \neq 1} I_n^2$. Such a specification on harmonic current then provides a limitation which is independent of the supply system impedance and is reasonable in the industry.

A usable harmonic voltage specification for a common point in the electric power system from which other loads are supplied is a value of 1 percent amplitude (of the fundamental) for each harmonic voltage produced by the harmonic current of the converter. Such a common point would be the supply bus for several converters, transformers, or the connection point to the utility. This specification is convenient to apply because harmonic voltage calculations can be made for each harmonic individually. For example, the effect of the 5th harmonic current can be calculated and a 5th harmonic filter section designed to limit its effect to 1 percent of fundamental voltage. A specification of 3 percent per voltage harmonic can be used for a three-phase power rail, at the power collector of a vehicle, and at the secondary voltage bus of transformers used to supply transit systems. All of the on-board auxiliary, communications and control equipment of a vehicle would be subject to the 3 percent harmonic voltage criteria. The harmonic voltage requirement could also be expressed as an overall rms harmonic value. A value of 2.5 percent rms for the common load connection, corresponding to the 1 percent per component criterion, and 7.5 percent rms for the power rail and vehicle, corresponding to the 3 percent per component criterion, would be acceptable.

A standard for harmonic voltage can also be given in terms of of a deviation from a sine wave. The voltage at the point of connection to the converter can be restricted to a deviation of ±5 percent from a sine wave drawn as an "average" of the actual waveform. This is a particularly stringent specification because it limits the amplitude of nicks and other short time deviations from the normal sine wave. However, this is a good specification for limiting high frequency electrical noise from converters.

The deviation factor D given in the previously referenced CIGRE paper[11] is a harmonic voltage specification in which the arithmetic sum of the harmonic voltage components is compared with the fundamental component. The value of D = 5 percent can be used for the connection point to the power system and D = 10 percent for the power rail and vehicle. The D factor is difficult to apply because it requires a summation of components, so that each component cannot be treated independently.

8. CONCLUSIONS

The American electric utility industry apparently has no existing standards, other than TIF Standards, governing the harmonics produced by customer equipment such as rectifiers and other power converters. The power harmonics produced by on-board and wayside transit equipment can have effects on cables, motors, and AC capacitors, as well as interfering with the function of control, telecommunications, and other electronics equipment. It is short sighted to assume in the design of transit systems that fixes will be made in the field wherever the harmonic problem is serious. Harmonic standards should be adopted and included in all equipment and system specifications, so that equipment will be designed initially taking into account the harmonic problem. We recommend that each harmonic voltage component be limited to 1 percent of fundamental amplitude at the connection point to the utility and 3 percent within the transit system, such as on the power rails. There should be no problem in having the Department of Transportation set up standards and impose them on manufacturers of transit equipment, with the full agreement of the electric utility industry.

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