J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

POWER SYSTEM HARMONICS

Definition of Harmonics

Harmonics can be generally defined as sinusoidal components of a periodic waveform that have frequencies that are some multiple of the fundamental frequency of the waveform. When dealing with power systems, harmonics are more specifically characterized as voltages or currents in the power system at a frequency that is a multiple of the fundamental frequency of the power system, which in the United States is 60 Hz. Typical harmonics that may be present in power systems are the odd harmonics such as the third harmonic (180 Hz), the fifth harmonic (300 Hz), the seventh harmonic (420 Hz), and so on.

Harmonics can be more easily viewed as a mathematical tool for analyzing the nonsinusoidal currents drawn by certain loads connected to the power system. To provide a better understanding of these nonsinusoidal currents and voltages, a review of some basic electrical engineering concepts will be presented.

In the United States, the utility companies generate voltages in the form of sine waves that have a frequency of 60 Hz (60 cycle/s), as shown in Fig. 1. This voltage can be expressed mathematically as

$$v(t) = V_m \sin(\omega t) \tag{1}$$

where V_m is the amplitude of the voltage waveform, and ω is the angular frequency of the sinusoidal signal ($\omega = 2\pi f = 2\pi$ (60 Hz) = 377 rad/s for a frequency of 60 Hz).

If the voltage from the power utility is placed across a resistive device, as shown in Fig. 2, the current that will flow in the circuit can be found by applying Ohm's law. Ohm's law simply states that the voltage across a device is equal to the product of the current flowing through the device and the resistance of the device:

$$V = I \cdot R \tag{2}$$

This equation can also be algebraically manipulated to give the current as the voltage divided by the resistance:

$$I = \frac{V}{R} \tag{3}$$

So, using Ohm's law to find the current that will flow in the circuit shown in Fig. 2 gives

$$I = \frac{V}{R} = \frac{V_m \sin(\omega t)}{R} = \frac{V_m}{R} \sin(\omega t) \tag{4}$$

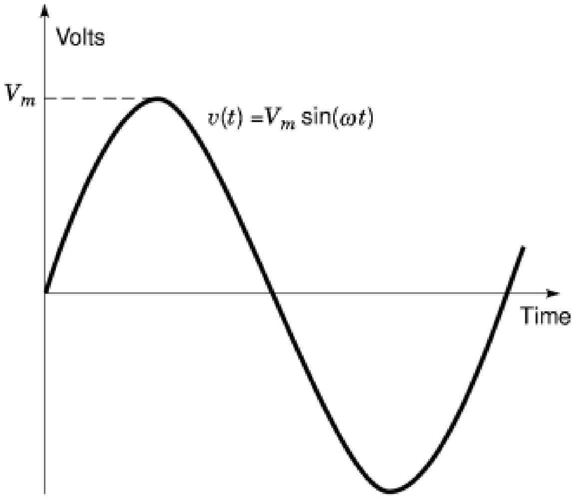

Fig. 1. Ideal sinusoidal voltage waveform.

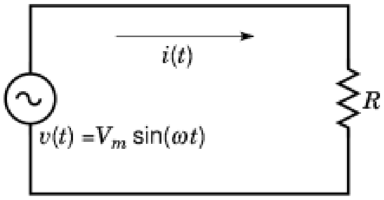

Fig. 2. Simplified circuit with a resistive load to illustrate the linear relation between sinusoidal inputs and outputs.

Equations (1)–(4) show that the current waveform is another sinusoid with the same frequency as the applied voltage but with a different amplitude as shown in Fig. 3.

This system is characterized as a linear time-invariant (*LTI*) system because the current is proportional to the applied voltage at all times, and the component values in the circuit are constant over time. Therefore, when a sinusoidal voltage is applied to a linear load, a sinusoidal current will be drawn. In this case, only the fundamental frequency of the system is seen in the current waveform, and no other harmonics exist. Many electrical loads, including incandescent lamps, heaters, and to some extent electric motors, fall into the category of linear loads (1).

Figure 4 depicts the relationship between the voltage and current waveforms for a linear load. Figure 4(a) shows a pure sinusoidal voltage waveform, and Fig. 4(b) illustrates the linear relationship between the voltage and current. The current waveform can be found by mapping every point on the voltage waveform to a corresponding current value from the voltage current relationship. An example of this mapping is represented by the dashed lines on the figure. The result is a pure sinusoidal current with only the fundamental, as shown in Fig. 4(c).

A problem arises, however, in that many loads placed on the power system are nonlinear loads in which the current is not proportional to the applied voltage. Figure 5 illustrates the relationship between the voltage and current waveforms for a nonlinear load. As before, the current waveform can be determined by matching each point on the sinusoidal voltage waveform in Fig. 5(a) to the corresponding current value from the nonlinear voltage current relationship in Fig. 5(b). Again the dashed lines illustrates an example of this correspondence.

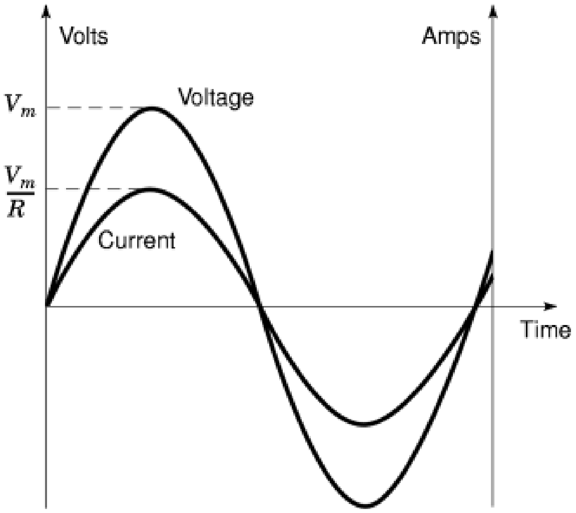

Fig. 3. Voltage and current waveforms for a linear resistive load. The linear relationship between the source voltage and the load current is easily seen.

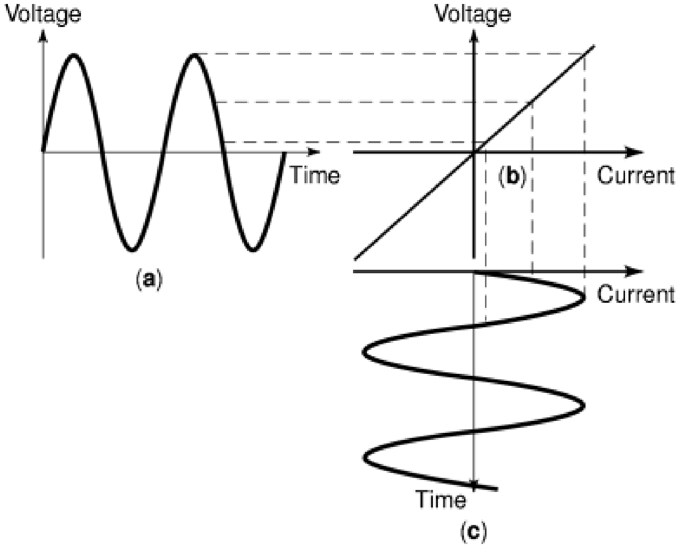

Fig. 4. Relationship between the voltage and current for a linear device. When a sinusoidal voltage is placed across the device, a sinusoidal current flows through the device.

The result in this instance though is not a purely sinusoidal current. Rather, the resulting current is distorted and contains harmonics as shown in Fig. 5(c).

High-efficiency electronic loads (e.g., computer power supplies, adjustable speed motor drives, and electric arc furnaces) are considered nonlinear loads. These systems are nonlinear because their effective resistance varies during the range of their operation, often as a result of the switching of power electronic devices in these systems.

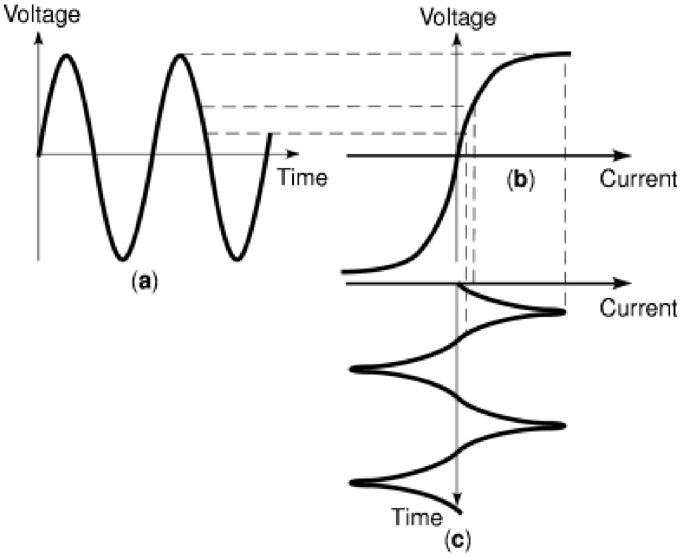

Fig. 5. Relationship between the voltage and current for a nonlinear device. When a sinusoidal voltage is placed across the device, a nonsinusoidal current flows through the device.

Figure 6 illustrates one cycle of the voltage and current waveforms for a typical switched nonlinear load, such as a rectifier or power supply. As shown, the current drawn by the system remains zero until the voltage reaches a certain level, known as the firing voltage or firing angle. When the firing angle is reached, the power electronic switches in the system are turned on and current begins to flow. This current increases to some maximum value and then decreases back to zero. The same phenomenon occurs for the negative half cycle. The result is a current that is a series of pulses rather than a pure sinusoid as seen with linear loads. These current pulses can take a variety of shapes depending on the particular nonlinear load attached to the power system.

Traditional analysis techniques are based on linear systems with sinusoidal voltages and currents and do not directly translate to nonlinear systems with pulsating currents. Thus, another tool is necessary for analysis of this type of system. To be better able to deal with nonlinear electrical systems, engineers employ Fourier theory, which states that any periodic waveform can be expressed as the sum of a series of sinusoids with different frequencies and amplitudes.

Thus, Fourier theory says that the current pulses drawn by nonlinear loads can be modeled as a series of sinusoidal waveforms with varying frequency and amplitude. The frequencies selected for the Fourier series are integer multiples of the fundamental frequency of the applied signal. These multiples of the fundamental frequency are called harmonics.

A common mistake is to confuse the harmonic content of a waveform with the actual waveform. Harmonics are simply tools that make the analysis and visualization of nonsinusoidal functions simpler. An oscilloscope connected to a power system will show the actual waveforms that exist on the system and will not directly display the harmonics. The harmonic decomposition of a waveform is simply a mathematical representation of the waveforms made up of a series of sinusoids with different magnitude, frequency, and phase.

As an example, the harmonic decomposition of a square waveform is illustrated in Fig. 7. Figure 7(a) shows a pure square wave whereas Fig. 7(b) illustrates the harmonic content of the square wave up to the tenth harmonic as determined by using the Fourier theory. The original square wave can then be reconstructed using the harmonics content of the signal. This reconstruction is depicted in Fig. 8, which shows that, as

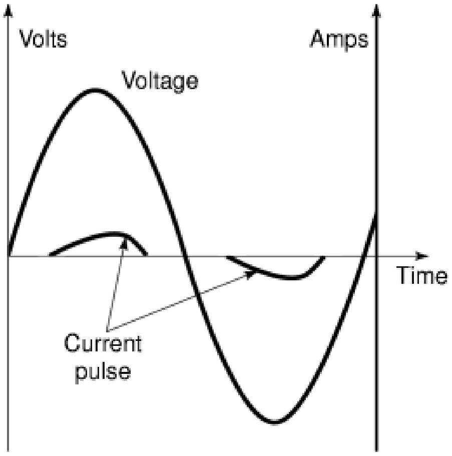

Fig. 6. Typical voltage and current waveforms for a switched nonlinear load. The nonlinear relationship between the voltage and current can be seen in that a sinusoidal voltage does not produce a pure sinusoidal current. Rather, the current is in the form of pulses created by the switching internal to the device.

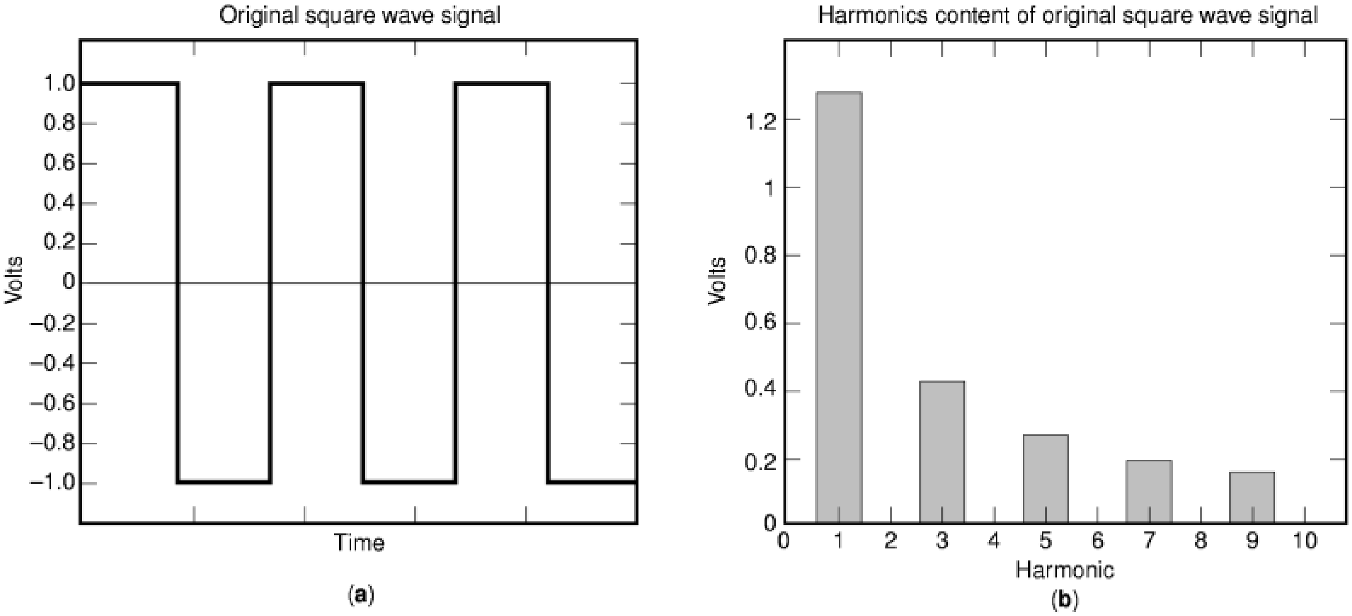

Fig. 7. (a) A typical square wave to be used as an example waveform for harmonic decomposition. (b) The harmonic decomposition of the square wave shown in (a).

additional sinusoidal harmonics are added to the series, the reconstructed signal becomes an increasingly better approximation of the original signal. Note that in the area of the points of discontinuity in the original signal, the reconstructed signal does not converge smoothly. Rather it tends to overshoot the original signal. This particular effect is known as the Gibbs phenomenon and is named for Josiah Williard Gibbs, who was a professor of mathematical physics at Yale.

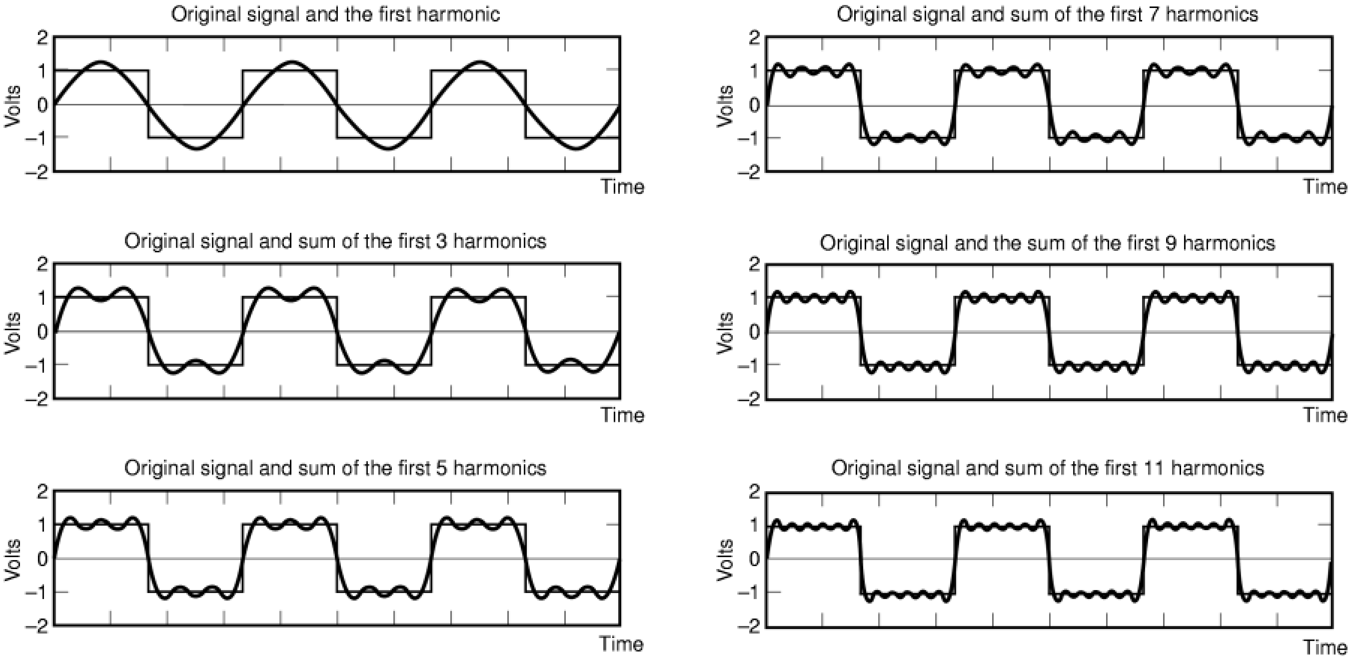

Fig. 8. Reconstruction of original square wave by summing successive harmonic components.

Sources of Harmonics

When dealing with power systems, harmonics are typically divided into two categories: characteristic harmonics and noncharacteristic harmonics. The characteristic harmonics are those produced by power electronic converters and equipment during the normal operation of these devices. These harmonics are at integer multiples of the fundamental frequency of the power system. Noncharacteristic harmonics, on the other hand, are harmonics that are usually produced by sources other than power electronic equipment and are at frequencies that are noninteger multiples of the fundamental frequency of the power system. In the following section, the sources of both characteristic and noncharacteristic harmonics will be explored in further detail.

The primary sources of harmonics in power systems are power converters and other power electronic devices including rectifiers, inverters, adjustable speed drives, cycloconverters, and switch mode power supplies (2). Electronic heating controls, light dimmers, and static var compensators are other power electronic systems contributing to harmonic problems on power systems.

Many of the harmonics generated by power electronic equipment can be illustrated by examining the operation of rectifier circuits. Harmonics are generated in rectifier circuits as a result of both the pulsating nature of the current drawn by the rectifier and the phenomenon of commutation overlap, which is also known as line notching or commutation notching. In an ideal case with no source inductance, a bridge rectifier with a highly inductive load will draw current consisting of a series of square pulses. Commutation overlap occurs when an inductance is present in the ac circuit feeding the rectifier. Because current in an inductor cannot change instantaneously, there exists a finite time during which the output current is transferred from one device to another. During this time, an effective short circuit exists between the two conducting devices, as shown in Fig. 9. This effective short circuit is broken when the current in the outgoing device decays to zero. The short circuit between the two phases appears as a notch on the line voltage, as depicted in Fig. 10. The length of the notch is related to the commutation angle of the rectifier and the inductance present in the feeder

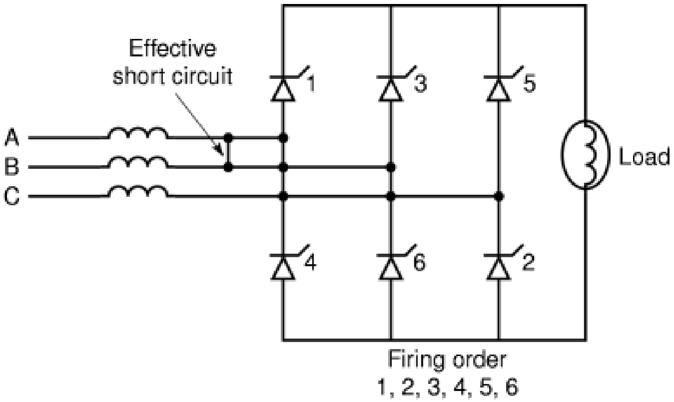

Fig. 9. Basic rectifier circuit with source inductance showing the effective short circuit occurring during the commutation overlap period when both diode 1 and diode 3 would be conducting.

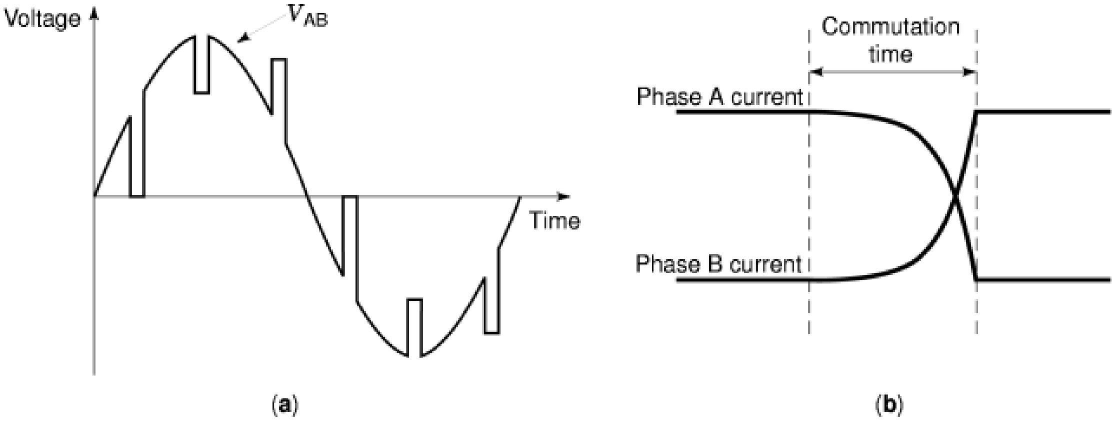

Fig. 10. (a) Line voltage notching due to commutation overlap. (b) Current waveforms during commutation overlap. In this instance, the phase A current is turning off and the phase B current is turning on, but the current transfer cannot happen instantaneously due to the source inductance present in the system.

circuit. Therefore, the harmonics generated by a rectifier load can vary significantly as the commutation angles are altered. Line notches can be decreased by reducing the reactances in the bus and feeder lines.

In addition to power converters, other nonlinear components are also capable of introducing harmonics into the power system. Rotating machinery can be a source of power system harmonics as a result of ripple in the machinery voltage waveforms, air gap reluctance variations, nonsinusoidal air gap flux distribution, and flux distortion caused by sudden load changes. Also, transformers can be a source of harmonics both from overexcitation and the nonsinusoidal shape of the transformer magnetizing currents (3). Several other sources of harmonics exist including electric arc furnaces, fluorescent lighting, and glow discharge lighting (4).

Switching transients can also introduce harmonics into the power system. Often capacitors are used for facility power factor correction and are ordinarily switched in and out of the circuit as necessary to regulate the facility power factor. The transient overvoltages that can be generated during this switching action usually contain high-frequency harmonics (5). This can cause problems associated with both the harmonics and the high overvoltages that are possible.

Several methods exist for the measurement of the harmonic distortion caused by equipment connected to the power system. The most common of these measures include total harmonic distortion (*THD*), harmonic factor (*HF*), and distortion factor (*DF*).

The THD of a signal is a measure of the distortion of a particular wave shape from the fundamental component of the waveform. The THD is defined as

$$\mathrm{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} I_n^2}{I_1^2}} \tag{5}$$

where I_n is the amplitude of the nth harmonic of the current waveform. In effect, the total harmonic distortion is a ratio of the power due the harmonic components of the current to the power of the fundamental.

The harmonic factor is another measure of the harmonic content of a waveform. Unlike THD, which is a single measurement for all the harmonics, the harmonic factor is given for each individual harmonic. The HF is defined as the ratio of the amplitude of the harmonic current to that of the fundamental component and is given by

$$\mathrm{HF}_1 = \frac{I_n}{I_1} \tag{6}$$

where I_n is the amplitude of the nth harmonic of the current waveform and I_1 is the amplitude of the fundamental.

The distortion factor is a third measurement parameter for examining harmonic content. THD is a measure of the total harmonic content of a waveform and does not provide information about the amplitude of particular harmonics. This information about the magnitude of the individual harmonics is necessary for the design of harmonic filters because of the higher-order harmonics can be filtered more effectively. The DF is a measure of the harmonic distortion remaining in a waveform after passing the waveform through a “brick wall” second-order filter. Therefore, the DF is really a measure of the effectiveness of second-order filtering on the particular waveform being analyzed. The DF is defined as

$$\mathrm{DF} = \frac{1}{I_1}\left[\sum_{n=2}^{\infty}\left(\frac{I_n}{n^2}\right)^2\right]^{1/2} \tag{7}$$

for the all the harmonics. The DF can also be given for each individual harmonic as

$$\mathrm{DF}_n = \frac{I_n}{I_1 n^2} \tag{8}$$

These various distortion measurements allows for comparison of the harmonic content of various waveforms.

Harmonic Impact

The impact of harmonics on a specific power system is dependent on the design of the power system and on the loads that are connected to that system. In particular, the impact depends on the size and sensitivity of the system and the loads to the harmonic distortion present on the system. Loads that are capable of using the harmonic energy (e.g., electric heating elements) can typically tolerate increased harmonic levels without significant effect on their operation. As a result, these loads may suffer premature aging and fatigue due to the stresses incurred by the harmonic levels on the power system. Conversely, equipment that requires a near perfect sinusoidal input for proper operation (e.g., data and communication equipment) can suffer substantial performance degradation as a result of harmonics on the power system.

Equipment that generates harmonic currents may affect other apparatus connected to a common source in the power system (e.g., a distribution transformer). The degree of the effect is inversely proportional to the impedance of the apparatus. In general, most of the harmonic currents generated in the system flow into the transformer because it represents the lowest impedance to the harmonic currents. In large to medium-sized power systems, the influence of the harmonic currents flow on the voltage is minimal, unless the size of the harmonic generating equipment is large relative to the power system.

In the following sections, the impact of harmonics on individual types of equipment and power system configurations will be examined.

Rotating Machinery. The primary effect of harmonics on rotating machinery is an increase in machine heating due to iron and copper losses at the harmonic frequencies. This increased heating results in a reduction of output rating, efficiency, and life of the machine. In addition to increased heating, harmonics can also cause pulsating torques in rotating machinery. These torques can lead to a degradation in product quality in applications that are sensitive to variations in motor torques and speeds. Also, in some situations, these pulsating torques can excite mechanical resonances in the system that may fatigue and accelerate the aging of the shaft and other associated mechanical components.

Transformers. Parasitic heating is the fundamental effect of harmonics on transformers. Voltage harmonics result in increased iron losses in the transformer, whereas copper and stray flux losses are increased by current harmonics. The resultant outcome of these increased losses is additional transformer heating when compared to pure sinusoidal excitation of the transformer. These losses in the transformer are directly dependent on the frequency of the harmonic voltages and currents, so the higher-frequency harmonics may have more impact on transformer heating than lower-order harmonics. Typically, the magnitude of the higher-order harmonics is significantly smaller than that of the lower-order harmonics and the fundamental frequency, thus helping to negate the additional heating effect. In some particular cases (e.g., harmonic resonance conditions), select harmonics could have amplitudes higher than normally expected. If these select harmonics are high-frequency harmonics, considerable transformer heating problems could arise.

Power Cables. Power cables used to transmit and distribute electrical energy are also subject to the harmful effects of voltage and current harmonics on the power system. First, as a result of the skin effect and the proximity effect, the effective ac resistance of a conductor is greater than the dc resistance. The amount of increase in the ac resistance is directly related to the frequency of the ac current flowing in the conductor. So, at higher frequencies, the effective ac resistance is much larger than the dc resistance. Thus, the resistive or I^2R losses of the cable increase as the harmonic content of the current in the cable increases, resulting in further heating of the conductor. Additionally, cables subjected to voltage harmonics are susceptible to voltage stresses and corona, which can result in a failure of the cable insulation (2).

Capacitors. As with most other devices discussed, the main impact of harmonics on capacitors attached to the power system is increased heating. The reactance of a capacitor decreases as frequency increases, so capacitors become a low-impedance path for high-order harmonic currents. This causes increased heating and voltages stresses, which ultimately reduce the effective life of the capacitors. In addition, capacitors connected to the power system will alter the natural frequency of the power system, which could introduce the possibility of system resonance.

All power systems have a natural frequency that is dependent on the inductive and capacitive reactances of the system. Resonance can occur when an excitation source exists on the power system, which is equal to the natural frequency of the power system. Often, power systems that employ capacitor banks for power factor correction have a natural frequency in the range of 300 Hz to 420 Hz, which corresponds to the fifth through the seventh harmonic (6). When a resonant condition occurs, the levels of voltages and current are amplified, so that even small amounts of harmonics can result in large disturbances on the power systems. Voltages and currents that are substantially larger than those that would be present without resonance can be present on the system. The large overvoltages that may occur can affect the operation and life of all equipment connected to the power system.

Electronic Equipment. Electronic equipment can be affected by the presence of harmonics on the ac supply system. Computers and other associated equipment such as programmable controllers are susceptible to malfunctions as a result of harmonics passing from the ac supply into system components. Also, power electronic equipment can be very susceptible to performance problems resulting from supply-side harmonics. In particular, power converters that rely on the voltage wave shape or the zero crossing of the voltage waveform can be adversely affected by the distortion of the voltage waveshape caused by harmonics (2).

Additionally, electronic instrumentation can produce erroneous data and perform unpredictably when harmonics are present on the power supply system. Medical instrumentation is of particular concern due to the critical nature of these components. Therefore, medical equipment is usually supplied with conditioned power to minimize the possibility of malfunctions resulting from poor power quality (2).

Carrier-based equipment, such as a clock system, can also be adversely affected by harmonic distortion if the carrier frequency of the equipment falls on or near the odd harmonics of the line frequency. Moreover, exposed cables or buses in power systems can act as antennas that radiate at harmonic frequencies, thereby affecting paging and phone systems. Furthermore, electrical noise in communication and electronic control equipment might be introduced as a result of harmonic currents by either conduction or radiation. This noise is known as electromagnetic interference (*EMI*).

Similarly, electric motor drives are susceptible to harmonics present on the ac power system supplying the drives. Harmonic distortion on the system could cause unpredictable operation of the drives. Additionally, drives may trip as a result of harmonics on the supply rather than an actual fault condition. These nuisance trips result in lost production and can often induce additional complications when the problem drive is in a critical area.

Relays. Solid state relays (*SSR*s) are used in many industrial control systems, including power switching, self-latching switching, and motor starting and reversing. These relays are also employed in voltage sensing, temperature control, light dimming, and transformer tap changing. Typically, it is desirable for these relays to be zero-switching devices that switch from an off state to an on state only when the voltage is either zero or close to zero. Zero switching is accomplished by detecting the zero crossing of the voltage waveform and switching on the relay either at the zero crossing or very early in the cycle when the voltage is still relatively low. This is done to limit the inrush current by switching when the voltage is low and to reduce EMI. These SSRs are normally constructed using thyristors, silicon-controlled rectifiers (*SCR*s), or triacs, which are devices that can be turned on at any time during the voltage cycle and turned off when the current through them falls to zero. Thus, for these devices to be used as SSRs, additional zero-crossing circuitry is necessary (7).

Harmonic distortion on the power system results in distorted voltage waveforms that can cause multiple zero crossings during a single cycle of the fundamental. These multiple zero crossings can cause improper operation of SSRs that rely on zero crossing detection circuitry. The study presented in 7 found that harmonics cause a number of different operational problems for SSRs including failure to turn on at the first zero crossing after given a control signal, failure to turn off at the first zero crossing after the control signal was removed, failure to turn on at the zero crossing, but turning on at much higher voltages in the cycle.

Metering. Metering, instrumentation, and measurement apparatuses can be unfavorably affected by the presence of harmonics on the power system. Watt-hour meters, which are used extensively to measure industrial, commercial, and residential power consumption, are typically designed to monitor only the fundamental current present on the system for power measurement. Thus, harmonic currents on the power system caused by nonlinear loads and/or phase imbalances can lead to erroneous operation. According to a study

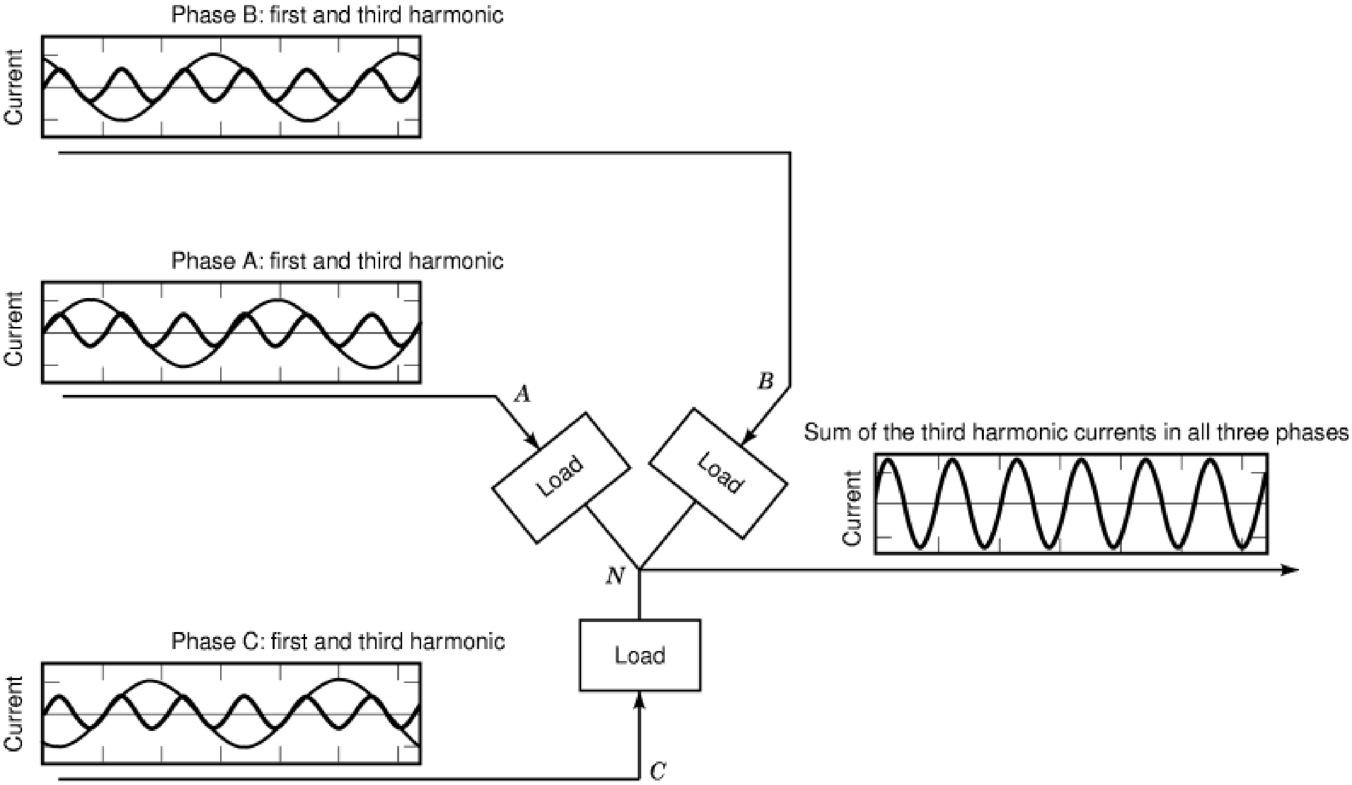

Fig. 11. Relationships between the fundamental and the third harmonic current in a three-phase, wye-connected system and the additive effects of the third harmonic components on the neutral current. Notice that in all three phases the third harmonic components are in phase and add at the neutral rather than canceling each other as the fundamental components do.

presented in 8, watt-hours meters consistently register higher power consumption when monitoring power systems with harmonic distortion than when connected to harmonic-free systems. The increased readings ranged from a fraction of a percent up to a 1.5% increase in the indicated power consumption when the harmonic amplitudes were 10% of the fundamental or less (8). Another study found that in a power system with a 20% fifth harmonic, electronic watt transducers could record errors of up to 15% (9). These increases in the instrumentation readings result in customers being charged for power that was not actually consumed.

Triplen Harmonics. In three-phase systems, triplen harmonics (third, sixth, ninth, etc.) are in phase with each other instead of being 120° out of phase as is the case with the fundamental currents. So, rather than canceling at the neutral like the fundamental components of the current, the triplen harmonics are additive, which allows for potentially high currents in the neutral conductor.

Figure 11 illustrates the phase relationship between the fundamental currents in a three-phase system and the third harmonic current on each of the phases. The figure shows that, although the fundamental currents are 120° different in phase, the third harmonic currents are all in phase with each other. When these third-harmonic components are added at the neutral of a wye connection, the resultant current is larger in amplitude than the individual phase currents, as shown in Fig. 11.

A major concern in commercial installations is that the proliferation of switched-mode power supplies used for single-phase electronic equipment (e.g., personal computers, printers, photocopiers, and facsimile machines) will result in considerable harmonic distortion on the power system. Commercial single-phase loads are typically supplied from the line to neutral of a three-phase wye-connected system with the single-phase loads distributed as evenly as possible among the three phases. Because of the input rectification and filtering stages of switched mode power supplies, the current drawn from the power system is rich in third harmonic content. The increased use of single-phase switched-mode power supplies results in increased third harmonic current levels in each of the three phases of the power system. Because these triplen harmonics are additive at the neutral of the wye connection, overloading of the neutral conductor can occur, especially in older installations where an undersized neutral may have been used. An additional cause for concern is that transformer heating can also occur on systems with a substantial number of switched-mode power supply loads (10).

In general, to minimize the effects of harmonics on equipment, sensitive loads and harmonic currents generating equipment should not be connected to the same transformer or feeder bus. Rather, loads should be grouped based upon both the sensitivity of the load to harmonic currents and the capability of the load to generate harmonic currents. For example, harmonic-generating loads such as rectifiers should be grouped with equipment that is not sensitive to harmonic currents such as resistive heating elements.

This discussion on the impact of harmonics on power system components makes it readily apparent that a large variety of effects exist. An understanding of how individual loads can be affected by harmonics on the power system is necessary for the use of these loads. Before any piece of equipment is connected to a power system, the effect of any existing power system harmonics on the operation of the equipment and the effect of the equipment on the power system should be examined.

Harmonic Elimination

A number of methods have been proposed for handling harmonics on power systems. These methods include directly dealing with the effect of harmonics on the power systems, filtering the harmonics both with passive filters and active filtering devices, and combinations of active and passive filtering.

Dealing with Harmonics. Rather than focusing efforts on reducing the harmonic levels present on power systems, some have suggested that the damaging effect of harmonics can be reduced by taking a few simple steps (11).

One such technique involves derating transformers. Because the primary effect of harmonics on transformers is heating, using a transformer designed for a load larger than necessary allows the additional heating effects of the harmonics to be accommodated.

A second technique involves oversizing the neutral conductors in three-phase feeder systems or monitoring the neutral currents and limiting system loads as necessary to maintain acceptable currents in the neutral conductor. Because of the additive nature of triplen harmonics, excessively high neutral currents are possible even with the individual phase currents within the intended operational limits. This results in a need to either oversize the neutral conductor or monitor the current in the neutral and limit the loads on the system (11).

Placing the emphasis on reducing the effects of the harmonics rather than trying to eliminate the harmonics from the power system offers the advantage of simplicity. Oversizing neutral conductors can easily be accomplished for new installations, whereas monitoring of the neutral current in existing system would not be difficult. The problem with such a technique is that harmonics are not prevented from entering equipment attached to the system or from entering the supply itself. Also, simply dealing with harmonic effects does not account for changes to the supply system that could result in differing harmonic levels that make the transformer derating or neutral size insufficient for the new levels present.

Although modifying equipment designs and ratings to make them more robust in a harmonic-rich environment is a possible remedy for the problem of power system harmonics, alternate solutions that address the reduction and elimination of harmonic levels must be examined.

Harmonic Filtering. Harmonic filtering is one of the most common methods used for eliminating harmonics on power systems. Instead of trying to mitigate the effects of the harmonics on equipment as previously suggested, harmonic filters are used to help reduce the harmonic levels present on power systems. The two basic types of harmonic filters are passive filters, which consist of only passive devices, and active filters, which employ active power electronic devices.

Passive Filtering. Passive harmonic filters are, as suggested by the name, made up of passive circuit elements including resistors, inductors, and capacitors. Series and shunt are two possible passive filter configurations.

Series filters are connected in series between the power system source and the load. These filters generally consist of low-pass filters and are designed to block harmonic currents. These devices function as a high impedance to harmonic currents, while appearing as a low impedance to the fundamental frequency. Therefore, the harmonic current cannot pass through the filter, and the fundamental current passes without attenuation.

Series filters are not commonly used because the filter must carry full load current and be insulated for full-line voltage, which can make the series filters both large in physical size and cost (12). One application in which series filter are used is the neutral of a grounded wye-connected three-phase capacitor bank. In this situation, the series filter would be designed to block the triplen harmonics flowing in the neutral while providing a good ground for the fundamental (10).

Shunt filters, on the other hand, are connected in parallel with the power system. These filters are usually made up of a bank of LC filters tuned to specific harmonic frequencies making a low-impedance shunt path for the specific harmonic to which they are tuned. Shunt filters are more commonly implemented because they are less expensive and carry much smaller currents than do series filters (12).

Passive filtering schemes, including series filters, shunt filters, and combinations of series and shunt filters, are often used to reduce harmonic distortion on power systems because these passive filters are relatively inexpensive. Passive filters require only passive devices, providing for a low initial cost. Furthermore, these filters are highly efficient (13) resulting in reduced operating costs. Passive filters can also be incorporated into the overall power factor correction strategy of an installation, possibly eliminating the need for additional power factor correction equipment.

Although the previously mentioned advantages are inherent, passive filters are not without disadvantages. In particular, passive filters must be tuned to specific harmonics and cannot be easily altered to accommodate changes to the power system that modify the level and order of the harmonics on the system. In addition, certain categories of converters (e.g., cycloconverters) create varying amounts of harmonics as loading conditions change during the normal operating cycle of the device.

Sizing of passive filters can also prove difficult. Inordinately high bus voltages can result from oversized filters, whereas overloads can easily occur if a filter is undersized. The task of sizing the filters is made even more difficult because harmonic pollution can often come from remote points on the distribution system that are not always evident during the filter design phase (14).

The addition of passive filtering elements will also have an impact on the natural frequency of the power system. This change in the frequency of the system could result in a system resonance condition, the effects of which were previously discussed.

Finally, the impedance of the source has a significant influence on the filtering characteristics of the passive filter (13). Therefore, changes in the impedance of the supply system could render particular passive filters useless.

Reference 15 presents a transfer function approach for the design of passive harmonic filters. Harmonic impedance, voltage, and current transfer functions are derived for six common filter configurations and are used to derive a practical filter design procedure. The four-step harmonic filter design procedure is presented in detail, and an example of the procedure is presented for the design of filtering for a variable speed motor drive. 12 investigates a passive harmonic filter design procedure for several types of shunt harmonic filters. These filters are then studied using traditional analysis as well as simulation programs. Finally, the actual

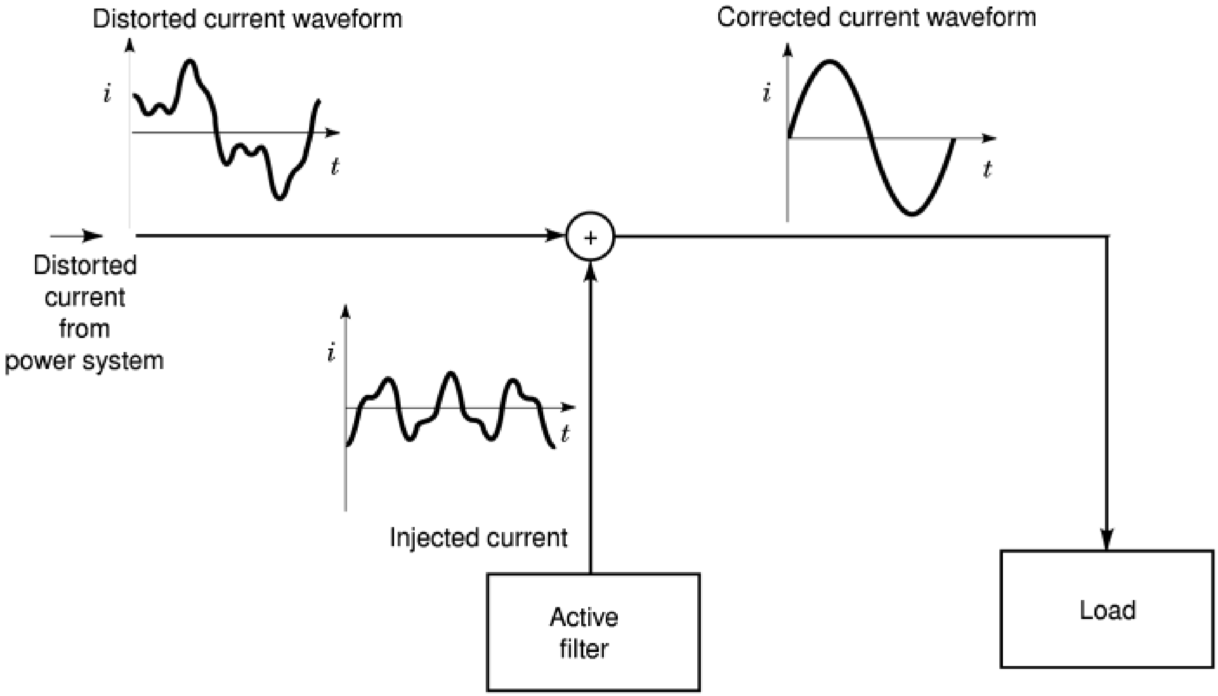

Fig. 12. A conceptual active filtering system. The injected current waveform is selected to be equal in magnitude to the distortion in the input signal but opposite in polarity so the injected current will cancel the distortion in the input signal when the two are added together.

performance of the filters is examined using several existing power systems for testing. 10 also examines a passive filter design methodology and uses a tuned notch filter as an example.

Active Filtering. The basic concept underlying active filtering is the injection of distortion into the system that is equal to the offending distortion, but opposite in polarity, thus canceling the original distortion (16). The shape of the system bus voltage waveform can be altered by a current injected in the system at the particular bus in question. This same phenomenon, which is in part responsible for the creation of voltage harmonics on the power system, can also be employed to help eliminate these same harmonics. If a current with the necessary amplitude and waveform is injected into the power system, a nonsinusoidal bus voltage can be corrected to a true sinusoid (16). Figure 12 illustrates the concept of active filtering.

Active filters can be divided into two types, voltage converters and current converters. In a voltage converter, the dc source for the inverter is a capacitor that opposes a change in voltage, whereas the source for a current converter is an inductor that opposes changes in current.

In addition to multiple converter types, a number of different methodologies are available for controlling active filters. These methodologies can be divided into two categories: time-domain correction and frequency-domain correction.

In time-domain correction schemes, the instantaneous waveforms are kept within some tolerance of a true sinusoid. First, an error function is computed as difference between the distorted waveform and the fundamental sine wave. Then, this error function is used to generate the inverter chopping sequence necessary to produce an injected waveshape capable of canceling the distortion on the system. Several approaches exist for generating the inverter switching signals including the triangular wave method, the hysteresis method, and the deadbeat control method (16).

The triangular wave technique involves the comparison of an instantaneous error signal to a high-frequency triangular carrier waveform. Inverter switching commands are generated each time the error signal intersects the triangular carrier wave. The resultant inverter output signal is equal to the distortion present on the system but opposite in polarity so as to cancel the distortion. This system responds extremely quickly to system changes. It is simple and inexpensive to implement, yet it incurs high-switching losses because the inverter must switch between two and four times during each cycle of the carrier wave and can cause high-frequency distortion on the power system.

In the hysteresis method, inverter switching signals are generated only when the instantaneous error signal exceeds a selected tolerance or hysteresis band, rather than requiring switching during every cycle of a carrier signal. This is the most commonly used time domain–active filter control method because it offers very fast response. It also offers significantly lower switching losses than the triangular method because the inverter is operated only when the error signal strays outside the predefined tolerance band (16).

Deadbeat control methods have not yet been implemented in active power filters, but the concepts have been used for general inverter switching signal generation. These ideas could be expanded for use in the control of active power filters, which would offer the advantages of having a level of intelligence that uses previous experience to predict and correct future distortion.

Instead of working with instantaneous quantities in the time domain, frequency-domain correction algorithms use Fourier analysis and the periodic nature of the harmonic distortion to generate the inverter switching signals needed to cancel the distortion present on the system. The inverter switching signals can be determined using one of two methods. The cancellation of M harmonics method allows for the compensation of harmonics up to the Mth harmonics, where M represents the highest compensated harmonic. The predetermined cancellations method compensates for a known level of harmonic distortion on the system.

The cancellation of M harmonics involves determination of the injected waveform by using the Fourier transform of the error signal as an input to a set of nonlinear equations and solving the nonlinear system of equations for the inverter switching times. Because an error function is used, this system can easily adapt to system changes that alter the harmonic distortion on the power system but requires intense calculations for determination of the necessary injected waveform (16).

The predetermined frequency method eliminates the need for such intense calculations by injection of specific fixed harmonic frequencies into the power system. The precise harmonics to be injected are determined when the active filtering system is designed and are based on prior knowledge of the harmonic levels on the power system, much like passive filters. Such a system is easy to implement and does not require real-time computation of switching signals, but the harmonic levels present on the power system must be known during the filter design phase, and each filter must be custom designed for the specific area in which it is to be used. Moreover, this method does not have the capability to adapt to changes in distortion levels, thereby suffering many of the problems inherent with passive filtering schemes. Additionally, the predetermined frequency method can add distortion to a system in which the harmonic levels have changed from the time the active filtering system was designed (16).

Although active filters offer a number of advantages over passive filters, some disadvantages do exist. First, it is often difficult to construct an inverter with the necessary capacity that has a response quick enough to cancel the harmonics on the system. In addition, active filters are much more complex than their passive counterparts, usually have a much larger initial cost as a result of the active elements necessary for operation, and typically operate inefficiently (13).

Active and Passive Filter Combinations. Because both active filtering methods and passive filtering methods have certain advantages and disadvantages inherent to their operation, it seems logical that a combination of the two filter types could exaggerate the advantages while minimizing the disadvantages.

One method for using both active and passive constructs involves the series connection of an active filter and a passive filter (13). The purpose of the active filter in this situation is to improve the filtering characteristics of the passive filter. This is accomplished by regulating the effective source impedance seen by the passive filter to force the harmonic currents to flow into the passive filter rather than allowing them to propagate back into the source. This makes the passive filter characteristics independent of the actual source impedance as a result of the regulatory nature of the active filter. In addition, resonance problems, which are intrinsic to passive filters alone, are damped by the active filter. Another advantage is that the active filter rating can be much smaller than what is necessary when a conventional active filter operating alone is used because the active filter is not tied directly to the supply system but rather is in series with the passive filter (13).

Equipment Design. Another method for eliminating harmonics from power systems is to deal with the production of harmonics in a more direct manner. One approach is to focus on reducing the harmonics generated by equipment connected to the system. Because the primary sources of harmonics on present day power systems are power converters and other power electronic equipment, the main thrust in this area is to develop control schemes that reduce or eliminate the production of harmonics. An optimally designed control scheme for power electronic equipment would affect the selection of the operating parameters in such a way that the equipment could produce the desired output while minimizing the harmonics injected into the power system.

Conclusion

With the continued improvements in power electronic technology, the number of power electronic-based systems connected to the power grid will undoubtedly continue to grow. Unless proper attention is paid to the impact the harmonics generated by these systems will have on the power grid, an abundance of power quality problems could result. Power outages, equipment failures, and improper equipment operation are possible as harmonic levels on power systems increase.

A number of different methods exist to combat the increasing harmonic levels on the power system. Improving installation design by derating transformers to account for harmonic distortion on the system is a possible solution for handling the harmonic problem. Unfortunately, this method does nothing to diminish the harmonic distortion and could lead to future problems.

Conversely, harmonic filtering in both passive and active forms functions to decrease the overall harmonic levels present on power systems. Filtering leads to a better solution because the harmonics are reduced or even eliminated, thereby allowing the loads connected to the power system to function properly in a harmonic-free environment.

Although filtering is a promising method for dealing with power system harmonics, alone it might not be enough. Instead, equipment designs and control algorithms must be formulated in such a way so as to reduce the harmonics injected into the power system by these devices. In this way, the harmonic levels on the system can be minimized by designing equipment that appears to the power system to be a linear load and draws a sinusoidal current.

None of these methods alone will completely eliminate the problems of power system harmonics. Rather, a combination of these methods—in conjunction with an effort by equipment manufacturers, industrial installations, and commercial power consumers to reduce harmonics—is necessary to keep the harmonic distortion on the power systems to acceptable levels.

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