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Understanding and Managing Power System Harmonics

by

Franklin H. Holcomb
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The application of nonlinear electrical loads has increased dramatically in recent years. These loads include computers and other equipment with switch-mode power supplies (SMPS), high-efficiency fluorescent lighting systems with electronic ballasts, and adjustable-speed drives with power electronic convertors. All these loads have nonlinear voltage-current characteristics, and all produce harmonic distortion on the power system.

Harmonic currents in the power system can cause unusual effects in the wiring and surrounding power equipment. These effects include the overheating of wires, circuit breakers, transformers, and other equipment, the nuisance tripping of breakers, the saturation of various magnetic components in the system, and the creation of voltage distortion for all joining and connecting loads.

This report offers a comprehensive overview of power system harmonics. It includes the causes, effects, and mitigation procedures for harmonic voltages and currents. Field engineers and designers of new facilities will find this report useful.

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Harmonic currents in the power system can cause unusual effects in the wiring and surrounding power equipment. These effects include the overheating of wires, circuit breakers, transformers, and other equipment, the nuisance tripping of breakers, the saturation of various magnetic components in the system, and the creation of voltage distortion for all joining and connecting loads.

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FOREWORD

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CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

TABLES (Cont'd)

Number **Page**

UNDERSTANDING AND MANAGING POWER SYSTEM HARMONICS

1 INTRODUCTION

Background

Power system harmonics are an increasingly serious problem due to their damaging effects on user loads and on the power network. Power losses due to harmonics also have an associated energy cost. Harmonics problems can be traced to two industry trends: (1) a dramatic increase in the use of nonlinear loads, such as static power converters (rectifiers), switching power supplies, and other electronic loads, and (2) a significant change in the design philosophy of all power apparatus and load equipment. Manufacturers are now designing power devices and load equipment with minimum design margins compared to those margins used only a few years ago. In iron core devices, for example, the operating points exhibit more nonlinear characteristics, resulting in a substantial increase in harmonics. Considerable attention has been paid to the higher harmonic frequencies that cause interference with communication and telephone circuits, but very little attention has been paid to lower-frequency bands that cause heating in electrical devices and apparatus.

Objective

This report provides information and guidance to engineers and technicians who install, operate, troubleshoot, and maintain AC power systems that supply linear and nonlinear loads.

Approach

This report contains several chapters. Chapter 2 defines harmonics, resonance, and total harmonic distortion. Chapter 3 describes the sources of harmonics and their system-response characteristics, needed for understanding their behavior relative to power system elements. Chapter 4 provides information on the effects of harmonics on power system elements and equipment. Chapter 5 discusses the criteria for the limits of harmonic distortion in the power system. Chapter 6 describes survey procedures and instrumentation for assessing power system problems. Chapter 7 provides generic guidelines and flow charts for troubleshooting harmonic and noise problems. Procedures are described for checking grounds (including the facility ground system) and common-mode noise. Chapter 8 provides criteria for new power system designs and the rehabilitation of existing installations. These criteria are recommended for use at Command, Control, Communication, and Intelligence (C^3I) facilities. Chapter 9 outlines safety precautions for personnel doing troubleshooting. Chapter 10 outlines the costs of electrical power distribution equipment used for mitigating harmonics, and also discusses cost benefit analysis of the mitigating equipment.

Scope

This report addresses harmonics problems in existing facilities as well as those introduced in the design process.

2 DEFINITIONS AND CONCEPTS

Huge amounts of electronic equipment (e.g., computers, microprocessor-based communications systems, safety and security systems, and facsimile equipment) are being used in new and existing U.S. Army facilities. Most of this equipment is affected by harmonics because these power systems are not designed for nonlinear loads. These problems range from overloading of the phase and neutral conductors of the power distribution system to premature failure of electrical equipment because of overheating. An understanding of basic definitions and concepts is necessary to correctly identify problems and solutions.

Harmonics

Harmonics are voltages and currents present on an electrical system at some multiple of the fundamental frequency (60 Hz), such as the 2nd (120 Hz), 3rd (180 Hz), and 5th (300 Hz). To understand harmonics, it is important to understand the nature of "clean" power. Clean power implies that the current and voltage waveforms of the power system are pure sine waves, as shown in Figure 2-1.

A sine wave is the plot over time of the sine of the angle (θ) that a vector (M) rotating at a uniform speed through a full revolution of 360 degrees makes from a start or zero degree position. This waveform contains only one frequency component whose period is the time of one rotation (revolution) and whose maximum amplitude is M. The positive maximum occurs when θ is 90 degrees ($\sin 90° = 1$), and the negative maximum occurs when θ is 270 degrees ($\sin 270° = -1$). Similarly, the amplitude is zero when θ is 0 degrees at the start, at 180 degrees (at half-cycle), and at 360 degrees (at the end of one cycle). Its period is the time it takes for the vector M to complete one revolution. The frequency of this sinusoidal waveform is 1/period. The frequency of power in the United States is maintained at 60 cycles per second (60 Hz). In real power systems, however, there is always some distortion of voltage and current waveforms. As such, the waveforms are not totally a sine wave. This deviation is equivalent to adding one or more sine waves of different frequency. The sine waves that distort a power system are integral (whole-number) multiples of the fundamental power frequency. These whole-number multiples are called "harmonics" of the fundamental. The distortion caused by superimposing or adding harmonics

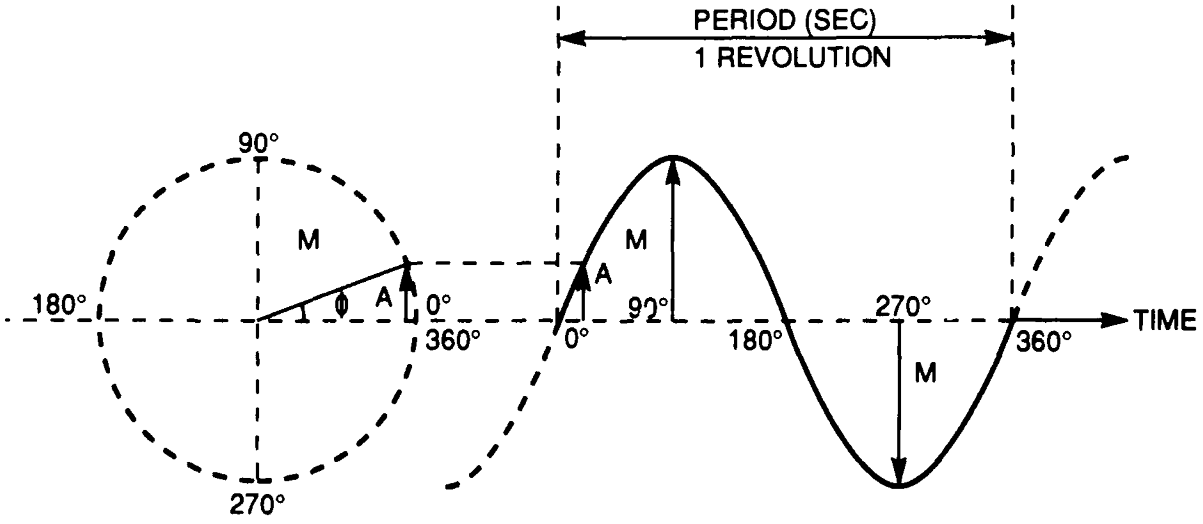

Figure 2-1. Sine Wave.

to the fundamental sine wave is determined by their frequency and by their amplitude and timing (or phase) relationship to the fundamental. Figure 2-2 illustrates 3rd harmonic distortion. In (A), the 3rd harmonic is one-third the amplitude and in-phase with the fundamental. In (B), the 3rd harmonic is one-third the amplitude and 180 degrees out of phase with the fundamental.

The composite waveform in Figure 2-2 (A) is relatively flat (square) compared to the peaked waveform in (B). The difference is due solely to the phase of the 3rd harmonic. Both waveforms, however, contain the same frequencies and the same amplitudes, and both have the same root mean square (rms) values. The composite waveform shown in Figure 2-2(A) is a sine wave whose peaks are clipped by the 3rd (odd) harmonic. Clipping can occur, for example, at load saturation when an increase in voltage does not produce a proportional increase in current. Such nonlinear behavior distorts the current waveform by introducing odd harmonics. This is why the many nonlinear loads in today's power systems cause harmonics.

Resonance

To improve the load-power factor of the electrical power system, the common practice is to add shunt-connected capacitors at the main substation to correct for the inductive loads (transformers, motors, etc.). Although shunt-connected capacitors may improve the power factor, they may also create serious problems, particularly when harmonics are present. Any capacitance and inductance forms a circuit tuned (capacitance and inductive reactance are equal) to what is called the "resonant" frequency. If enough harmonic energy is present and its frequency matches that of the resonant circuit, then a very large current (many times the original harmonic current) will flow. This current will produce extreme voltage drops across all circuit elements, blowing fuses, damaging components, and deflecting an excessively high harmonic level back into the power system. Resonance often occurs when shunt capacitors are located near a harmonic current source and, thus, create a parallel resonant circuit with the equivalent system

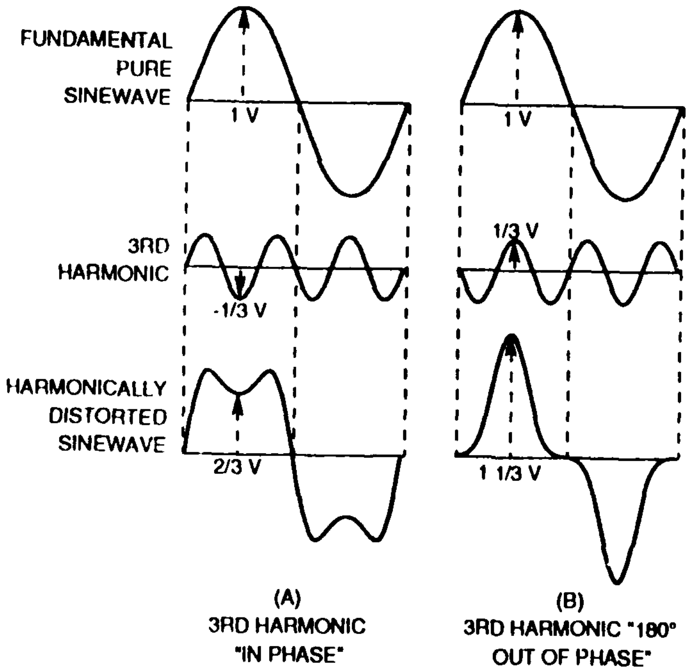

Figure 2-2. Harmonic Distortion and Phase.

impedance of the power system, as shown in Figure 2-3. System response characteristics under resonance conditions are discussed in Chapter 3.

Total Harmonic Distortion

The total harmonic distortion (THD) is defined as the square root of the sum of the squares of amplitude of all harmonic voltages or current divided by the amplitude of the fundamental voltage or current, expressed in percent. It is calculated as follows:

$$\text{THD}\ (\%) = \frac{1}{V_1}\sqrt{\sum_{k=2}^{n}(V_k)^2} \times 100 \qquad \text{[Eq 1]}$$

where:

V_k = voltage at the kth harmonic
V_1 = fundamental frequency voltage
n = order of harmonics.

The THD is used to quantify the effect of the harmonics on the power system voltage or current. The THD is a rough measure of how distorted the waveform is compared to a pure sine waveform.

Harmonic Limits

The harmonic limits for current and voltage distortion are discussed in detail in Chapter 5. The criteria on which the harmonic limits are based can be classified into the following three groups:

1. Voltage distortions are limited to a maximum value. This method of harmonic limitation is used primarily to protect electronic loads, instrumentation, and electrical power distribution equipment against the harmful effects of harmonics. As discussed before, maintaining the THD factor in the range of 3 to

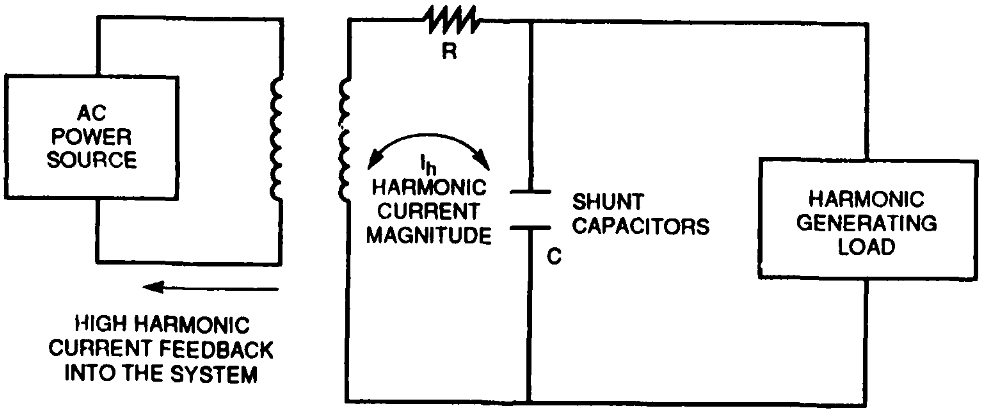

Figure 2-3. Resonance Due to Power-Factor-Correcting Capacitors.

10 percent is a first step in protecting performance and ensuring the long lifespan of a wide range of electrical equipment.

2. Injected current harmonics are limited to maximum values that depend on the "stiffness" of the power system. The usual cause of voltage distortion is the flow of nonsinusoidal currents. Current harmonics also upset communication systems. Therefore, it is important to set limits on current harmonics to keep the electromagnetic interference (EMI) and the active losses within tolerable limits.

3. Both voltage and injected current are limited to minimize the effects of the harmonics on load equipment and power distribution equipment. In summary, limiting both the voltage and the current harmonics will minimize their harmful effects. These effects are discussed in more detail in Chapter 4.

3 SOURCES OF HARMONICS AND SYSTEM RESPONSE CHARACTERISTICS

Power system harmonics can seriously degrade equipment performance and overall power quality. A brief discussion of sources of harmonics and system response characteristics follows.

Sources of Harmonics

Harmonics are generated by any load that draws current that is not proportional to the applied voltage. These include transformers during energization, motors with fractional pitch windings, and nonlinear loads. Power systems containing nonlinear circuit elements carry currents that are nonsinusoidal (not a pure sine wave), even when the applied voltage is a pure sine wave. Most loads are somewhat nonlinear, especially electronic loads that do not draw a continuous current, loads that are switched on for only part of the cycle. Such loads create considerable harmonic distortion on the power system. Table 3-1 shows typical harmonic currents for several types of loads.

Power electronics, a major source of harmonics, are being used in devices ranging from small appliances to huge convertors on the power system. The power rectifier, widely used in power electronics for converting AC to DC, causes switching within a cycle. These circuits are nonlinear and draw currents of high harmonic content from the source.

System Response Characteristics

The nonlinear loads discussed in this chapter can be represented as current sources of harmonics. The harmonic voltage distortion on the power system depends on the impedance-versus-frequency characteristics in these harmonic current sources. The factors that affect the system frequency-response characteristics are discussed below. These factors should be considered when evaluating a system.

Load Characteristics

Resistive loads provide a damping effect and reduce the magnification of harmonic levels near parallel resonance frequencies. Inductive loads, such as motors, which contribute to the short-circuit capacity of the system, can shift the resonance frequency. Inductive loads do not provide significant damping.

Capacitor Banks

Capacitor banks, such as those used for power-factor improvement (reactive var compensation) and for commutation of some static converters, affect system frequency response characteristics. Because capacitors can cause resonance conditions, they magnify harmonic levels. Power-factor improvement capacitors, normally installed at the main substation, may contribute to harmonics problems on the line side, as opposed to the load side.

Insulated Cables

The line-charging capacitance of insulated cables acts as a parallel circuit with the system inductance similar to that of capacitors. Therefore, insulated cables also affect system frequency-response characteristics, but not as much as shunt-connected capacitors do.

Table 3-1

Typical Harmonic Current Magnitudes

Transformer Inrush	DC, up to several times Rated Load Current Fundamental, up to several times Rated Load Current 2nd, up to 67% Rated Load Current 3rd, up to 23% Rated Load Current 4th, 5th, up to 8% Rated Load Current		
Transformer Magnetizing	1st, 0.5 to 2% of Rated Load Current 3rd, up to 80% of Fundamental Magnetizing Current 5th, up to 55% of Fundamental Magnetizing Current 7th, up to 35% of Fundamental Magnetizing Current		
Motors	Up to 3% of Rated Load Current at the 2/5, 4/5, 8/5, 22/5 and 32/5 harmonics due to rotor and pole imbalances		
Arc Furnaces	Order	Steady Melting	Boring In
	2	4.5%	up to 50%
	3	4.7%	up to 50%
	4	2.8%	up to 30%
	5	4.5%	up to 50%
	6	1.7%	
	7	1.6%	up to 30%
	8	1.1%	
	9	1.0%	
	10	1.0%	
Fluorescent Lighting	Neutral current is almost entirely 3rd harmonic, can exceed Line Current.		
3-Phase Converters	Order	Magnitude	
	5	up to 20%	
	7	up to 14%	
	11	up to 9%	
	13	up to 8%	
	17	up to 6%	
	19	up to 5%	
	23	up to 4%	
	25	up to 45%	
1-Phase Converters	Order	Magnitude	
	2	up to 50%	
	3	up to 33%	
	4	up to 25%	
	5	up to 20%	
	6	up to 17%	
	7	up to 14%	

Resonance Conditions

Harmonic currents generated by nonlinear load currents flow toward the lowest impedance. Usually the system impedance (utility) is much lower than the parallel impedance paths of the loads. However, the harmonic current will divide according to the impedance ratio of the system impedance and the parallel impedance paths of the loads. When shunt capacitors are connected in the distribution system, the system offers a very low impedance path to higher-frequency harmonic currents. Parallel resonance occurs when the system inductive reactance is equal to the capacitative reactance of the shunt-connected capacitors at one of the characteristic harmonic frequencies generated by the nonlinear load. Under these conditions, the harmonic current is magnified. This high current causes voltage distortion and telephone interference on nearby distribution and telephone circuits. Series resonance results when the series combination of capacitive reactance (capacitor banks) and inductance (line or transformer) are equal. Series resonance offers a low impedance path to harmonic currents and can result in high levels of voltage distortion. An example is a load-center transformer with capacitors connected to its secondary, which appears as a series circuit when viewed from the transformer primary.

Transformer

The transformer can be represented as a leakage reactance in series with an internal resistance. At high frequencies, the leakage reactance becomes large and can block harmonic currents from reaching the connected load. Isolation transformers are used with this principle in mind, to isolate or protect some loads from harmonic currents.

Impact of Power System

Power system frequency-response characteristics are controlled by the interaction between shunt-connected capacitors and system inductances. Insulated cables can also influence the system resonances. Most severe resonant conditions occur when a large, single-capacitor bank is the primary means of shunt compensation on the system. In this case, there is one resonant point on the system. Significant voltage distortion and magnification of harmonic currents can occur if this resonance occurs at a harmonic current generated by nonlinear load.

4 EFFECTS OF HARMONICS

The harmful effects of harmonic currents can be divided into three categories: *thermal stress* due to current flow, *insulation stress* due to voltage effects, and *load disruption* due to voltage distortion. This chapter describes each of these categories, as well as specific effects on parts of the power system.

Thermal Stress

Harmonic currents increase copper, iron, and dielectric losses in the equipment. These losses increase thermal stress. In general, the resistance of a power apparatus increases with frequency. Therefore, the resistance of the apparatus at higher harmonic frequencies is greater than at the fundamental frequency. This variation is due to the skin effect inside the conductor of the power apparatus.

Harmonic currents cause increased copper losses in the power equipment and loads. Iron loss consists of hysteresis and eddy current loss. The total iron loss is a nonlinear function of frequency and magnetic flux density. In particular, the eddy current losses are proportional to the square of the frequency. In addition, some harmonics, notably the 5th, are negative sequence (backward rotating) and can give rise to additional losses by inducing higher frequency currents in machine rotors. Dielectric losses occur in the insulation of the power equipment. They are functions of the square of the voltage, the loss factor, the frequency, and the capacitance.

Insulation Stress

Insulation stress depends on the instantaneous voltage, the magnitude of the voltage, and the rate of rise of voltage. The presence of voltage harmonics can cause an increase of the crest value of the voltage, which increases insulation stress. This increase is not of concern for most power system equipment. However, capacitor banks are sensitive to overvoltages and should be protected.

Load Disruption

Load disruption is defined as an objectionable, abnormal operation or failure caused by voltage distortion. Electronic loads whose normal operation depends on a pure sinusoidal voltage source are susceptible to load disruption.

Effects of Harmonics on Power System Equipment

The effects of harmonics on specific classes of power system equipment are as follows.

Transformers

The effects of harmonics on transformers are increased copper and iron losses, insulation stress, and in some cases, resonance between transformer winding and line capacitance. The transformer losses are frequency-dependent and grow as frequency increases. Therefore, higher-frequency harmonics may be more detrimental to transformer heating than lower-frequency harmonics. In particular, transformers serving nonlinear (electronic) loads exhibit increased winding (eddy-current) losses due to the harmonics generated by these loads. Also, transformer windings connected as delta-wye, where the wye winding supplies the electronic loads, can suffer from an additional heating. This is because the 3rd and odd multiples of the 3rd harmonic current are additive in the neutral of the wye-connected secondary winding. These currents are then reflected back into the delta primary winding as a circulating current. This causes additional heating of the transformer winding.

The Neutral

For neutrals serving linear loads, the neutral current magnitudes are generally low in 3-phase, balanced circuits. For neutrals serving nonlinear loads, however, the neutral current magnitudes can be significantly greater than the associated phase currents. This problem is caused by the 3rd and odd multiples of the 3rd harmonic current (9th, 15th, 21st, etc.), because they are equal and in phase. At any point, the sum of the 3rd harmonic currents equals three times the value of any one of the phase currents. That is, these harmonics arithmetically add in the neutral of the 3-phase, 4-wire system. A neutral that is not sized properly can overheat, burn insulation, and become a fire hazard. The theoretical maximum neutral current with harmonics is at least 1.73 times, if not more, the phase current.

Protective Relays

Harmonics affect relay operation in a complex manner. Electromechanical relays (with induction disk) are susceptible to additional torque components when harmonic currents alter their time-delay characteristics. Ground relays cannot distinguish between zero-sequence current and the 3rd harmonic current. Therefore, excessive 3rd harmonic current can trip them. Relays that depend on voltage/current crest or voltage zeroes for their operation are also affected. Harmonic voltage and current levels of 10 to 20 percent are generally considered harmful to relay operation.

Metering and Instrumentation Devices

Metering and instrumentation devices are affected by voltage and current harmonics. Induction disk-type meters and instruments are designed and calibrated only for the fundamental current and voltage. Harmonics generate additional electromagnetic torque on these devices causing errors in data and information processing. Solid state meters measure power based on waveshape. In general, distortion has to be severe (greater than 20 percent) to cause significant errors in these measurements.

Electronic Equipment

Harmonic distortion can shift the zero-crossing of the voltage waveform. This can cause faulty operation in many types of electronic equipment, such as processors, magnetic disk drives, and peripheral controllers, which are sensitive to high-frequency noise and to frequency changes.

Switchgear

Harmonic components in the current waveform can affect the interruption capability of the switchgear. Harmonics affect the operation of the blowout coil that is used for pulling the arc into the arc chute of the breaker during an opening cycle. Also, the harmonic components affect the transient recovery voltage and the maximum transient voltage. Severe harmonics can cause circuit breakers to fail to interrupt currents successfully.

Capacitor Banks

Capacitor impedance decreases with frequency. Capacitor banks (usually found at the main substation) act as harmonic "sinks." As a result, most harmonic problems are first manifested at shunt-capacitor banks. There, depending on their severity, they can cause blown fuses and capacitor failure. Harmonics at capacitor banks can increase dielectric losses, create resonance conditions resulting in the magnification of harmonics, and cause overvoltages.

Rotating Machinery

Harmonic voltages above 5 percent increase heating in rotating machinery. This is due to copper and iron losses, machine inefficiency, and machine torsional oscillations. Torque pulsations in motors due to harmonics can excite mechanical resonances creating excessive noise and vibration. Induction motors may have difficulty starting. Solid-state controllers may operate poorly due to high harmonic voltages produced elsewhere in the power system.

Communications and Information Processing Systems

Harmonics can cause interference with communications, telephones, and data systems due to electromagnetic induction, capacitive coupling, and radiation or flow of ground currents. These noise signals can cause problems at distances remote from their source.

Generator Controls

Modern generators use electronic controls to regulate the output voltage of the generator, to control the speed of the engine or prime mover, and to share the load proportionately among parallel units. Many of these control devices use circuits that measure the zero-crossing point of the voltage or current wave. Harmonics can cause the zero-crossings to shift or to increase in number compared to 60 Hz. This can cause instability in speed and frequency control and can make the paralleling of generators difficult.

Lighting Devices

Incandescent lamps are highly sensitive to increased heating effects. A large distortion of the voltage significantly shortens bulb life. The effect of harmonics on arc lamps depends on the ballast type. With inductive ballasts, moderate distortion due to harmonics does not cause a significant shift in the lamp operating point. Effects on capacitive ballasts are not clear. This is due in part due to the nonlinearity of the arc lamp bulb. The reactance of the ballast does decrease as the harmonic frequency increases, which could shorten ballast lifespan.

5 HARMONIC DISTORTION LIMITS

The levels of power system harmonics are rising, due mainly to the proliferation of computers and electronic equipment. The types of equipment most affected by harmonics are those designed to operate on relatively pure sine wave power. These include electronic devices used for communications or data processing. Their power supplies are designed to block harmonics to some degree, but severe distortions are not always avoidable. When severe distortion occurs, power equipment is likely to be affected: computers exhibit data errors; controls on electronic processes operate out of sequence, lose data or fail; and computer-controlled robots or machine tools operate erratically. Telephone lines, which may be located close to power lines, can pick up interference, even from low-level harmonics. Excessive harmonics fed back into the power system can cause television interference.

The higher frequencies of harmonics create some basic problems for whole classes of equipment. In inductive equipment such as transformers, motor windings, and power lines, excessive harmonics cause inductive reactance that increases with frequency. This changes equipment operating characteristics and causes heating effects. In capacitive equipment, capacitive reactance decreases with frequency, causing shunt capacitors across power lines to draw off too much current. In general, power harmonics degrade power and load-equipment performance.

To deal with harmonics problems in an electrical power system, a harmonic analysis study should be conducted to ascertain and verify harmonics and their magnitudes on the system. This study should involve the development of corrective measures that are needed to limit harmonics. The criteria for conducting this study are identified in Chapter 9, "Harmonic Analysis Studies," of ANSI/IEEE-STD-399-1980, *Industrial and Commercial Power System Analysis* (ANSI 1980). They are summarized below. The values obtained from this study should be compared against the values recommended in the ANSI/IEEE-STD-519-1981, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems* (ANSI 1981).

Need for Harmonic Analysis Study

A harmonic analysis study should be performed if thermal and insulation stress are evident or load disruption and communication interference is experienced *and* if any of the following problems exists: transformers, motors, cables, and generators are overheating even when run at or below their rating; capacitor fuses are continuously blowing; there is excessive telephone interference; nuisance tripping of circuit breakers and ground relays is occurring; or the system neutral is overheating. The study should also be performed to determine: (1) whether the capacitor banks being added to correct the power factor will cause harmonic problems, (2) the optimum size of a filter to tune out offending harmonics, and (3) the effect of rectifiers on the performance of electronic load equipment.

Software for harmonics analysis is available commercially from Westinghouse, EDSA Micro Corporation, CYME, and others. These programs calculate and plot totalized harmonic voltages, currents, and kVA magnitudes at the buses, plot the system impedance as a function of frequency, and recommend ways to reduce excessive harmonic overvoltages and overcurrents.

The values obtained from the study should be compared against the criteria discussed in Chapter 6 for harmonic levels. An assessment should be made to see if any corrective measures are needed to reduce the calculated/measured levels to within acceptable limits.

Harmonic Distortion Levels

The current, voltage, and THD levels that are considered low enough to ensure that the equipment will operate satisfactorily are discussed in ANSI/IEEE-STD-1986 (ANSI 1986) and ANSI/IEEE-STD-519-1992 (ANSI 1992). The recommendations described in this standard are considered to reduce the harmonic effects at any point in the entire system by establishing limits on current and voltage at the point of common coupling (PCC). The traditional definition of the point of common coupling is the point where the power from the utility is delivered to the customer. For commercial and residential customers, the PCC would typically be at the point where power was delivered to a building, ie., at the service entrance. Since harmonic distortion levels are typically highest inside buildings, it is recommended that the aforementioned guidelines be applied not only at the PCC (the PCC of an Army installation is at the distribution substation), but also at individual buildings.

Current Distortion Limits

Harmonic current limitations are based on the size of the supply (utility) network. The relative size is defined as the short-circuit ratio (SCR) at the PCC. The size of the utility system is defined by the level of short-circuit (I_{SC}) at the PCC. The consumer's plant size is the total fundamental frequency current in the load (I_L) including all linear and nonlinear loads. Therefore, the short-circuit ratio is given by I_{SC} divided by I_L ($SCR = I_{SC}/I_L$). The objective of current limits is to limit the maximum individual frequency voltage to 3 percent of the fundamental and to limit the voltage harmonic distortion to 5 percent for systems without major parallel resonance at one of the injected harmonic frequencies. Table 5-1 lists the harmonic current limits based on the size of the load with respect to the size of the power system to which the load is connected. The load should be calculated as the average current of the maximum demand for the proceeding 12 months. The limits shown in Table 5-1 should be used as system design values for the worst case for normal operation in a steady-state condition (i.e., lasting longer than 1 hour). For shorter periods, during start-ups or universal conditions, the limit may be exceeded by 50 percent.

Limits on Commutation Notches

Line notching, notch depth, and notch area are characteristics related to the operation of thyristors and other switching semiconductor devices, such as those found in ac-to-dc convertors. "In a full convertor, the thyristors operate in pairs to convert ac to dc by switching the load current among the various thyristor pairs six times per ac cycle. During this process, known as commutation, a brief short circuit occurs, which produces notches in the line-to-line voltage waveform, as shown in Figure 5-1." (Jarc and Schieman 1985) The notch depth refers to the magnitude of the notch (volts), and can be expressed as a ratio of inductances; source/total. "The notch area is the area of the main notch in the line-to-line voltage. It is dependent only upon the source reactance and the current being commutated." (TCI Tech Tips 1990) Figure 5-2 is an example of an ac-to-dc convertor, illustrating the source reactance, point of common coupling (PCC), and the line reactance of the system. "The 'Source Reactance' includes distribution transformers and lines upstream from the coupling point. The 'Line Reactance' includes lines, isolation transformers, or reactors between the coupling point and the convertor" (TCI Tech Tips 1990).

The notch depth, the THD, and the notch area of the line-to-line voltage at the PCC should be limited to the percentages and values shown in Table 5-2 for a low voltage system. Special systems are power systems that serve C^3I facilities, hospitals, airports, and other specialized facilities. General systems are power systems that supply general commercial and industrial electrical and electronic loads. Dedicated systems are power systems that serve rectifier/convertor loads exclusively.

Table 5-1
Current Distortion Limits for Distribution Systems
(120 V - 69,000 V)

MAXIMUM HARMONIC CURRENT DISTORTION IN % OF I_L						
INDIVIDUAL HARMONIC ORDER (ODD HARMONICS)						
I_{sc}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25 percent of the odd harmonic limits above.

Current distortions that result in a direct current offset (e.g., half-wave converters) are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

I_{sc} = maximum short circuit at PCC
I_L = maximum demand load current (fundamental frequency component)
PCC = point of common coupling with utility
TDD = total demand distortion (the total harmonic current distortion as percentage of the maximum demand load current)

Source: IEEE-519-1986

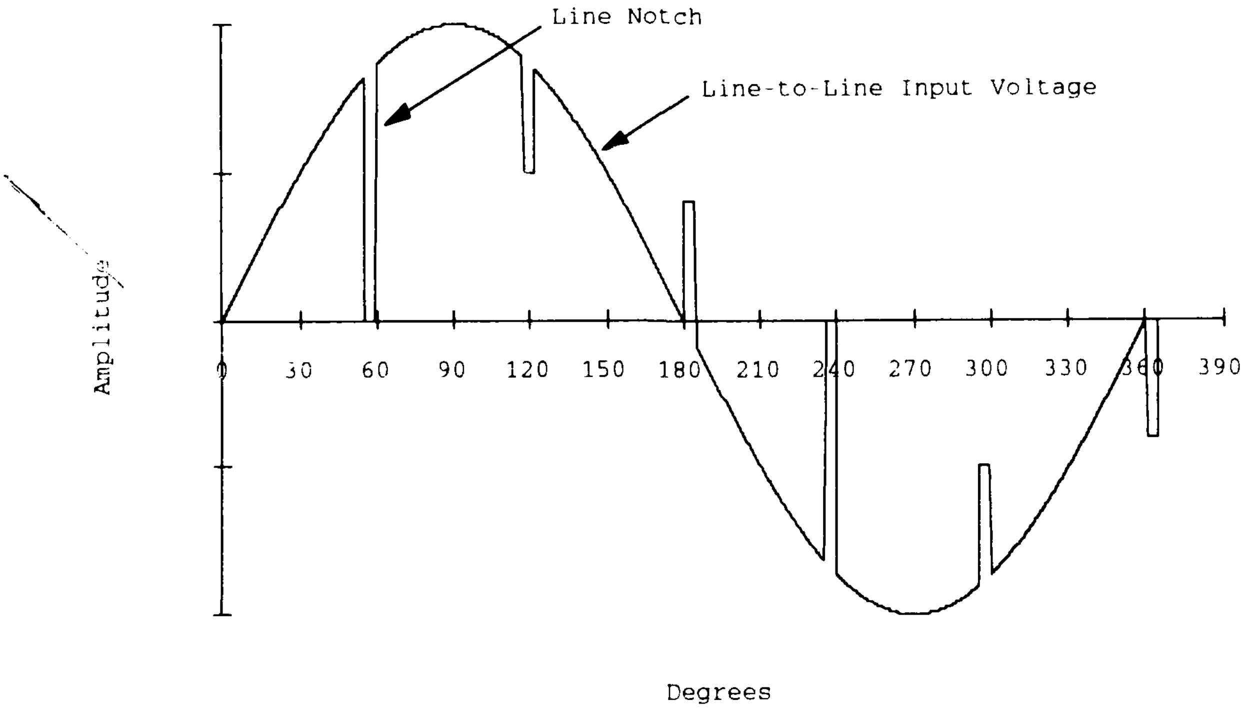

Figure 5-1. Example of Line Notching from an ac-to-dc Convertor. (Adapted from Jarc and Schieman 1985).

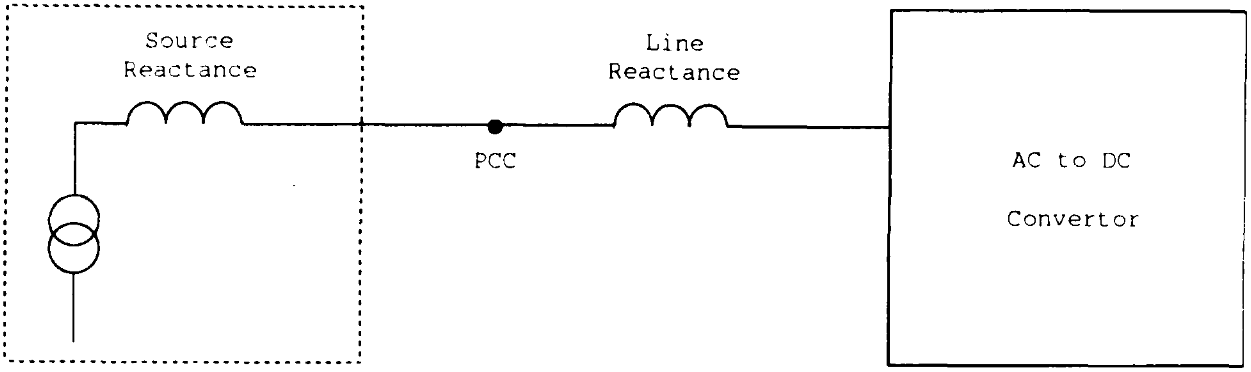

Figure 5-2. Reactance Distribution for an ac-to-dc Convertor. (Adapted from TCI Tech Tips 1990).

Table 5-2
Voltage Distortion Limits for Distribution Systems
(120 Volts - 69000 Volts)

	Special Systems	General Systems	Dedicated Systems
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area (A_N)*	16,400	22,800	36,500

* This value is in volt-microseconds at rated voltage and current.

The value A_N for other than 480 V systems should be multiplied by V/480

Source: IEEE-519-1986

6 ASSESSING POWER SYSTEM PROBLEMS

If harmonics problems are suspected, answering these basic questions will help to identify the causes and determine solutions:

- Are harmonics present in both voltage and current waveforms?
- How large are each of the voltage and current harmonics?
- Do they exceed reasonable limits?
- Where are they present?
- Are they localized, or do they exist throughout the system?
- Are they present all the time or only intermittently?
- Were they always present, or did they appear recently?

These questions can be answered by taking voltage and current measurements at various points of the power system. A full inspection of the power system should also be conducted.

On-site inspections and measurements are generally required to verify that power disturbances are the cause of electronic equipment malfunction or failure. The specific objectives of such an inspection, listed in order of priority, are to determine:

- The condition and adequacy of the wiring and grounding system
- The voltage quality at the point of use
- Potential sources and impacts of power disturbances on the equipment performance
- Immediate and near-term cost-effective solutions.

Site Inspection

Site inspection involves examining components of the electrical power distribution system. This typically begins with the inspection of the sensitive electronic load equipment, progresses through review of the branch circuit wiring, breaker panel, feeder wiring, main breaker panel, and switchboard, and ends with examination of the service entrance. Details of these inspections follow.

Sensitive Load Equipment

Examine the wiring for code violations, unsecured connections, bad insulation, visible damage, and miswired connectors (e.g., phase and neutral reversed or phase sequence reversed). Also, measure the phase, neutral, and ground voltages and currents.

Load Breaker Panel

Locate the breaker panel which feeds the sensitive electronic load. Visually check for code violations, unsecured connections, inadequate insulation, flashovers, arcing, burnt areas or carbonization indicating previous faults, and any other visible damage. Compare the size of incoming and outgoing conductors, especially that of the neutral and the phase conductor. The neutral should be the same size or larger than the phase conductor. Check the temperature of the insulated face of circuit breakers, and look for signs of overheating. Measure phase, neutral, and ground voltages and currents. Check the voltage drop across each critical barrier.

Transformer

Record the nameplate data of the transformer. Check the transformer for code violations, unsecured connections, visible damage, and signs of neutral overheating. Listen for hissing and buzzing noises. Examine the primary and secondary conductors, including the neutral and ground. Check the transformer temperature. Measure and record primary and secondary voltages and currents (including neutral and grounds), and the current in the neutral-to-ground bond. When the latter is more than a few hundred milliamperes, additional neutral-to-ground bonds exist.

Main Breaker Panel and Switchboards

Look for code violations, unsecured connections, inadequate insulation and visible damage, including burnt areas, flashovers, arcing, and other signs of previous faults. Note the size of incoming and outgoing conductors. Check for visual signs of overheating. Use an infrared camera, if available, to examine the hot spots in the main breaker panel and switchboard.

Service Entrance

Examine the incoming service, including the wiring, and note whether there are demand meters and/or power factor meters. Determine whether there are inductive loads regulated by a demand controller.

Earth-Grounding System

If questions exist about the state of the earth ground system, use an earth ground tester (available from AVO-Biddle or AFMC Corporation) to measure the resistance of the grounding system. Examine rms voltage levels (phase-to-phase, phase-to-neutral, and phase-to-ground) and current levels (phase, neutral, and ground). Verify the proper neutral-ground bonding. Test each panel in the power distribution system that serves the affected equipment, examining voltages, currents, phase rotation, ground impedance, and neutral impedance. Examine the isolation of the neutral conductor, conductor sizing, tightness of connections, and the types of loads served.

Miscellaneous

Determine if there is a correlation between the equipment failure and the disturbance occurrences. For instance, can the disturbance be correlated with shift changes, machine cycles, or air conditioning cycles? Check whether the disturbances are of sufficient magnitude to disrupt the sensitive electronic loads.

Factors to Consider in Evaluating Inspection Findings

All data collected through site inspection should be analyzed to determine which equipment is causing the power system problems. To determine the cause of these problems, consider the following.

Continuity of Conduit/Enclosure Grounds

A separate equipment grounding conductor should be used to ground electronic equipment. This conductor can be terminated either in an isolated grounding system (insulated from the conduit ground) or in the conduit ground system. Both ground systems are ultimately connected to the facility ground systems. However, the isolated ground and conduit ground must terminate at the first upstream neutral-ground bonding point. Ground impedance testers (available from ECOS, Inc., Chicago, Illinois) can measure the quality of both the isolated ground and conduit ground systems from the equipment to the power source. A continuously grounded metal conduit provides a shield for radiated interference. Therefore, phase, neutral, and equipment grounding conductors should be routed through a continuously grounded metallic conduit.

Wiring and Grounding

Wiring and grounding measurements can detect problems in the feeders and branch circuits serving the critical load. Test instruments should be selected carefully. *Do not use commonly available 3-light circuit testers.* These instruments have limitations, and they can falsely indicate that a circuit has no problems. They also cannot determine the integrity of power conductors. Recommended instruments include:

- A true rms multimeter
- A true rms multimeter clamp-on ammeter
- Ground impedance testers.

These instruments are described later in this chapter under "Instrumentation."

Load Phase and Neutral Currents

Load phase and neutral current measurements can determine (1) whether the load is sharing a neutral conductor with other loads and (2) whether the neutral conductor size is adequate. When sizing neutral conductors, one should remember that the current in the neutral can exceed the current in the phase conductor. This occurs because 3-phase circuits supplying single-phase loads have nonlinear current characteristics and share a common neutral. Phase and neutral conductor measurements should be made using a true rms reading clamp-on ammeter. To determine whether the neutral serving the sensitive electronic load is shared with other loads, check the neutral current with the sensitive load deactivated. If the current is not zero, the neutral is shared.

Transformer Sizing

Measurements are necessary to verify that the transformers are sized according to load. For nonlinear loads, the recommended practices for transformer derating are discussed in Chapter 8.

Neutral-Ground Bonds

The National Electric Code (NEC) requires bonding of the neutral and equipment-grounding conductor at the main service panel (NEC-250-53) and at the secondary side of separately derived systems (NEC-250-26(a)). If not properly bonded, neutral-ground bonds can create shock hazards for operating personnel and degrade the performance of sensitive electronic equipment. These bonds can be evaluated using a wiring and grounding tester. A voltage measurement between neutral and ground at the outlets may indicate voltage from a millivolt to a few volts under normal operating conditions. A zero voltage indicates the presence of a nearby neutral-ground bond. Excessive current on equipment grounds in distribution panels indicates the possibility of a load-side neutral-ground bond.

Equipment-Grounding Conductor Impedance

A ground impedance tester (available from ECOS, Inc., Chicago) can be used to measure the impedance of the equipment-grounding conductor. Very low impedance levels suggest properly installed and maintained equipment ground conductors. High impedance measurements indicate either poor quality connections in the equipment-grounding system or an improperly installed equipment-grounding conductor. An open-ground measurement reveals no equipment-grounding conductor connection. Verifying an impedance level of 0.25 ohms or less is recommended. This level helps protect personnel under fault conditions.

Neutral Conductor Impedance

A low-impedance neutral is essential to minimize neutral-ground potentials at the load and to reduce common-mode noise. A ground impedance tester can be used to conduct measurements of neutral conductor impedance.

Grounding Electrode Resistance

The grounding electrode system provides an earth reference point for the facility and a path for lightning and static electricity. Since the electrode connects the facility grounding system and the earth, an accurate measurement can be taken only when the grounding electrode is disconnected from all other grounds. For new construction, an earth ground tester (available from AVO-Biddle Inc. or AEMC Corporation) can measure the resistance of the grounding electrode system using the fall-of-potential method. The measured resistance should be in accordance with the design values and NEC standards.

A clamp-on ammeter can be used to measure current flow in the grounding electrode conductor. In most cases, a small current flow will exist. When there is zero current flow, an open connection probably exists. Current flow on the order of the phase currents indicates serious problems or possible fault conditions.

Isolated Ground and Conduit Ground Systems

The quality of both the isolated ground and conduit ground systems from the equipment to the ground source needs to be measured. This ensures that sensitive electronic loads are grounded with a separate equipment-grounding conductor and that they are ultimately connected to the facility grounding system. Both ground systems terminate at the first upstream neutral-ground bonding point. The phase, neutral, and equipment grounding conductors should be routed through a continuously grounded metallic conduit. If this is done, sensitive electronic equipment will perform better, and safety codes will be met.

Dedicated Feeders and Direct Path Routing

Measure phase currents with the critical loads turned off. This will determine whether sensitive electronic loads are being served by dedicated branch feeders with efficient conductor routing. If any current flow exists, the feeder is being used to serve other loads.

Separately Derived Systems

There should be no direct electrical connection between separately derived systems and input and output conductors. The NEC requires that separately derived systems have a load-side, neutral-ground bond connected to the grounding electrode system. All equipment grounding conductors, any isolated grounding conductors, neutral conductors, and the metal enclosure of the separately derived systems are required to be bonded together, and bonded to the grounding electrode conductor. The quality of these connections can be determined by visual inspection and by measurement with a ground impedance tester.

Measurement of Power System Harmonics

If a harmonic problem is suspected in a power system, the first step toward a solution is to check for harmonic currents and/or voltages at locations in the power system that are probable points of distortion. Oscilloscopes, waveform analyzers, and frequency analyzers are examples of general-purpose measuring instruments that can be used for this purpose. Figures 6-1, 6-2, and 6-3 illustrate recommended hookup procedures for power monitors in various applications. The typical waveform and spectrum analysis data obtained from these instruments is depicted in Figures 6-4, 6-5, 6-6, and 6-7 for single-phase and 3-phase circuits. (Information for these figures was obtained from BMI Corporation.)

Using twisted-pair cables for monitor inputs reduces the possibility of picking up radiated RFI/EMI* fields. It is recommended that the monitors be connected in the same mode that the equipment is connected (phase-to-phase or phase-to-neutral).

Input power to the monitor should come from a circuit other than the circuit to be monitored. Grounding of the power monitor should be performed carefully. Since a chassis ground is provided through the AC input power cord, chassis ground connections to the monitored circuit can create ground loops that add noise on the sensitive equipment feeder. To avoid this problem, *make no chassis ground connection to the monitored circuit.* Contact the instrument manufacturer for guidance, as required.

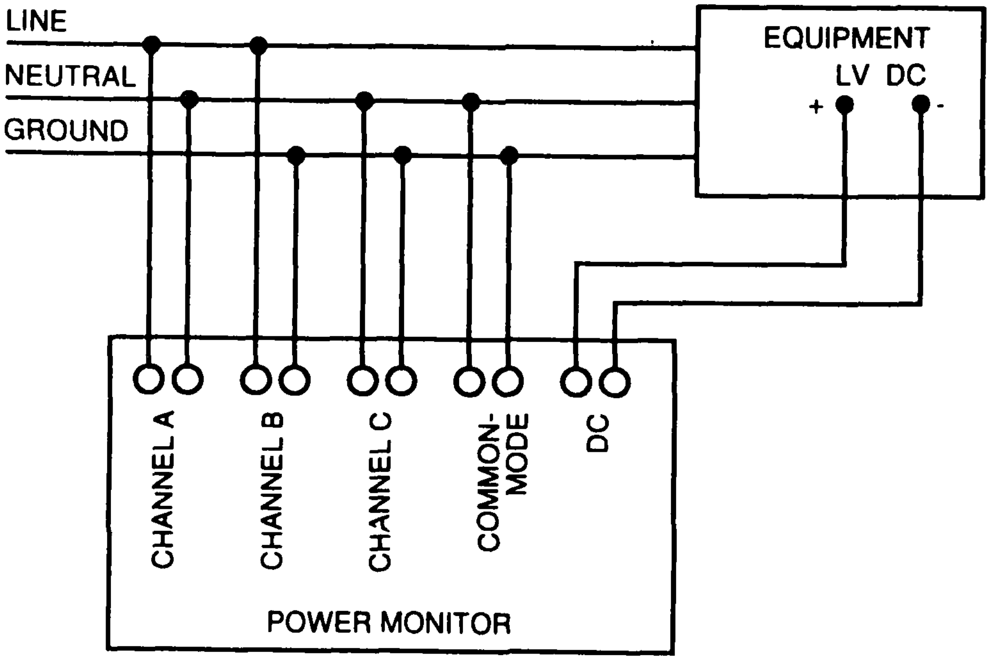

Figure 6-1. Recommended Power Monitor Hookup Procedure for Single-Phase Application.

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*RFI/EMI: radio frequency interference/electromagnetic interference.

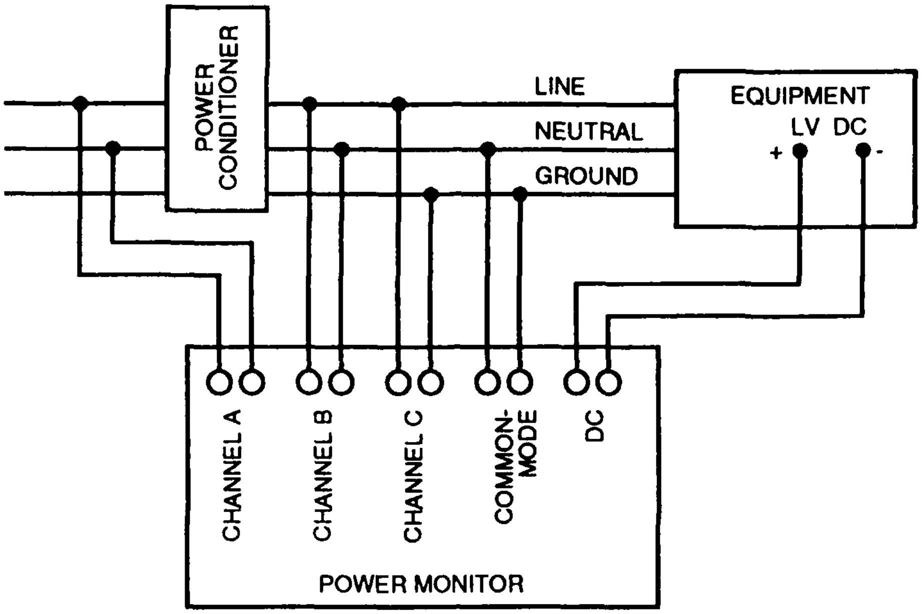


Figure 6-2. Recommended Power Monitor Hookup Procedure for Single-Phase Application With Power Conditioner.

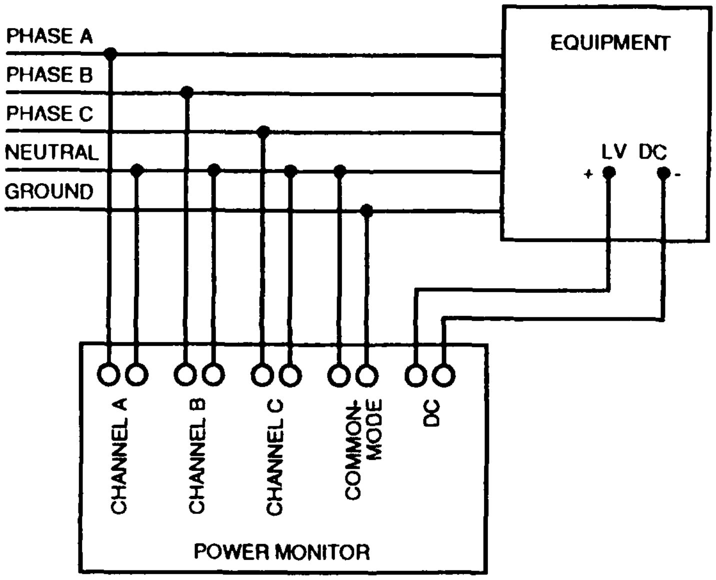


Figure 6-3. Recommended Procedure for 3-Phase Wye Application.

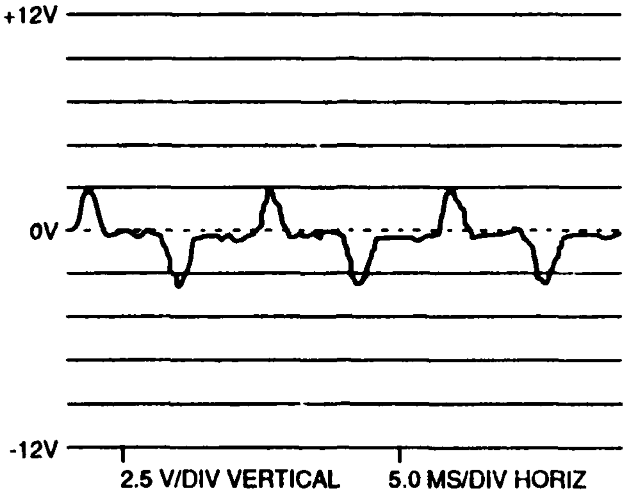


Figure 6-4. Neutral-to-Ground Voltage for a Single-Phase Electronic Load.

HAR	PCT	Ø	HAR	PCT	Ø
FUND	100.0	0°	2nd	1.1	209°
3rd	85.0	163°	4th	1.7	207°
5th	32.2	335°	6th	6.5	39°
7th	27.5	13°	8th	1.2	145°
9th	5.8	223°	10th	1.8	9°
11th	8.5	225°	12th	1.2	61°
13th	6.7	1°	14th	1.5	26°
15th	4.8	224°	16th	1.5	220°
17th	0.6	220°	18th	0.7	304°
19th	1.6	87°	20th	1.1	197°
21st	4.6	85°	22th	0.7	178°
23rd	4.6	38°	24th	0.9	319°
25th	3.8	342°	26th	0.6	75°
27th	2.0	245°	28th	1.3	151°
29th	2.1	229°	30th	2.1	248°
31st	2.8	110°	32nd	2.8	289°
33rd	5.4	177°			
			EVEN	8.6	
ODD	96.4				
THD:	96.8				

Figure 6-5. Neutral-to-Ground Spectrum Analysis for a Single-Phase Electronic Load.

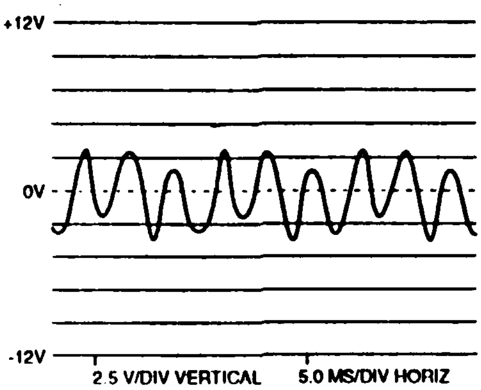
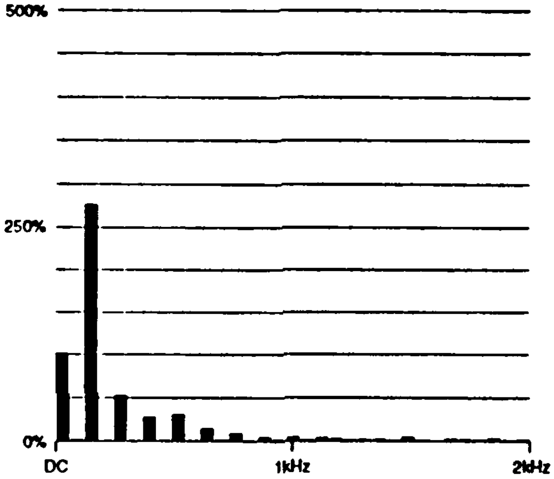


Figure 6-6. Neutral-To-Ground Voltage for a 3-Phase Electronic Load.



HAR	PCT	Ø	HAR	PCT	Ø
FUND	100.0	0°	2nd	1.6	315°
3rd	275.7	62°	4th	0.8	18°
5th	52.0	83°	6th	0.9	130°
7th	26.5	257°	8th	0.7	151°
9th	30.1	292°	10th	0.7	134°
11th	13.7	120°	12th	1.5	134°
13th	8.4	110°	14th	0.3	272°
15th	3.9	22°	16th	1.8	348°
17th	4.3	73°	18th	1.1	82°
19th	3.6	81°	20th	2.0	321°
21st	1.1	81°	22th	1.8	334°
23rd	1.4	235°	24th	1.1	174°
25th	4.1	230°	26th	1.0	302°
27th	0.5	234°	28th	2.0	131°
29th	1.5	226°	30th	1.7	147°
31st	2.6	189°	32nd	0.8	54°
33rd	1.9	41°			
			EVEN	5.4	
ODD	284.0				

THD: 284.1

Figure 6-7. Neutral-To-Ground Spectrum Analysis for a 3-Phase Electronic Load.

Location and duration of power monitoring equipment is also important. Install the monitor at the power panel feeding the system to obtain an overall profile of voltage, particularly at sites that serve several loads. The monitor can then be relocated to the circuits serving individual loads, such as central processing units (CPUs), disk drives, and other equipment experiencing malfunctions or failures. Power disturbance sources and solutions can be found when disturbance data is compared. Recommended practice is to monitor for at least 1 day.

Instrumentation

Test instruments recommended for various uses are summarized in Table 6-1 and discussed below.

True rms Digital Multimeter

A true rms digital multimeter measures voltage and continuity.

True rms Clamp-On Ammeter

A true rms clamp-on ammeter measures current and analyzes current waveforms, particularly when sinusoidal waveforms are involved. Several types of ammeters currently are available, including direct-reading and indirect reading ammeters.

Ground Impedance Tester

A ground impedance tester (available from ECOS Inc.) is a multifunctional instrument designed to detect wiring and ground problems in low-voltage power distribution systems. Such problems can include wiring errors, neutral ground shorts and reversals, isolated ground shorts, and neutral impedance shorts. Some testers are designed for use on 120 VAC single-phase systems, while others can be used on both single and 3-phase systems up to 600 VAC.

Earth Ground Tester

An earth ground tester measures the ground electrode impedance. Ground resistance tests should be conducted with a fall-of-potential method instrument. Clamp-on instruments that do not require the grounding electrode to be isolated from the facility grounding systems for the test are generally not recommended.

Oscilloscope

An oscilloscope can be used to detect harmonics in an electrical system. It can also be used with a line decoupler to measure noise. In this case, the input is connected to the voltage of interest with the appropriate lead. If a voltage above the range of the oscilloscope is to be examined, probes with resistance-divider networks will extend the range of the instrument.

The oscilloscope measures a voltage only as current passes through the input resistance. It cannot measure current directly. Current measurements can be made through use of a current transformer and/or shunt (current-viewing resistor) if a differential input is provided to the oscilloscope. If only a single-ended input is available, the signal is then applied between the high input and the oscilloscope chassis, creating a ground loop. Attempts are sometimes made to break this ground loop by disconnecting the equipment safety grounding conductor (green wire) of the oscilloscope. This practice, known as "floating the scope," is a safety risk and must be prohibited.

Power Disturbance Monitor

A power disturbance monitor detects AC and DC voltage disturbances. Some monitors can also record temperature/humidity levels and other parameters. Time-domain and limited-frequency domain measurements also are possible. These devices output strip charts of data such as voltage, frequency, impulses, temperature, and humidity.

Although developed to detect voltage aberrations, power disturbance monitors have other uses. Features include data output, measurement performance, channel capacity, and other features.

Spectrum Analyzer

A spectrum analyzer measures harmonics, electrical noise, and frequency deviations. It breaks down the voltage or current waveform into its constituent frequency components and displays them as amplitude versus frequency. This instrument allows for the quantitative measurement of each displayed frequency component. The spectrum analyzer is the most convenient instrument for harmonic analysis. It automatically measures the amplitude and percentage of each harmonic and calculates THD. Some spectrum analyzers can measure phase relationship, power factor, total power (volt-amp) and reactive power (vars).

Infrared Detector

An infrared detector detects overheating of transformers, circuit breakers, and other electrical apparatus.

Table 6-1

Recommended Test Instruments for Conducting a Site Survey

Measurement	Ground Impedance Tester	True rms Multimeter	True rms Clamp-on Ammeter	Earth Ground Tester	Oscilloscope With Line Decoupler	Oscilloscope With Current Transformer	Power Disturbance Monitor	Spectrum Analyzer
Conduit/enclosure ground continuity	Yes	Yes			Yes		Yes	
Load phase and neutral currents			Yes					
Neutral-ground bonds		Yes			Yes		Yes	
Equipment grounding conductor impedance	Yes							
Neutral conductor impedance	Yes							
Grounding electrode conductor integrity			Yes					
Grounding electrode impedance				Yes				
Dedicated feeders/direct path routing			Yes			Yes	Yes	
Separately derived system grounding	Yes	Yes						
Voltage disturbances		Yes			Yes			
Interruptions					Yes		Yes	
Frequency variations							Yes	Yes
Harmonics							Yes	Yes
Electrical noise					Yes		Yes	Yes

7 GENERIC GUIDELINES FOR TROUBLESHOOTING HARMONIC PROBLEMS

Nonlinear loads and their resultant harmonic currents can have an adverse impact on the operation of electrical equipment such as transformers, motors, generators, capacitors, and neutral and ground conductors. The main effect is to increase operating temperatures of the electrical equipment and the neutral conductor. This can cause serious operational and safety problems.

Troubleshooting Harmonic Problems

The troubleshooting of harmonic problems should be performed under various load conditions. Since all loads may not always be on, harmonics may not be generated continuously. Harmonics should be monitored when suspected sources are on and when they are off. The harmonic content of each power circuit feed of a suspected source should be measured. Each phase should be measured individually, including the neutral. Existing voltage and current transformers can be used for making measurements. However, it should be noted that their frequency characteristics are often not known above 60 Hz. (In most cases, a frequency response up to 3000 Hz, for measuring voltages and currents up to the 50th harmonic, is suitable.) Using clamp-on current transformers and voltage dividers (potential transformers) has certain advantages. These transformers can be installed close to the point of interest, and their operating characteristics can be well documented.

Noise on Ground Conductors

The term "noise" describes unwanted electrical signals that appear on the ground conductor. There are two general types of noise: common-mode noise and normal-mode noise. Common-mode noise typically involves a ground path, while normal-mode noise does not. The noise induced by electrostatic or electromagnetic coupling is usually common-mode noise. Nonlinear loads can cause common-mode noise; potential differences between two or more ground connections produce these ground loop currents.

When checking and troubleshooting ground problems, begin with easier local inspections discussed in Chapter 6 and then expand the investigation, if required. The general procedure is: (1) check local equipment bonding to the system ground, (2) check the facility service entrance to see that the facility ground conductor is bonded to the neutral conductor and to the service entrance ground, (3) check to see that no connections between the ground and neutral conductors exist anywhere else in the facility, (4) check the wiring to ensure that the green or base ground conductor remains separate from the current-carrying neutral conductor, (5) trace possible ground loops by checking nearby transformers, cables, and ground connections, and (6) inspect the facility ground system including ground resistance and ground connection measurements.

Ground current measurements can help identify sources of common-mode noise or unwanted bonds to the neutral conductor. They are measured with a clamp-on current transformer around the ground conductor. An oscilloscope is the best instrument for this measurement, but a true rms voltmeter is also acceptable. If the current in the ground conductor is measurable, then common-mode noise may be present. An oscilloscope will help show the nature of the noise. If the current in the ground conductor exceeds a few milliamperes, there is probably a connection between the neutral and ground somewhere beyond the utility service entrance. This endangers equipment and personnel, so the unwanted bond should be located and removed immediately. By moving the clamp-on current transformer to various locations in the ground system, it is possible to zero-in on the portion of the ground system where the highest currents are flowing.

Neutral Conductors

In a 3-phase, 4-wire system, neutral conductors can be severely affected by single-phase nonlinear loads. The 3rd and odd multiples of the 3rd harmonic arithmetically add in the neutral conductor. As more nonlinear loads are added to the power system, the neutral current may exceed the phase current. The neutral will then become overheated and cause a higher-than-normal voltage drop. Such a condition poses a serious safety and operational problem.

The first step in the inspection process is to conduct a visual survey of the facility, including the facility power system drawings, to determine the kind of loads present. If the facility has harmonic-generating loads, the next step is to check the transformer and neutral for overheating. Next, measure and record the current using a true rms meter in each phase and in the neutral of the transformer secondary. Compare the measured neutral current to the amount that can be predicted by the imbalance in the phase currents. Measure the frequency of the neutral current to determine the presence of 3rd harmonic currents (the 3rd harmonic frequency will read 180 Hz). Similar readings of phase and neutral conductors should be made for individual circuits feeding nonlinear loads to determine whether the neutrals of these circuits are carrying excessive currents. Measure the voltage between the neutral and ground with the loads connected. If the measured voltage is 2 V or less, the neutral is probably not carrying excessive harmonic currents. If it is between 2 and 5 V, the situation is questionable. If the voltage is greater than 5 V, a problem of excessive neutral current exists and is probably due to 3rd and odd multiples of 3rd harmonic currents.

Transformers

When high-frequency currents flow in transformers, they generate heat due to losses associated with eddy currents and hysteresis in the transformer core. Such transformers run hot and can fail prematurely. Transformers feeding harmonic loads should be inspected and voltage and current measurements taken to assess harmonic problems. The following procedure is suggested:

- Inspect transformer temperature and load current against the nameplate data. Provide additional cooling or derate the transformer to assure that the transformer is not operated beyond its rating. (Refer to derating of transformers in Chapter 8.)

- Measure transformer phase voltages and currents, and neutral currents. If the neutral is carrying current in excess of expected imbalance of phase currents, triplen harmonics are present.

- Measure the voltage between the neutral and ground. If the voltage is in excess of 5 volts, harmonics are present.

Electrical Panels

As discussed before, the primary symptom of nonlinear loads is excessive heating or damage caused from excessive heating. In the electrical panel, a likely hot spot is the neutral bus bar and its connection. Therefore, to assess harmonic problems in electrical panels, do the following:

- Inspect the electrical panel for signs of overheating, especially at the neutral bus bar connections.

- Measure the individual phase and neutral currents of each of the circuits.

- Measure the neutral to ground voltage.

- Listen for noise (due to high frequency harmonic currents).

Troubleshooting Charts

Troubleshooting is the act of systematically identifying the cause or causes of a problem or suspected problem based on a set of identified symptoms and the results of various checks and tests. For this process to work effectively, it must be systematic, logical, investigative, and efficient. To be an effective troubleshooter, the maintenance technician or engineer must possess certain basic skills. These include: (1) understanding the normal operational characteristics and principles of electrical power equipment and apparatus, (2) quickly recognizing abnormal conditions and symptoms, (3) following a logical cause-and-effect sequence, (4) asking each question to generate more and leading questions, (5) being skillful in the use of the appropriate troubleshooting aids and diagnostic tools available, (6) confirming or eliminating possible causes based on the answers to each question, and (7) being able to think quickly and accurately to pinpoint the problem and its possible cause. Troubleshooting charts are provided in this chapter for assessing harmonic and noise problems on the power system. The troubleshooting charts assume that the personnel conducting these activities have the skills discussed above. Figure 7-1 provides an overview of the troubleshooting procedures. Table 7-1 through 7-6 are charts covering the six general tasks required for thorough assessment of harmonic problems.

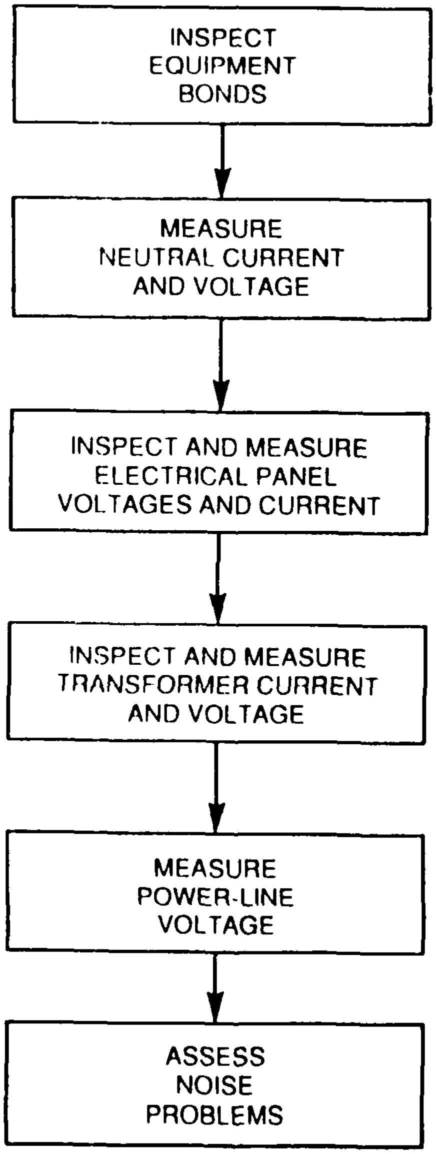


Figure 7-1. Troubleshooting Harmonics Problems: Overview Chart.

Table 7-1

Inspecting Equipment Bonds

1. Check that each piece of equipment is bonded to the local ground conductor.
    - Is it traceable to the green wire?
2. Inspect each bond.
    - Is the bond a solid connection?
    - Is the bond a low inductance strap?
3. Check power-plug polarity at the outlet.
4. Measure voltage between chassis pairs with an rms voltmeter or oscilloscope.
    - Is the measured voltage less than 1 V?
        - If yes, measure neutral current and voltage (Table 7-2).
        - If no, decrease bond inductance by using wider or parallel straps, or by reducing the length of the bond (by removing the bends).

Table 7-2

Measuring Neutral Current and Voltage

1. Inspect the neutral for signs of overheating.
2. Using a true rms meter, measure voltages and current.
3. Measure the frequency of the neutral current to determine 3rd harmonic currents (1800Hz currents).
    - If voltage is less than 2 V, neutral is not carrying excessive current.
    - If voltage is between 2 and 5 V, the neutral may be carrying harmonics.
    - If the voltage is greater than 5 V, the neutral is probably carrying excessive harmonic current due to 3rd and odd multiples of 3rd harmonic.

Table 7-3

Measuring Power-Line Voltage

1. Measure power-line voltages with an oscilloscope or a spectrum analyzer.
    - Is the 3rd, 5th, 7th, etc., harmonic less than 5%?
        - If yes, inspect and measure transformer current and voltage (See Table 7-4).
        - If 3rd harmonic is greater than 5% isolate harmonic producing devices such as photocopiers, laser printers, fluorescent lights, and large-scale, single-phase electronic loads on dedicated circuits.
        - If the problem cannot be solved by isolating the circuits, install shunt harmonic filters.
        - If 5th, 7th, etc., harmonics are greater than 5%, isolate harmonic-producing loads such as 3-phase UPS, 3-phase rectifiers, motor drives, and battery chargers on dedicated circuits.

Table 7-4

Inspecting and Measuring Transformer Current and Voltage

1. Inspect the facility transformer.

    - Are the cooling units working properly?
    - Is the transformer nameplate a delta-wye transformer?
    - Verify that the temperature of the transformer is within its rated limit. If not, provide additional cooling or reduce the load.

2. Measure the phase and neutral current of the transformer using a true rms meters.

    - Compare the neutral current against the phase imbalance expected. If it is more than expected, harmonics problems exist.
    - To resolve overheating of the transformer due to harmonic currents, derate the transformer according to CBEMA criteria.

Table 7-5

Inspecting and Measuring Electrical Panel Voltage and Current

1. Inspect the electrical panel neutral for signs of discoloration due to heat near the neutral connection points.

2. Listen for noise due to higher-frequency harmonics.

3. Measure the voltage between the neutral and the ground using a true rms meter. If the voltage is above 5 V, harmonics are present.

Table 7-6

Assessing Noise Problems

1. Measure signal input with an oscilloscope.

    - If there is normal-mode noise, install EMI line filters.
    - If there is common-mode noise, identify the current loops that are causing the noise.
    - If there is not common-mode noise, troubleshoot the facility ground system to verify that all metallic conductors in the facility bond to the ground system at the point of entrance. Look for ground faults, failed surge suppressors, or chafing and frayed wires.

8 CRITERIA FOR NEW AND EXISTING POWER SYSTEMS DESIGNS

The criteria in this chapter pertain to new power system designs and to the rehabilitation of existing installations. It is more effective to anticipate harmonics problems in new designs than to eliminate them later. In new designs, equipment can be ordered to ANSI/IEEE-519-1986 (ANSI 1986) specifications or to other relevant industry standards that limit the generation of harmonics. Loads that are sensitive to harmonics should be isolated from those that produce harmonics by using isolating transformers, motor-generator sets, or uninterruptible power supplies (UPS). Adding filters can be expensive and may increase the possibility of new resonances.

New Power System Design

When selecting equipment for new design, the following criteria should be used.

Transformers

Nonlinear loads can cause overheating in both liquid-filled and dry-type transformers, increasing copper and iron losses. Use delta-wye connected, 3-phase transformers to supply nonlinear loads to block 3rd and multiples of 3rd harmonics. Use 3-legged, core-construction type transformers instead of 3 single phase transformers or an open delta arrangement type. Dry type transformers used to supply nonlinear loads must have an impedance below 6 percent, preferably in the range of 3 to 5 percent as calculated at the nominal frequency. For supplying computer and sensitive electronic loads, use *isolating transformers.* Isolating transformers help break up ground loop circuits because they provide for common-mode shielding between separated primary and secondary circuits. The transformers used for supplying electronic and nonlinear loads will be derated using one of the following methods:

ANSI/IEEE-C57.110-1986, *Recommended Practice for Establishing Transformer Compatibility When Supplying NonSinusoidal Load Currents* (ANSI 1986), recommends practice for derating conventional transformers in applications where nonsinusoidal load currents are present. This standard assumes that the eddy-current losses are approximately proportional to the square of the rms load current at that harmonic and to the square of harmonic number.

The Computer and Business Equipment Manufacturers Association (CBEMA) has proposed a method for derating transformers supplying nonlinear loads. The CBEMA method consists of 1.414 x rms load current divided by peak load current. This formula typically provides a derating factor of 0.5 to 0.7 depending on peak amperes.

Underwriters Laboratory (UL) and transformer manufacturers have established a rating method called "K-factor" for dry type transformers to indicate their suitability for nonsinusoidal load currents. The K-factor relates the transformer's ability to serve varying degrees of nonlinear loads without exceeding the rated temperature rise limits. The K-factor is based on predicted losses similar to the derating criteria given in ANSI-C57.110-1986 (ANSI 1986). Standard K-factor ratings are 4, 9, 13, 20, 30, 40 and 50. The K-factor for a linear load is always 1. For any given nonlinear load, if the harmonic current components are known, the K-factor can be calculated and compared to the transformer's nameplate K-factor. As long as the load's K-factor is equal to or less than the transformer's K-factor, the transformer need not be derated.

Switchboards

Use switchboards serving nonlinear loads that are equipped with an equipment-grounding conductor bus-bar system. Termination of an equipment-grounding conductor without a proper bus degrades the reliability of the grounding path, especially for high-frequency currents. For 120/208 V switchboards supplying load feeders, use oversized neutrals (between 1.73 to 2 times the phase) to allow high 3rd-harmonic current flow without overheating the neutral. Switchgear/switchboard comprise two basic types of construction: draw-out and fixed designs. Use the draw-out type, because it is easier to inspect and maintain.

Panelboards

Use heavy-duty panelboards to supply nonlinear loads. For these panelboards, the minimum line bus-bar ampacity should be based on a full load plus 25 percent (80 percent derated). The neutral bus-bar assembly should be sized no less than 1.73 times the phase for accommodating the 3rd harmonic currents. The panelboard must be located in the area that serves nonlinear loads.

Protective Devices/Circuit Breakers

Use protective devices and circuit breakers, fuses, etc., that are designed to respond to the true rms value of the current. This prevents premature tripping due to harmonic currents. Use of any devices other than true-rms devices on nonlinear loads can result in premature tripping or, even worse, failure to trip on overcurrent.

Feeder Neutral

Run a separate neutral to 120-V outlet receptacles on each phase. Avoid sharing a neutral conductor for single-phase, 120-V outlet on different phases. Where a shared neutral conductor for a 120/208-V system must be used for multiple phases, use a neutral conductor having at least 1.73 times the ampacity of the phase conductors.

Existing Power System

The diversity of conditions and power system designs makes it difficult to determine what type of harmonics are present and causing problems. Weak power systems and communication systems in close proximity to power systems are particularly vulnerable. Using instruments described in Chapter 6, measure the harmonics present. If they exceed the acceptable limits, several remedial measures are available. In some cases, it is possible to make system modifications to reduce harmonic levels. When such modifications are too expensive or impractical, it may be sufficient to eliminate their harmful effects.

Power Distribution System Equipment

Harmonic considerations for power distribution system equipment (transformers, switchgear/ switchboard, panels, and load feeder/circuits) were discussed in Chapter 6. A periodic inspection (at least yearly and particularly after any change in system configuration) should be conducted to assess harmonic problems. In critical installations, such as some computer and communications facilities, continuous on-line monitoring should be implemented. The inspection should include measurements of phase, neutral, ground currents, and voltages, transformer temperatures and of connections in the distribution system. A portable infrared temperature detector should be used for measuring the temperatures of connections and equipment. If high temperatures (above 50 °C) are detected, measurements should be made to determine if excessive currents or loose connections are the cause.

Stiffen the Power System

When the probability of harmonic problems is high, the power system will be stiffened. This may include increasing the main transformer's size, increasing the size of the conductors and connectors, or the implementation of additional transformers and conductors. Existing transformers and motors can be derated or replaced with large ones. Loads can be redistributed to balance harmonics (as well as load currents) in all phases of the 3-phase system.

Filtering

If the resonant frequency cannot be changed, filters will be used to reduce the most troublesome harmonics. Adding filters must not create additional-low frequency resonances. Therefore, all harmonics below the offending one also must be filtered, with each harmonic requiring a separate filter. Filters are usually most effective when added near the source of harmonics.

Miscellaneous

Harmonics increase heating of electrical equipment. This causes cooling loads to go up. If sufficient cooling is not provided in the original design of the facility, the harmonic effects will be magnified, resulting in premature equipment failure and operating problems. In addition, the expansion and contraction from the heating and cooling cycle can loosen grounding bonds, the connections in the power system, or cause harmonic problems.

9 SAFETY PRACTICES

Safety is an overriding goal of all electrical design and installation. Safety of electrical installations is governed by numerous codes and standards, such as NEC, Institute of Electrical and Electronics Engineers (IEEE), American National Standards Institute (ANSI), and those established by local governments and commercial entities. The performance of electrical and electronic equipment is tied to the method of equipment installation, especially the grounding of the equipment. Many times, variations exist between the manufacturer's requirements and the applicable safety codes. When this occurs, safety requirements must take precedence. The NEC, Occupational Safety and Health Administration (OSHA), and ANSI standards describe grounding safety requirements. The following are highlights of these requirements:

- Do not use isolated or dedicated (clean) grounds for electrical and electronic subsystems fed from the same facility electrical supply

- Ensure that all ground system bonding connections should have low impedance at high frequencies and adequate fault current capability

- Do not use soldered connections in the ground system

- Bond the external chassis and frame of all electronic and electrical equipment to the facility ground.

Personnel Safety

The purpose of equipment grounding is to achieve a uniform potential in all parts of the structure and to ensure that personnel also are at the same potential at all times. The following safety practices should always be followed at all times when working on or troubleshooting electrical equipment:

1. IF YOU DO NOT UNDERSTAND IT, DO NOT DO IT.

2. Treat all grounds as live wires.

3. When checking grounds or testing for grounds, wear safety gloves to minimize the shock hazard due to any potential on the ground wire.

4. Install a properly sized alternate ground or ground jumper before opening any ground connections.

5. Don't get shocked.

    a. Remember that power lines cause lethal shocks and burns.

    b. Keep one hand in your pocket at all times.

    c. Point with your chin, not your finger.

    d. Use the right safety equipment, e.g., rubber gloves, dowels, mats.

    e. Don't defeat interlocks. Don't count on them, either.

    f. Never ground yourself.

    g. Touch equipment with the back of your hand.

6. Don't cause a fire or explosion.

    a. Always work downstream of fuses and circuit breakers.

    b. Clean up and report any safety hazards, including water, solvents, sawdust, etc.

    c. Be absolutely certain of disassembly procedures. Metal parts can fall into conductors. If you're not sure, get a licensed electrician.

7. Have a backup plan.

    a. Know which way you're going to jump if something goes wrong.

    b. Always work with a partner. Make sure your partner knows what you intend to do. Make sure your partner has safety tools and knows how to use them.

8. Assume all circuits are live.

Rules for Preventing Electrical Accidents

Some rules for preventing electrical accidents are as follows:

- Know the work to be done and how to do it.
- Review the work area for hazards of environment or of facility design other than those directly associated with the assigned work objective.
- Wear flame-retardant coveralls, safety glasses, and other recommended protective gear when working around energized equipment.
- Isolate (de-energize) the circuits and/or equipment to be worked on.
- Lock out and tag open all power sources and circuits to and from the circuit/equipment to be worked on.
- Test with two pre-tested testing devices for the presence of electrical energy on circuits and/or equipment (both primary and secondary) while wearing electrical protective gloves.
- Ground all sides of the work area with protective grounds applied with "hot sticks." All grounds must be visible at all times to those in the work area.
- Enclose the work area with tape barrier.

Testing of Electrical Circuits and/or Equipment

When testing electrical circuits and/or equipment, consider the following:

- All circuits and equipment should be considered energized until proven de-energized by testing with voltage detectors, and until grounding cables are connected. The voltage detectors selected should be for the class of voltage supplied to the circuits and equipment to be serviced.

- Personnel assigned to on-site electrical service work should be supplied with at least 2 electrical voltage detectors. The voltage detectors provided shall be capable of safely detecting the voltage present in the circuits and/or equipment to be serviced. The assigned personnel shall be instructed in the correct operation of each detector before each on-site electrical job.

- Each electrical circuit and/or piece of equipment to be serviced should be tested by an assigned draftsman with 2 detectors and then tested by one other person who has been trained in the correct operation of the voltage detectors. This testing shall be performed in the assigned craftsman's presence to ensure that the electrical circuit and/or equipment is de-energized.

- The voltage detectors should be checked for proper operation immediately prior to and immediately after testing the electrical circuits and/or equipment to be serviced.

- While testing circuits and/or equipment, the craftsman performing the tests should wear lineman's safety rubber gloves designed for the class of voltage in the circuits and/or equipment to be serviced and other protective equipment for this work.

Use and Care of Rubber Gloves for Electrical Work

Rubber gloves with leather protectors that have been tested to at least 10,000 V must be worn when work is performed on or within reach of energized conductors and/or equipment.

Available rubber gloves and protectors are of two types:

- Low-voltage rubber gloves and protectors (Class 0). These gloves are tested and approved for work on equipment energized at 750 V or less. (Permission should be given by the foreman for the use of low-voltage gloves when working on conductors and/or equipment energized below 750 V)

- High-voltage rubber gloves and protectors. The gloves are tested at 10,000 V (Class 1) for use on 5 kV or less, tested for 15,000 V for use on 10 kV or less (Class 2), and tested at 20,000 V (Class 3) for use on 25 kV or less voltage ratings.

Both high- and low-voltage rubber gloves are of the gauntlet type and are available in various sizes. To get the best possible protection from rubber gloves, and to keep them serviceable as long as possible, follow these rules whenever using them in electrical work:

- Always wear leather protectors over your gloves. Any direct contact of a rubber glove with sharp or pointed objects may cut, snag, or puncture the glove and rob you of the protection you are depending on.

- Always wear rubber gloves right side out (serial number and size to the outside). Turning gloves inside out places a stress on the preformed rubber.
- Always keep the gauntlets up. Rolling them down sacrifices a valuable area of protection.
- Always inspect and give a field air test (described later) to your gloves before using them. Check the inside of the protectors for any bit of metal or short pieces of wire that may have fallen in them.
- Always store gloves where they cannot come into contact with sharp or pointed tools that may cut or puncture them.
- Inspect gloves before use.

Inspection of Rubber Gloves (All Classes)

Before rubber gloves are used, a visual inspection and an air test should be made at least once every day and at any other time deemed necessary during the progress of the job.

Visual Inspection

When inspecting rubber gloves in the field, stretch a small area at a time, checking to be sure that no defects exist. Check for embedded foreign material, deep scratches, pin holes or punctures, snags, or cuts. Look for signs of deterioration caused by oil, tar, grease, insulating compounds, or any other substance which may be injurious to rubber. Inspect the entire glove thoroughly, including the gauntlet.

Gloves that are found to be defective should not be mutilated in the field. Tag them with a yellow tag, and turn them in for proper disposal.

Air Test

After visually inspecting the glove, other defects may be observed by applying the air test, as follows:

- Hold the glove with thumbs and forefingers.
- Twirl the glove around quickly to fill it with air.
- Trap the air by squeezing the gauntlet with one hand. Use the other hand to squeeze the palm, fingers, and thumb in looking for weaknesses and defects.
- Hold the glove to your face to detect air leakage, or hold it to your ear and listen for escaping air.

Use of Low-Voltage Tester

A low-voltage tester measures AC or DC voltage from 110 to 600 V when accuracy is not required. It can test for continuity, blown fuses, the grounded side of a circuit or a motor, and polarity. This tester operates on the principle that the current passing through the solenoid of the instrument is proportional to the voltage under test and will cause the tester solenoid plunger to move in the same proportion. A pointer attached to the plunger indicates the voltage on the tester scale. This instrument has no internal protection; extreme caution must be used at all times. Some models have a 2-part neon bulb. Both parts glow when energized by alternating current. Only the part that is connected to the negative side of a circuit will glow when energized by direct current.

When the low-voltage tester is used:

- Wear rubber gloves with protectors.
- Check the operation of the tester by testing a known energized circuit.
- Ensure good contact with the tester probes across the circuit being tested.
- Read the voltage on the tester.
- Use the tester only intermittently. Continuous operation can burn out the solenoid, especially with higher voltage.

Effects of Electrical Shock

Current is the killing factor in electrical shock. Voltage determines only how much current will flow through a given body resistance. The current necessary to operate a 10 W light bulb has 8 to 10 times more current than would kill a human if it broke through skin and body resistance and flowed at this amperage. A voltage of 120 V is enough to cause a current many times greater than that necessary to kill. Currents of 100 to 200 mA cause a fatal heart condition known as ventricular fibrillation, for which there is no known remedy. Table 9-1 lists human resistance values to electrical current.

With 120 V and a skin resistance plus internal resistance totaling 1200 ohms, there would be a 1/10 A electric current, 100 mA. If skin contact in the circuit is maintained while the current flows through the skin, the skin resistance gradually decreases. Table 9-2 lists the effects of current values.

First Aid

First-aid kits for the treatment of minor injuries should be available. Except for minor injuries, obtain the services of a physician. A person qualified to administer first aid should be present on each shift of on-site jobs.

Prior to starting on-site jobs, telephone communications to summon medical assistance, should be available and tested. Each on-site job should have the telephone number of the closest hospital and of available medical personnel.

Proper Treatment of Shock

Shock occurs when there is any severe injury to any part of the body. Every injured person is potentially a victim of shock and should be regarded and treated as such, whether symptoms of shock are present or not.

Table 9-1

Human Resistance to Electrical Current

TYPE OF RESISTANCE	RESISTANCE VALUES
Dry skin	100,000 to 600,000 ohms
Wet skin	1,000 ohms
INTERNAL BODY	
Hand-to-foot	400 to 600 ohms
Ear-to-ear	About 100 ohms

Table 9-2

Effects of 60-Hz Current on an Average Human

Current Values Through Body Trunk	Effect	
SAFE CURRENT VALUES	1 mA or less	Causes no sensation not felt. Is a threshold of perception.
	1 to 8 mA	Sensation of shock. Not painful. Individual can let go at will, as muscular control is not lost. (5 mA is accepted as maximum harmless current intensity.)
UNSAFE CURRENT VALUES	8 to 15 mA	Painful shock. Individual can let go at will, as muscular control is not lost.
	5 to 20 mA	Painful shock. Cannot let go. Muscular control of adjacent muscles lost.
	20 to 50 mA	Painful. Severe muscular contractions. Breathing is difficult.
	100 to 200 mA	VENTRICULAR FIBRILLATION. (A heart condition that results in death. No known remedy.)
	200 mA or greater	Severe burns. Muscular contractions so severe that chest muscles clamp heart and stop it during duration of shock. (This prevents ventricular fibrillation.)

Procedures for treatment of shock are as follows:

- Keep the patient warm and comfortable, but not hot. In many cases, the only first-aid measure necessary or possible is to wrap the patient underneath as well as on top to prevent loss of body heat.
- Keep the patient's body horizontal or, if possible, position patient so that the feet are 12 to 18 inches higher than the head. Always keep the patient's head low. The single exception to this positioning is the case of a patient who obviously has a chest injury and has difficulty breathing. This patient should be kept horizontal with head slightly raised to make breathing easier.
- Do not let the patient sit up, except as indicated for a chest injury or where there is a nosebleed. If there is a head injury and perhaps a skull fracture, keep the patient level and do not elevate the feet.
- If the patient is conscious, you may give hot tea, coffee, or broth in small quantities, since the warmth is valuable in combating shock.
- Proper transportation practice is never more imperative than in the case of a person who may develop shock. It is the single most important measure in the prevention and treatment of shock. Use an ambulance, if possible. If other means must be used, follow the above points as closely as possible.

10 ECONOMIC ANALYSIS AND COSTS

The cost associated with solving and reducing harmonic problems can vary significantly in the facility. Checking for loose wiring connections and overheated neutrals are examples of inexpensive solutions compared to purchasing and installing an uninterruptible power supply. Some specific costs should be considered when purchasing any electrical product. These include site preparation, installation, maintenance, operating costs, parts replacement, and costs of mitigating equipment. The cost of purchasing and installing any mitigating equipment should be weighed against the protection required.

Cost Versus Savings

Chapter 3 addressed the effects of harmonics on various power distribution equipment including electronic equipment. One of these effects is energy loss due to overheating of electrical equipment. When considering the purchase of mitigating devices to solve harmonic problems, the energy savings resulting from the use of these devices should be included in the cost-benefit analysis. The mitigating devices employed for solving or reducing harmonic problems are:

1. Isolating transformers
2. Power-line filters
3. Power distribution equipment specifically designed for addressing harmonics, including:

- K-rated transformers (or derated transformers)
- Switchboard with oversize neutrals and grounds
- Panelboards with oversize neutrals
- Additional wiring due to running a separate neutral conductor
- Protective devices and circuit breakers specially designed for harmonic service.

When the safety of personnel or of the facility is involved, the decision to buy mitigating devices can be made on safety considerations alone, and no cost-benefit analysis may be needed. In situations where safety is not a concern but enhanced equipment performance is desired, cost-benefit analysis may be required.

To perform a cost-benefit analysis, the costs incurred due to harmonic problems must be assessed. Costs of harmonics problems include the cost of power interruption, data loss, equipment loss, loss due to fires, loss of working-hours, and maintenance and operating costs. The cost of mitigating devices, including design and installation, must be gathered as well. When all these costs have been gathered, calculating the payback period to justify the cost of improving the system is simple. A payback period of 5 years or less is usually considered appropriate.

Cost-Benefit Analysis

The cost-benefit analysis can be made using the following formula to calculate the payback:

$$n = \log_{10}\left[\frac{\frac{c(a-1)+a}{s}}{a}\right] \div \log_{10}a \qquad \text{[Eq 2]}$$

where:

a = $(1 + g)/(1 + i)$
n = payback period in years
c = cost of harmonic mitigating devices
i = interest rate
g = inflation rate
s = annual savings due to elimination of energy losses, power interruptions, data loss, corruptions, equipment burnout, etc.

Cost of Harmonic Mitigating Equipment

Harmonic mitigating equipment was discussed in Chapter 8. The approximate cost of this equipment is summarized below.

Transformers

The cost varies with the type of transformer. The costs of three types of transformers are as follows:

Derated Conventional Distribution Transformer: This standard power distribution transformer is either liquid-filled or dry type. For harmonic loads, this transformer has to be derated as discussed in Chapter 8. The approximate costs (based on 1992 prices) of these transformers are:

Liquid Filled		Dry-Type	
KVA*	Cost ($)	KVA	Cost ($)
500	31,200	500	14,724
225	22,275	225	7,245
		112.5	4,160
		75	3,126
		45	2,074

*480-208/120 V, 3-phase, 60 Hz, 150°C rise

K-rated transformers: These transformers are the dry type listed by UL for serving harmonic loads. The approximate costs (based on 1992 prices) of these transformers are:

	Cost ($)	
KVA*	K4	K13
500	23,348	---
225	12,200	16,290
112.5	5,990	9,200
75	3,600	4,470
45	2,635	3,150
30	2,280	2,680
25		

*480-208/120 V, 3-phase, 60 Hz, 115°C rise

Isolating Transformers: These transformers are used for computer rooms or for supplying sensitive electronic loads. The approximate costs (based on 1992 prices) of these transformers are:

KVA*	Cost ($)
500	16,309
225	8,124
112.5	4,755
75	3,652
45	2,425
30	2,016
Single-phase 15**	1,665
Single-phase 10**	1,192

*480-208/120 V, 3-phase, 60 Hz, 115°C rise
**208-120/240 V, 1-phase, 60 Hz, 115°C rise

Switchboards

The switchboards serving computers and sensitive electronic loads (harmonic-producing loads) are required to have oversized neutrals (1.73 to 2 times the phase size). The cost associated with this type of switchboard compared to the standard switchboard results from the additional size of the neutral and the ground bus. The approximate costs (based on 1992 prices) of typical switchboards are:

Size* (AMPS)	Cost ($)
1000	6,750
800	5,995
600	5,245
400	4,515
225	4,195
100	4,195

*480 V, 3-phase, CU bus, without circuit breakers

Panelboards: Similar to switchboards, the panelboards serving harmonic-producing loads have oversize neutrals and ground bus. The costs of these panelboards are:

Size* (AMPS)	Cost($)
400	2,432
225	2,102
100	1,610
60	1,610

*480/277 V, 3-phase, 4-wire, without circuit breakers

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9
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