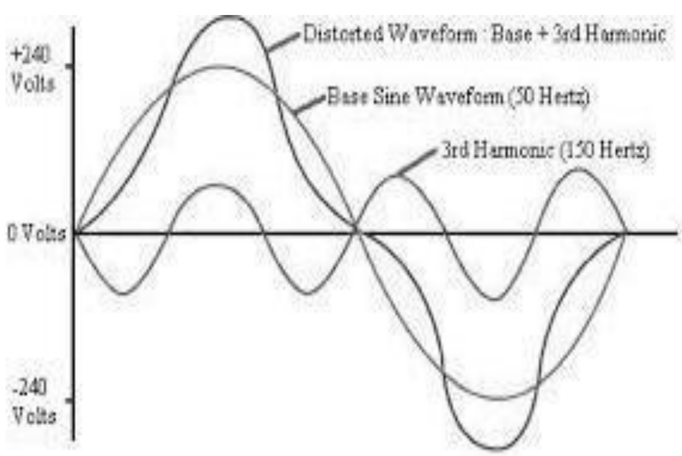
Unit II - Harmonics

Harmonic sources from commercial and industrial loads, locating harmonic sources. Power system response characteristics - Harmonics Vs transients. Effect of harmonics - harmonic distortion - voltage and current distortion - harmonic indices - inter harmonics – resonance. Harmonic distortion evaluation - devices for controlling harmonic distortion - passive and active filters. IEEE and IEC standards.

2.1. Introduction

Harmonic voltages and currents in an electric power system are a result of non-linear electric loads. Harmonic frequencies in the power grid are a frequent cause of power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors

A harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency, i.e. if the fundamental frequency is *f*, the harmonics have frequencies 2*f*, 3*f*, 4*f*, . . . etc. The harmonics have the property that they are all periodic at the fundamental frequency; therefore the sum of harmonics is also periodic at that frequency. Harmonic frequencies are equally spaced by the width of the fundamental frequency and can be found by repeatedly adding that frequency. For example, if the fundamental frequency (first harmonic) is 25 Hz, the frequencies of the next harmonics are: 50 Hz (2nd harmonic), 75 Hz (3rd harmonic), 100 Hz (4th harmonic) etc.



Harmonic Sources from Commercial Loads

Commercial facilities such as office complexes, department stores, hospitals, and Internet data centers are dominated with high-efficiency fluorescent lighting with electronic ballasts, adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads, elevator drives, and sensitive electronic equipment supplied by single-phase switch-mode power supplies. Commercial loads are characterized by a large number of small harmonic-producing loads. Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other. The voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion. Since power factor correction capacitors are not typically used in commercial facilities, the circuit impedance is dominated by the service entrance transformers and conductor impedances. Therefore, the voltage distortion can be estimated simply by multiplying the current by the impedance adjusted for frequency. Characteristics of typical nonlinear commercial loads are detailed in the following sections.

Single-phase power supplies

Electronic power converter loads with their capacity for producing harmonic currents now constitute the most important class of nonlinear loads in the power system. Advances in semiconductor device technology have fueled a revolution in power electronics over the past decade, and there is every indication that this trend will continue. Equipment includes adjustable-speed motor drives, electronic power supplies, dc motor drives, battery chargers, electronic ballasts, and many other rectifier and inverter applications.

A major concern in commercial buildings is that power supplies for single-phase electronic equipment will produce too much harmonic current for the wiring. DC power for modern electronic and microprocessor- based office equipment is commonly derived from single-phase full-wave diode bridge rectifiers. The percentage of load that contains electronic power supplies is increasing at a dramatic pace, with the increased utilization of personal computers in every commercial sector.

There are two common types of single-phase power supplies. Older technologies use ac-side voltage control methods, such as transformers, to reduce voltages to the level required for the dc bus. The inductance of the transformer provides a beneficial side effect by smoothing the input current waveform, reducing harmonic content. Newer-technology switch-mode power supplies (see Fig. 2.5) use dc-to-dc conversion techniques to achieve a smooth dc output with small, lightweight components. The input diode bridge is directly connected to the ac line, eliminating the transformer. This results in a coarsely regulated dc voltage on the capacitor. This direct current is then converted back to alternating current at a very high frequency by the switcher and subsequently rectified again. Personal computers, printers, copiers, and most other single-phase electronic equipment now almost universally employ switch-mode power supplies. The key advantages are the light weight, compact size, efficient operation, and lack of need for a transformer. Switch-mode power supplies can usually tolerate large variations in input voltage.

Because there is no large ac-side inductance, the input current to the power supply comes in very short pulses as the capacitor $C1$ regains its charge on each half cycle. Figure 4.6 illustrates the current waveform and spectrum for an entire circuit supplying a variety of electronic equipment with switch-mode power supplies.

A distinctive characteristic of switch-mode power supplies is a very high third-harmonic content in the current. Since third-harmonic current components are additive in the neutral of a three-phase system, the increasing application of switch-mode power supplies causes concern for overloading of neutral conductors, especially in older buildings where an undersized neutral may have been installed. There is also a concern for transformer overheating due to a combination of harmonic content of the current, stray flux, and high neutral currents.

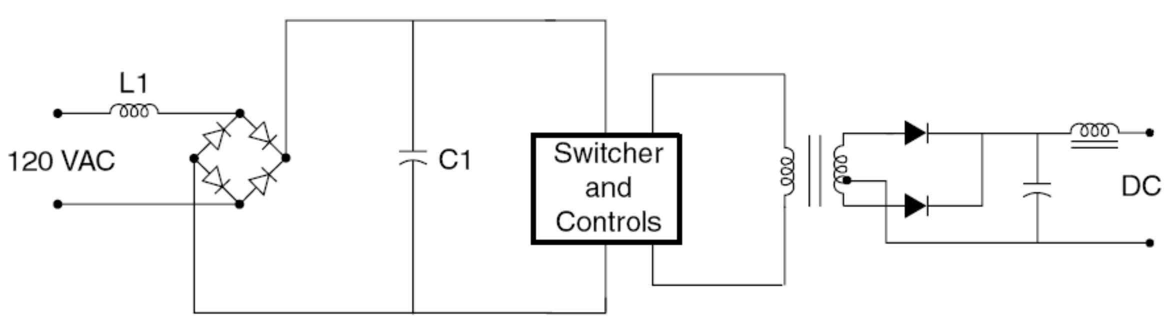


Figure 2.5 Switch-mode power supply.

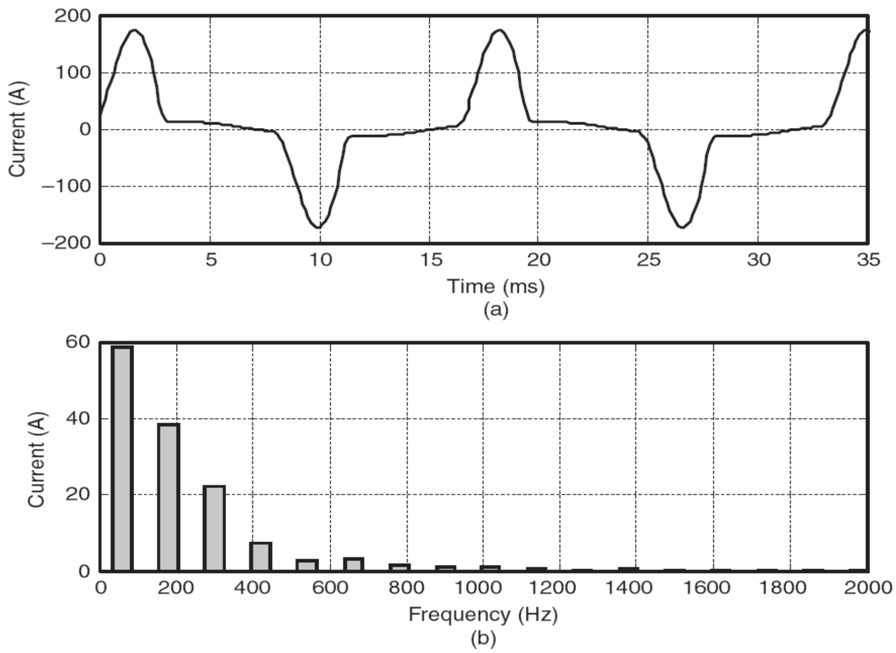


Figure 2.6 SMPS current and harmonic spectrum.

Fluorescent lighting

Lighting typically accounts for 40 to 60 percent of a commercial building load. According to the 1995 Commercial Buildings Energy Consumption study conducted by the U.S. Energy Information Administration, fluorescent lighting was used on 77 percent of commercial floor spaces, while only 14 percent of the spaces used incandescent lighting.1 Fluorescent lights are a popular choice for energy savings.

Fluorescent lights are discharge lamps; thus they require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases. It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current-limiting device in lighting applications.

There are two types of ballasts, magnetic and electronic. A standard magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. A single magnetic ballast can drive one or two fluorescent lamps, and it perates at the line fundamental frequency, i.e., 50 or 60 Hz. The iron-core magnetic ballast contributes additional heat losses, which makes it inefficient compared to an electronic ballast.

An electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit the arc current. Second, the high frequency eliminates or greatly reduces the 100- or 120-Hz flicker associated with an iron-core magnetic ballast.

Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves since the main harmonic distortion comes from the behavior of the arc. Figure 4.7 shows a measured fluorescent lamp current and harmonic spectrum. The current THD is a moderate 15 percent. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. Figure 4.8 shows a fluorescent lamp with an electronic ballast that has a current THD of 144.

Other electronic ballasts have been specifically designed to minimize harmonics and may actually produce less harmonic distortion than the normal magnetic ballast-lamp combination. Electronic ballasts typically produce current THDs in the range of between 10 and 32 percent.

A current THD greater than 32 percent is considered excessive according to ANSI C82.11-1993, *High-Frequency Fluorescent Lamp Ballasts.* Most electronic ballasts are equipped with passive filtering to reduce the input current harmonic distortion to less than 20 percent.

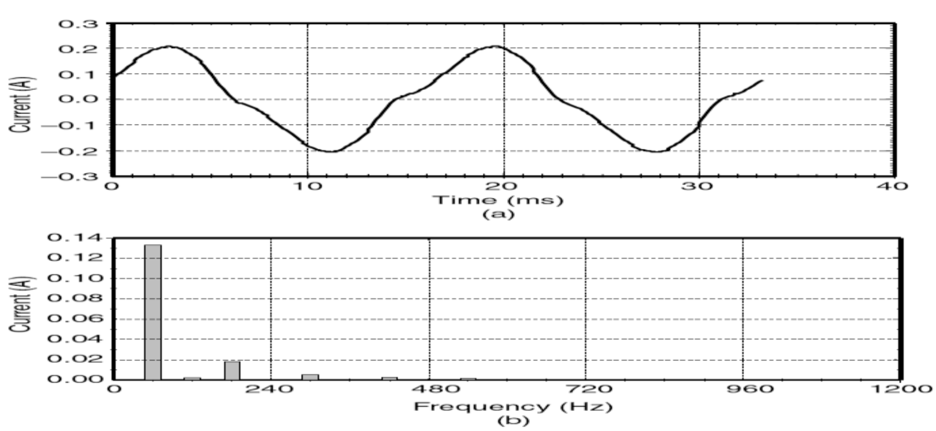


Figure 2.7 Fluorescent lamp with (*a*) magnetic ballast current waveform and (*b*) its harmonic spectrum.

Since fluorescent lamps are a significant source of harmonics in commercial buildings, they are usually distributed among the phases in a nearly balanced manner. With a delta- connected supply transformer, this reduces the amount of triplen harmonic currents flowing onto the power supply system.

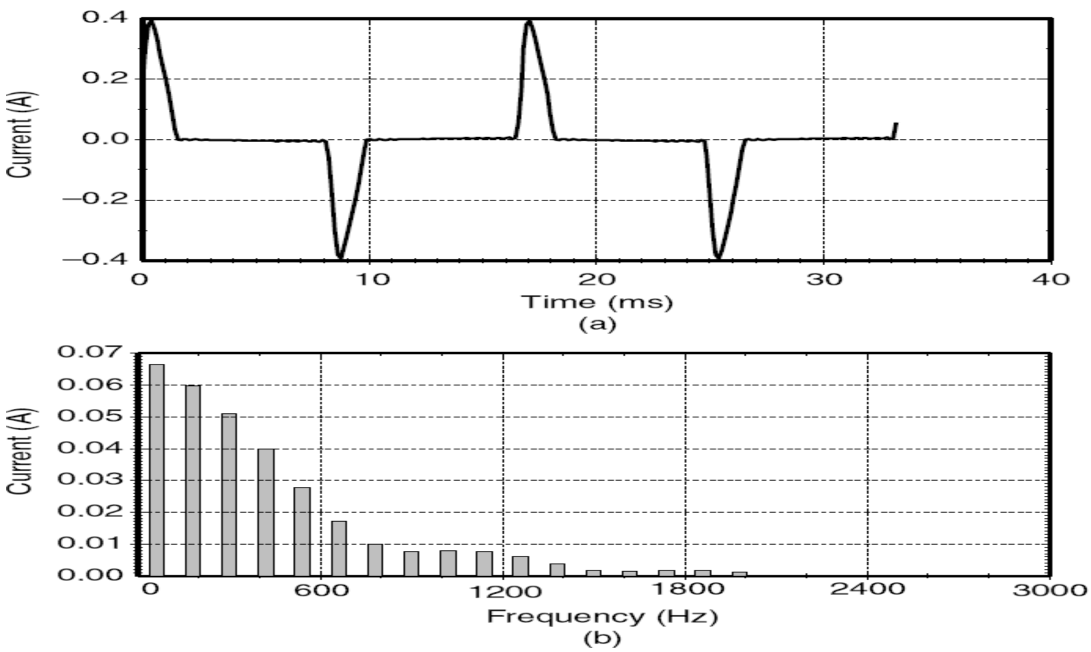


Figure 2.8 Fluorescent lamp with (*a*) electronic ballast current waveform

and (*b*) its harmonic spectrum**.**

Adjustable-speed drives for HVAC and elevators

Common applications of adjustable-speed drives (ASDs) in commercial loads can be found in elevator motors and in pumps and fans in HVAC systems. An ASD consists of an electronic power converter that converts ac voltage and frequency into variable voltage and frequency. The variable voltage and frequency allows the ASD to control motor speed to match the application requirement such as slowing a pump or fan. ASDs also find many applications in industrial loads.

Harmonics sources from industrial loads:

Modern industrial facilities are characterized by the widespread application of nonlinear loads. These loads can make up a significant portion of the total facility loads and inject harmonic currents into the power system, causing harmonic distortion in the voltage. This harmonic problem is compounded by the fact that these nonlinear loads have a relatively low power factor. Industrial facilities often utilize capacitor banks to improve the power factor to avoid penalty charges. The application of power factor correction capacitors can potentially magnify harmonic currents from the nonlinear loads, giving rise to resonance conditions within the facility. The highest voltage distortion level usually occurs at the facility's low-voltage bus where the capacitors are applied. Resonance conditions cause motor and transformer overheating, and misoperation of sensitive electronic equipment.

Nonlinear industrial loads can generally be grouped into three categories: three-phase power converters, arcing devices, and saturable devices. Sections 4.6.1 to 4.6.3 detail the industrial load characteristics.

Three-phase power converters

Three-phase electronic power converters differ from single-phase converters mainly because they do not generate third-harmonic currents. This is a great advantage because the third-harmonic current is the largest component of harmonics. However, they can still be significant sources of harmonics at their characteristic frequencies, as shown in Fig. 4.9. This is a typical current source type of adjustable-speed drive. The harmonic spectrum given in Fig. 4.9 would also be typical of a dc motor drive input current. Voltage source inverter drives (such as PWM-type drives) can have much higher distortion levels as shown in Fig. 4.10.

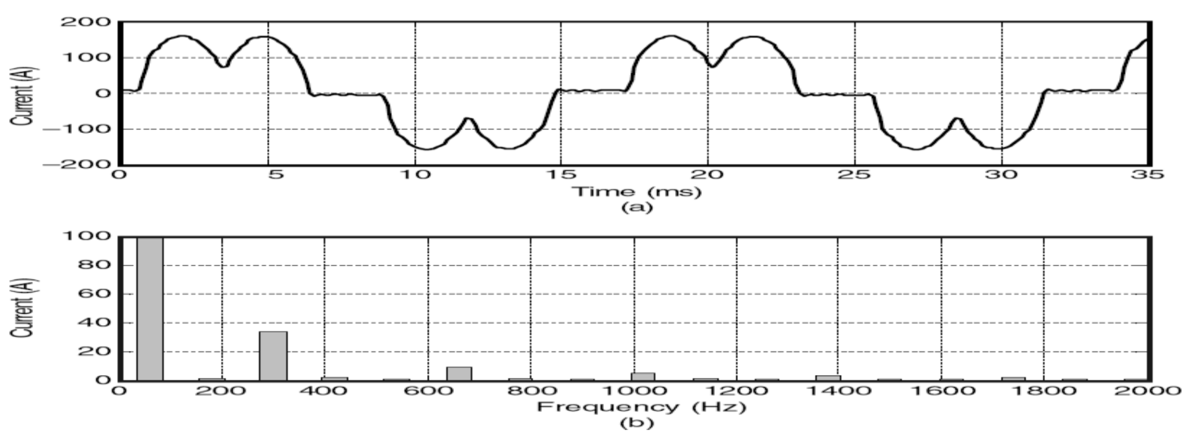


Figure 2.9 Current and harmonic spectrum for CSI-type ASD.

The input to the PWM drive is generally designed like a three-phase version of the switch-mode power supply in computers. The rectifier feeds directly from the ac bus to a large capacitor on the dc bus. With little intentional inductance, the capacitor is charged in very short pulses, creating the distinctive “rabbit ear” ac-side current waveform with very high distortion. Whereas the switch-mode power supplies are generally for very small loads, PWM drives are now being applied for loads up to 500 horsepower (hp). This is a justifiable cause for concern from power engineers.

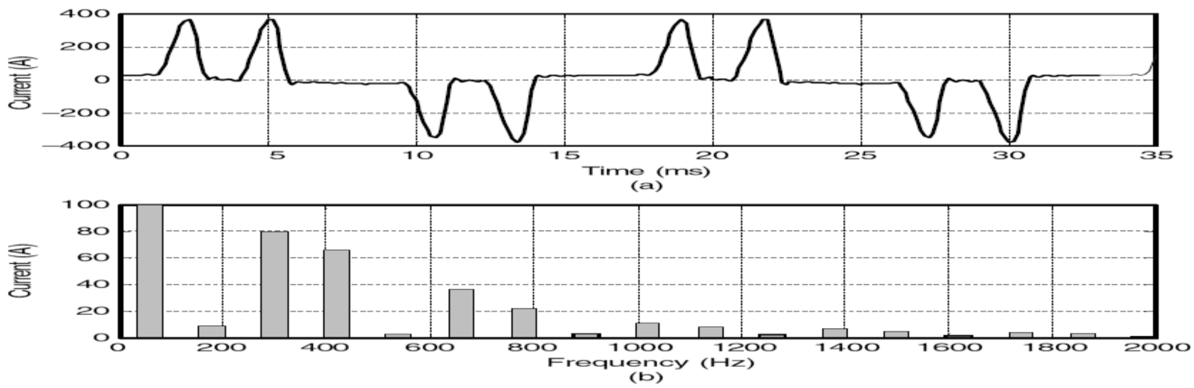


Figure 2.10 Current and harmonic spectrum for PWM-type ASD.

DC drives. Rectification is the only step required for dc drives. Therefore, they have the advantage of relatively simple control systems. Compared with ac drive systems, the dc drive offers a wider speed range and higher starting torque. However, purchase and maintenance costs for dc motors are high, while the cost of power electronic devices has been dropping year after year. Thus, economic considerations limit use of the dc drive to applications that require the speedand torque characteristics of the dc motor.

Most dc drives use the six-pulse rectifier shown in Fig. 4.11. Large drives may employ a 12-pulse rectifier. This reduces thyristor current duties and reduces some of the larger ac current harmonics. The two largest harmonic currents for the six-pulse drive are the fifth and seventh.

They are also the most troublesome in terms of system response. A 12-pulse rectifier in this application can be expected to eliminate about 90 percent of the fifth and seventh harmonics, depending on system imbalances. The disadvantages of the 12-pulse drive are that there is more cost in electronics and another transformer is generally required.

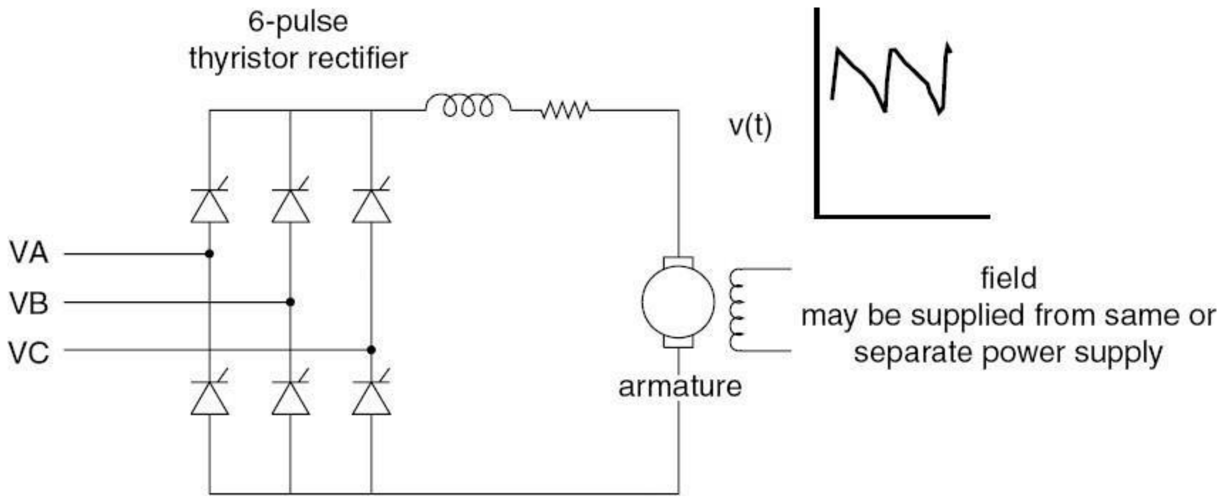


Figure 2.11 Six-pulse dc ASD.

AC drives. In ac drives, the rectifier output is inverted to produce a variable-frequency ac voltage for the motor. Inverters are classified as voltage source inverters (VSIs) or current source inverters (CSIs). A VSI requires a constant dc (i.e., low-ripple) voltage input to the inverter stage. This is achieved with a capacitor or *LC* filter in the dc link. The CSI requires a constant current input; hence, a series inductor is placed in the dc link.

AC drives generally use standard squirrel cage induction motors. These motors are rugged, relatively low in cost, and require little maintenance. Synchronous motors are used where precise speed control is critical.

A popular ac drive configuration uses a VSI employing PWM techniques to synthesize an ac waveform as a train of variable-width dc pulses (see Fig. 2.11). The inverter uses either SCRs, gate turnoff (GTO) thyristors, or power transistors for this purpose. Currently, the VSI PWM drive offers the best energy efficiency for applications over a wide speed range for drives up through at least 500 hp. Another advantage of PWM drives is that, unlike other types of drives, it is not necessary to vary rectifier output voltage to control motor speed. This allows the rectifier thyristors to be replaced with diodes, and the thyristor control circuitry to be eliminated.

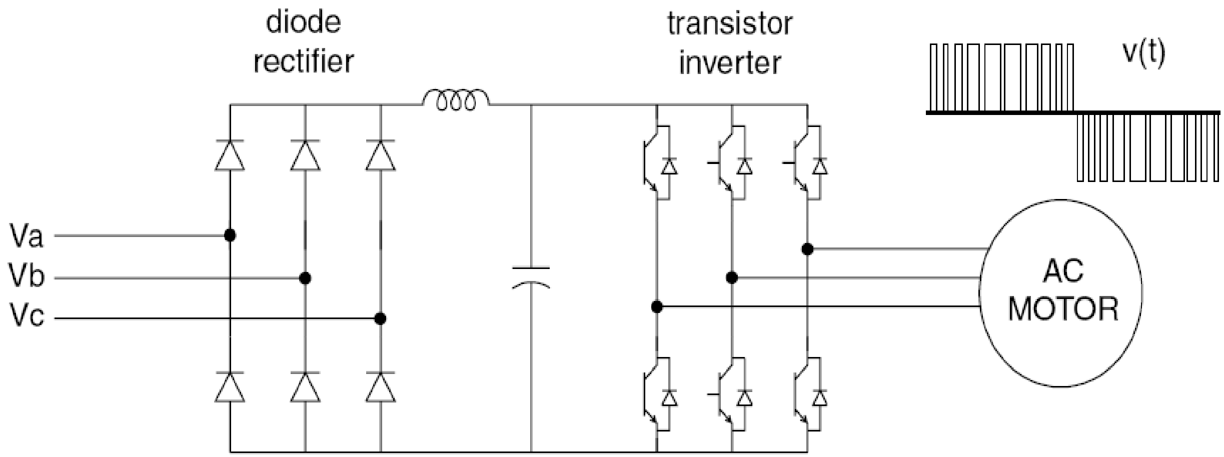


Figure 2.11 PWM ASD.

Very high power drives employ SCRs and inverters. These may be 6- pulse, as shown in Fig. 2.12, or like large dc drives, 12-pulse. VSI drives (Fig. 2.12*a*) are limited to applications that do not require rapid changes in speed. CSI drives (Fig. 2.12*b*) have good acceleration/deceleration characteristics but require a motor with a leading power factor (synchronous or induction with capacitors) or added control circuitry to commutate the inverter thyristors. In either case, the CSI drive must be designed for use with a specific motor. Thyristors in current source inverters must be protected against inductive voltage spikes, which increases the cost of this type of drive.

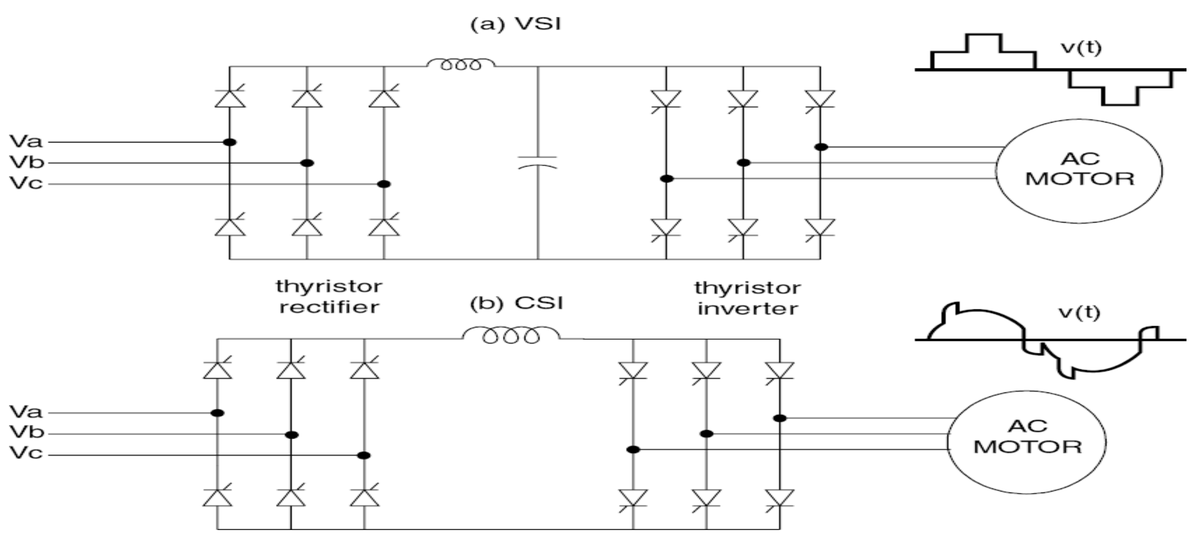


Figure 4.12 Large ac ASDs.

Impact of operating condition. The harmonic current distortion in adjustable-speed drives is not constant. The waveform changes significantly for different speed and torque values. Figure

2.13 shows two operating conditions for a PWM adjustablespeed drive. While the waveform at 42 percent speed is much more distorted proportionately, the drive injects considerably higher magnitude harmonic currents at rated speed. The bar chart shows the amount of current injected. This will be the limiting design factor, not the highest THD. Engineers should be careful to understand the basis of data and measurements concerning these drives before making design decisions

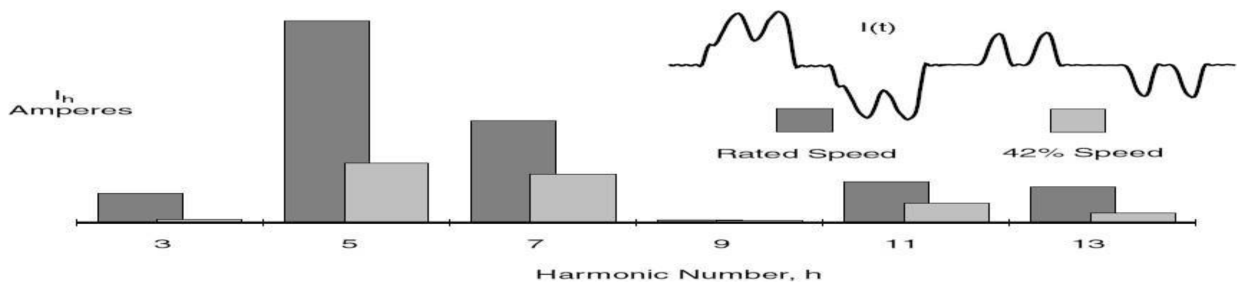


Figure 2.13 Effect of PWM ASD speed on ac current harmonics.

Arcing devices

This category includes arc furnaces, arc welders, and discharge-type lighting (fluorescent, sodium vapor, mercury vapor) with magnetic

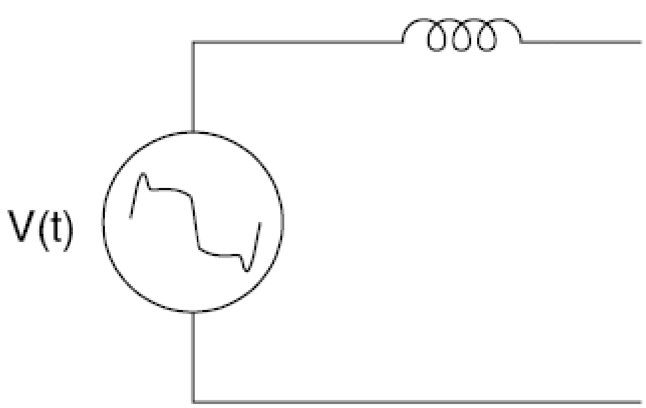


Figure 2.14 Equivalent circuit for an arcing device.

(rather than electronic) ballasts. As shown in Fig. 2.14, the arc is basically a voltage clamp in series with a reactance that limits current to a reasonable value.

The voltage-current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This gives the arc the appearance of having a negative resistance for a portion of its operating cycle such as in fluorescent lighting applications.

In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer. Currents in excess of 60,000 A are common.

The electric arc itself is actually best represented as a source of voltage harmonics. If a probe were to be placed directly across the arc, one would observe a somewhat trapezoidal waveform. Its magnitude is largely a function of the length of the arc. However, the impedance of ballasts or furnace leads acts as a buffer so that the supply voltage is only moderately distorted. The arcing load thus appears to be a relatively stable harmonic current source, which is adequate for most analyses. The exception occurs when the system is near resonance and a Thevenin equivalent model using the arc voltage waveform gives more realistic answers.

Saturable devices

Equipment in this category includes transformers and other electromagnetic devices with a steel core, including motors. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel (see Fig. 2.15).

Power transformers are designed to normally operate just below the “knee” point of the magnetizing saturation characteristic. The operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors. Many electric utilities will penalize transformer vendors by various amounts for no-load and load losses, and the vendor will try to meet the specification with a transformer that has the lowest evaluated cost. A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents.

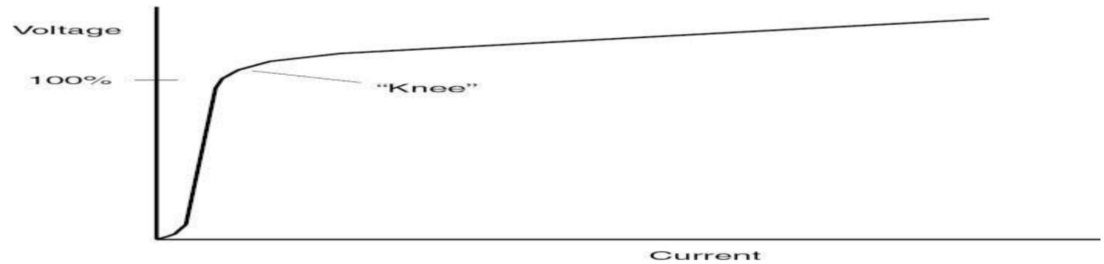


Figure 2.15 Transformer magnetizing characteristic.

Although transformer exciting current is rich in harmonics at normal operating voltage (see Fig. 2.16), it is typically less than 1 percent of rated full load current. Transformers are not as much of a concern as electronic power converters and arcing devices which can produce harmonic currents of 20 percent of their rating, or higher. However, their effect will be noticeable, particularly on utility distribution systems, which have hundreds of transformers. It is common to notice a significant increase in triplen harmonic currents during the early morning

hours when the load is low and the voltage rises. Transformer exciting current is more visible then because there is insufficient load to obscure it and the increased voltage causes more current to be produced. Harmonic voltage distortion from transformer over excitation is generally only apparent under these light load conditions.

Some transformers are purposefully operated in the saturated region. One example is a triplen transformer used to generate 180 Hz for induction furnaces.

Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence. There are, however, some fractional horsepower, single-phase motors that have a nearly triangular waveform with significant third-harmonic currents.

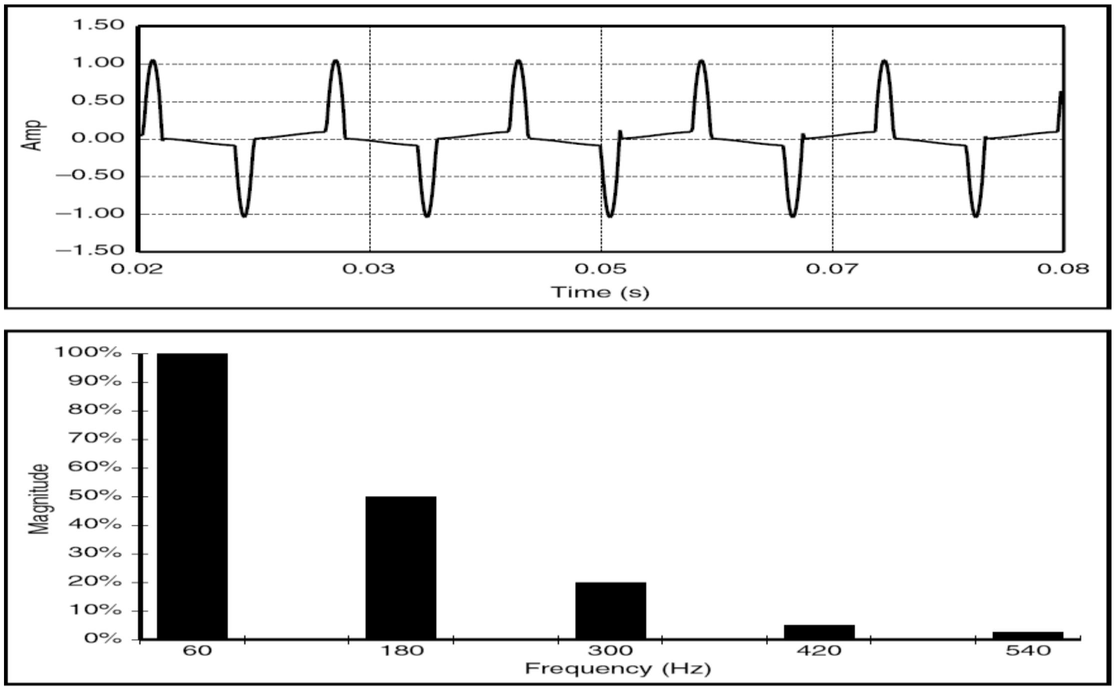


Figure 2.16 Transformer magnetizing current and harmonic spectrum.

Locating Harmonic Sources:

When harmonic problems are caused by excessive voltage distortion on the supply system, it is important to locate the sources of harmonics in order to develop a solution to the problems. Using a power quality monitor capable of reporting the harmonic content of the current, simply measure the harmonic currents in each branch starting at the beginning of the circuit and trace the harmonics to the source.

There are two basic approaches to find the sources of harmonic currents on the power systems:

1. Compare the time variations of the voltage distortion with specific customer and load characteristics.
2. Monitor flow of harmonic currents on the feeder with capacitor banks off.

Power System Response Characteristics:

The power system response characteristics are:

1. The system impedance characteristics

2. The presence of a capacitor bank causing resonance
3. The amount of resistive loads in the system

1. System impedance

At the fundamental frequency, power systems are primarily inductive, and the equivalent impedance is sometimes called simply the short-circuit reactance. Capacitive effects are frequently neglected on utility distribution systems and industrial power systems. One of the most frequently used quantities in the analysis of harmonics on power systems is the short-circuit impedance to the point on a network at which a capacitor is located. If not directly available, it can be computed from short-circuit study results that give either the short-circuit mega volt ampere (MVA) or the short-circuit current as follows:

$$Z_{SC} = R_{SC} + jX_{SC} = \frac{\mathrm{kV}^2}{\mathrm{MVA}_{SC}} = \frac{\mathrm{kV} \times 1000}{\sqrt{3} I_{SC}}$$

where Z_{SC} = short-circuit impedance
R_{SC} = short-circuit resistance
X_{SC} = short-circuit reactance
kV = phase-to-phase voltage, kV
MVA_{SC} = three-phase short-circuit MVA
I_{SC} = short-circuit current, A

*Z*SC is a phasor quantity, consisting of both resistance and reactance. However, if the short-circuit data contain no phase information, one is usually constrained to assuming that the impedance is purely reactive. This is a reasonably good assumption for industrial power systems for buses close to the mains and for most utility systems. When this is not the case, an effort should be made to determine a more realistic resistance value because that will affect the results once capacitors are considered. The inductive reactance portion of the impedance changes linearly with frequency. One common error made by novices in harmonic analysis is to forget to adjust the reactance for frequency. The reactance at the *h*th harmonic is determined from the fundamental impedance reactance *X*1 by:

$$X_h = hX_1$$

In most power systems, one can generally assume that the resistance does not change significantly when studying the effects of harmonics less than the ninth. For lines and cables, the resistance varies approximately by the square root of the frequency once skin effect becomes significant in the conductor at a higher frequency. The exception to this rule is with some transformers.

Because of stray eddy current losses, the apparent resistance of larger transformers may vary almost proportionately with the frequency. This can have a very beneficial effect on damping of resonance as will be shown later. In smaller transformers, less than 100 kVA, the resistance of the winding is often so large relative to the other impedances that it swamps out the stray eddy current effects and there is little change in the total apparent resistance until the frequency reaches about 500 Hz. Of course, these smaller transformers may have an X/R ratio of
1.0 to 2.0 at fundamental frequency, while large substation transformers might typically have a ratio of 20 to 30. Therefore, if the bus that is being studied is dominated by transformer impedance rather than line impedance, the system impedance model should be considered more carefully. Neglecting the resistance will generally give a conservatively high prediction of the harmonic distortion.

At utilization voltages, such as industrial power systems, the equivalent system reactance is often dominated by the service transformer impedance. A good approximation for XSC may be based on the impedance of the service entrance transformer only:

$$X_{\mathrm{SC}} \approx X_{\mathrm{tx}}$$

While not precise, this is generally at least 90 percent of the total impedance and is commonly more. This is usually sufficient to evaluate whether or not there will be a significant harmonic resonance problem. Transformer impedance in ohms can be determined from the percent impedance Ztx found on the nameplate by

$$X_{\mathrm{tx}} = \left(\frac{\mathrm{kV}^2}{\mathrm{MVA}_{3\phi}} \right) \times Z_{\mathrm{tx}}\ (\%)$$

where MVA3_ is the kVA rating of the transformer. This assumes that the impedance is predominantly reactive. For example for a 1500-kVA, 6 percent transformer, the equivalent impedance on the 480-V side is

$$X_{tx} = \left(\frac{\mathrm{kV}^2}{\mathrm{MVA}_{3\phi}}\right) \times Z_{tx}\,(\%) = \left(\frac{0.480^2}{1.5}\right) \times 0.06 = 0.0092\ \Omega$$

A plot of impedance versus frequency for an inductive system (no capacitors installed) would look like Fig. 4.19. Real power systems are not quite as well behaved. This simple model neglects capacitance, which cannot be done for harmonic analysis.

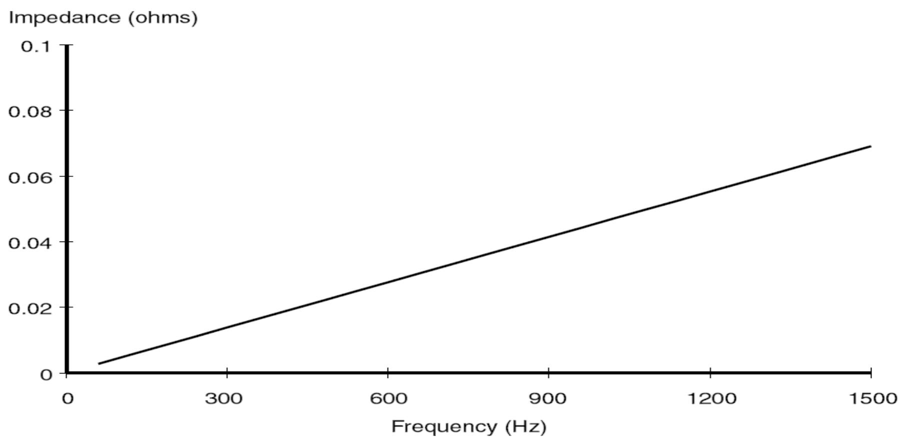


Figure 2.19 Impedance versus frequency for inductive system.

2. Capacitor impedance

Shunt capacitors, either at the customer location for power factor correction or on the distribution system for voltage control, dramatically alter the system impedance variation with frequency. Capacitors do not create harmonics, but severe harmonic distortion can sometimes be attributed to their presence. While the reactance of inductive components increases proportionately to frequency, capacitive reactance *XC* decreases proportionately:

$$X_C = \frac{1}{2\pi f C}$$

C is the capacitance in farads. This quantity is seldom readily available for power capacitors, which are rated in terms of kvar or Mvar at a given voltage. The equivalent line-to-neutral capacitive reactance at fundamental frequency for a capacitor bank can be determined by

$$X_C = \frac{\mathrm{kV}^2}{\mathrm{Mvar}}$$

For three-phase banks, use phase-to-phase voltage and the three phase reactive power rating. For single-phase units, use the capacitor voltage rating and the reactive power rating. For example, for a three phase, 1200-kvar, 13.8-kV capacitor bank, the positive-sequence reactance in ohms would be

$$X_C = \frac{\mathrm{kV}^2}{\mathrm{Mvar}} = \frac{13.8^2}{1.2} = 158.7\ \Omega$$

Parallel resonance

All circuits containing both capacitances and inductances have one or more natural frequencies. When one of those frequencies lines up with a frequency that is being produced on the power system, a resonance may develop in which the voltage and current at that frequency continue to persist at very high values. This is the root of most problems with harmonic distortion on power systems. Figure 4.20 shows a distribution system with potential parallel resonance problems. From the perspective of harmonic sources the shunt capacitor appears in parallel with the equivalent system inductance (source and transformer inductances) at harmonic frequencies as depicted in Fig. 4.21*b*. Furthermore, since the power system is assumed to have an equivalent voltage source of fundamental frequency only, the power system voltage source appears short circuited in the figure. Parallel resonance occurs when the reactance of *XC* and the distribution system cancel each other out. The frequency at which this phenomenon occurs is called the parallel resonant frequency. It can be expressed as follows:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{1}{L_{\mathrm{eq}}C} - \frac{R^2}{4L_{\mathrm{eq}}^2}} \approx \frac{1}{2\pi}\sqrt{\frac{1}{L_{\mathrm{eq}}C}}$$

At the resonant frequency, the apparent impedance of the parallel combination of the equivalent inductance and capacitance as seen from the harmonic current source becomes very large.

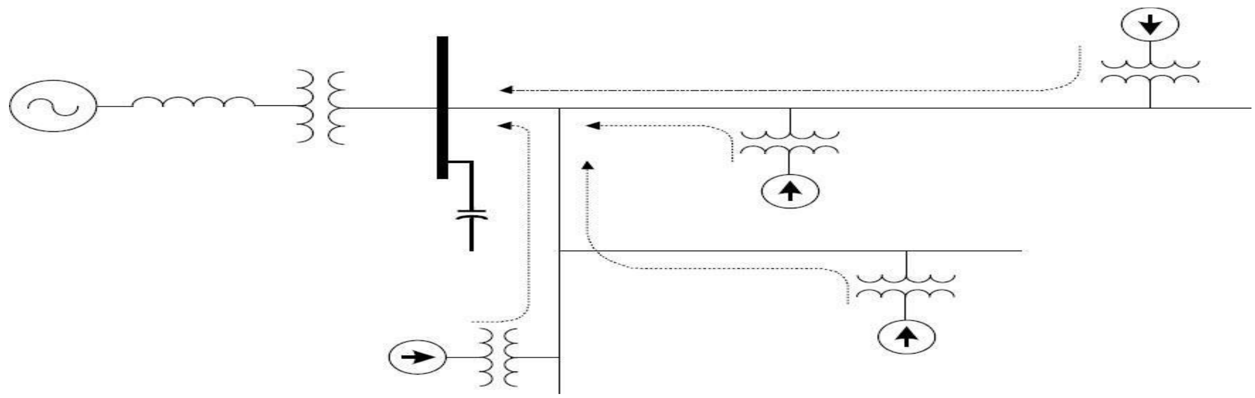


Figure 2.20 System with potential parallel resonance problems.

11.

Where Q _ XL/R _ XC/R and R XLeq. Keep in mind that the reactance in this equation are computed at the resonant frequency.

Q often is known as the quality factor of a resonant circuit that determines the sharpness of the frequency response. Q varies considerably by location on the power system. It might be less than 5 on a distribution feeder and more than 30 on the secondary bus of a large step-down transformer. From Eq. (5.22), it is clear that during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance, i.e., Vp = Q XLeq I_h. The voltage near the capacitor bank will be magnified and heavily distorted. Let us now examine current behavior during the parallel resonance. Let the current flowing in the capacitor bank or into the power system be I resonance; thus,

$$I_{\text{resonance}} = \frac{V_p}{X_C} = \frac{QX_C I_h}{X_C} = QI_h$$

(or)

$$I_{\text{resonance}} = \frac{V_p}{X_{Leq}} = \frac{QX_{Leq} I_h}{X_{Leq}} = QI_h$$

From Eq. It is clear that currents flowing in the capacitor bank and in the power system (i.e., through the transformer) will also be magnified Q times. This phenomenon wills likely cause capacitor failure, fuse blowing, or transformer overheating.

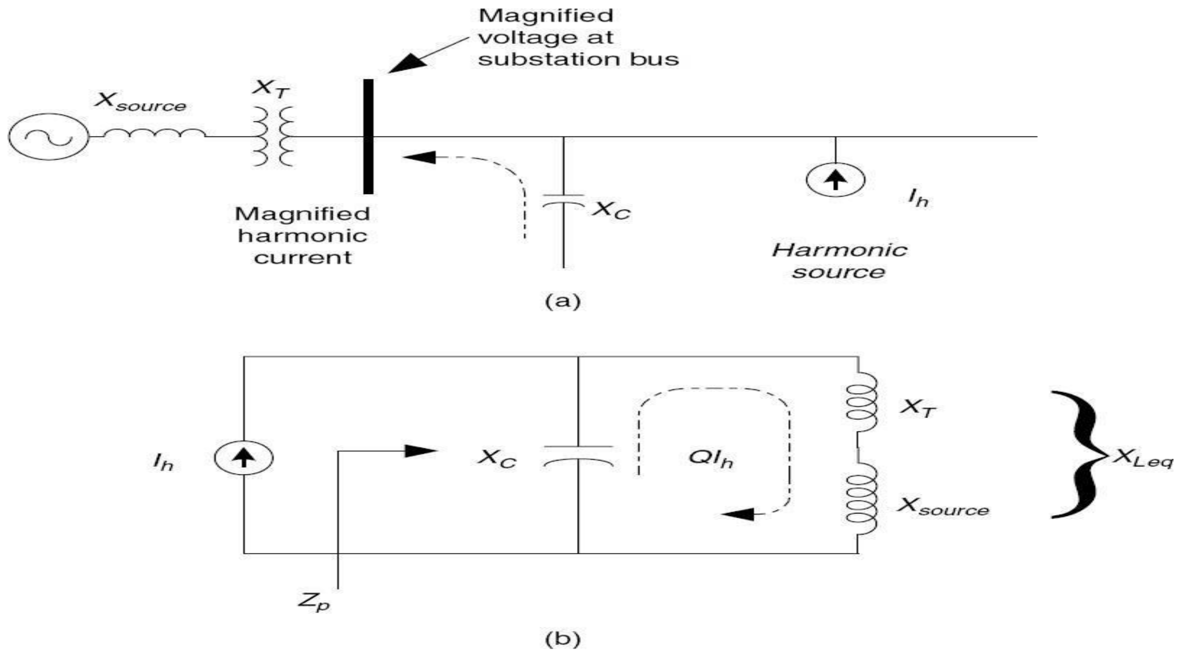


Fig 2.21 at harmonic frequencies, the shunt capacitor bank appears in parallel with the system inductance. (*a*) Simplified distribution circuit; (*b*) parallel resonant circuit as seen from the harmonic source.

The extent of voltage and current magnification is determined by the size of the shunt capacitor bank. Fig 2.22 shows the effect of varying capacitor size in relation to the transformer on the impedance seen from the harmonic source and compared with the case in which there is no capacitor. The following illustrates how the parallel resonant frequency is computed. Power systems analysts typically do not have L and C readily available and prefer to use other forms of this relationship. They commonly compute the resonant harmonic *hr* based on fundamental frequency impedances and ratings using one of the following:

$$h_r = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{\mathrm{MVA_{SC}}}{\mathrm{Mvar_{cap}}}} \approx \sqrt{\frac{\mathrm{kVA_{tx}} \times 100}{\mathrm{kvar_{cap}} \times Z_{tx}\,(\%)}}$$

where h_r = resonant harmonic
X_C = capacitor reactance

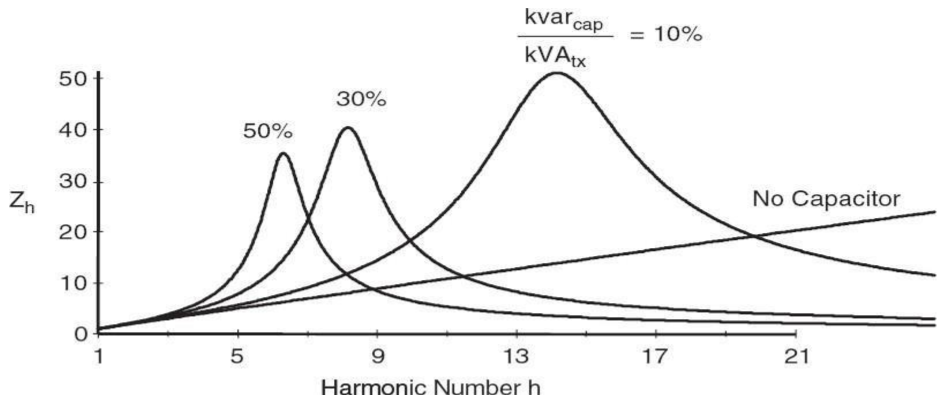


Fig 2.22 System frequency response as capacitor size is varied in relation to transformer.

$$X_{SC} = \text{system short-circuit reactance}$$
$$MVA_{SC} = \text{system short-circuit MVA}$$
$$MVA_{cap} = \text{Mvar rating of capacitor bank}$$
$$kVA_{tx} = \text{kVA rating of step-down transformer}$$
$$Z_{tx} = \text{step-down transformer impedance}$$
$$kvar_{cap} = \text{kvar rating of capacitor bank}$$

For example, for an industrial load bus where the transformer impedance is dominant, the resonant harmonic for a 1500-kVA, 6 percent transformer and a 500-kvar capacitor bank is approximately

$$h_r \approx \sqrt{\frac{kVA_{tx} \times 100}{kvar_{cap} \times Z_{tx}\,(\%)}} = \sqrt{\frac{1500 \times 100}{500 \times 6}} = 7.07$$

4. Series resonance

There are certain instances when a shunt capacitor and the inductance of a transformer or distribution line may appear as a series *LC* circuit to a source of harmonic currents. If the resonant frequency corresponds to a characteristic harmonic frequency of the nonlinear load, the *LC* circuit will attract a large portion of the harmonic current that is generated in the distribution system. A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high harmonic voltage distortion due to neighboring harmonic sources. This situation is depicted in Fig. 2.23.

During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources. The simplified circuit is shown in Fig. 2.24. The harmonic source shown in this figure represents the total harmonics produced by other loads. The inductance in series with the capacitor is that of the service entrance transformer. The series combination of the transformer inductance and the capacitor bank is very small (theoretically zero) and only limited by its resistance. Thus the harmonic current corresponding to the resonant frequency will flow freely in this circuit. The voltage at the power factor correction capacitor is magnified and highly distorted. This is apparent from the following equation:

$$V_s \text{ (at power factor capacitor bank)} = \frac{X_c}{X_T + X_C + R} V_h \approx \frac{X_C}{R} V_h$$

where *Vh* and *Vs* are the harmonic voltage corresponding to the harmonic current *Ih* and the voltage at the power factor capacitor bank, respectively. The resistance *R* of the series resonant circuit is not shown in Fig. 2.24, and it is small compared to the reactance.

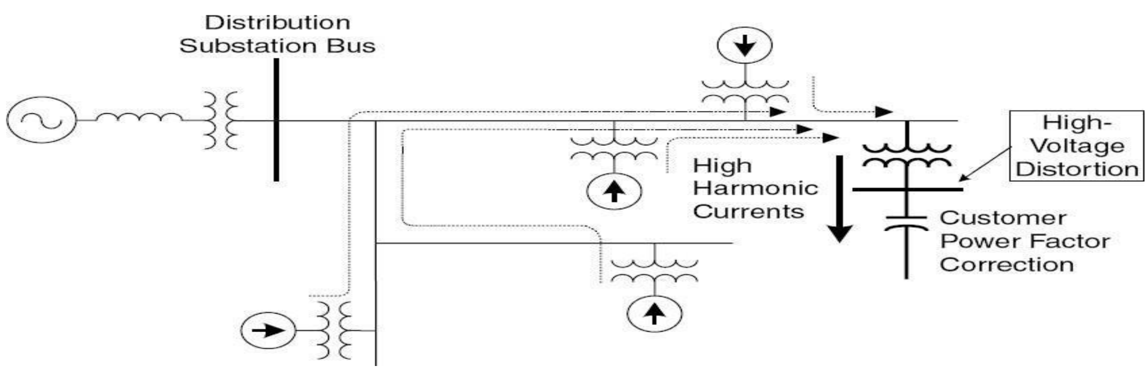


Figure 2.23 System with potential series resonance problems.

The negligible impedance of the series resonant circuit can be exploited to absorb desired harmonic currents. This is indeed the principle in designing a notch filter. In many systems with potential series resonance problems, parallel resonance also arises due to the circuit topology. One of these is shown in Fig. 2.24 where the parallel resonance is formed by the parallel combination between *X* source and a series between *XT* and *XC.* The resulting parallel resonant frequency is always smaller than its series resonant frequency due to the source inductance contribution. The parallel resonant frequency can be represented by the following equation:

$$h_r = \sqrt{\frac{X_C}{X_T + X_{\text{source}}}}$$

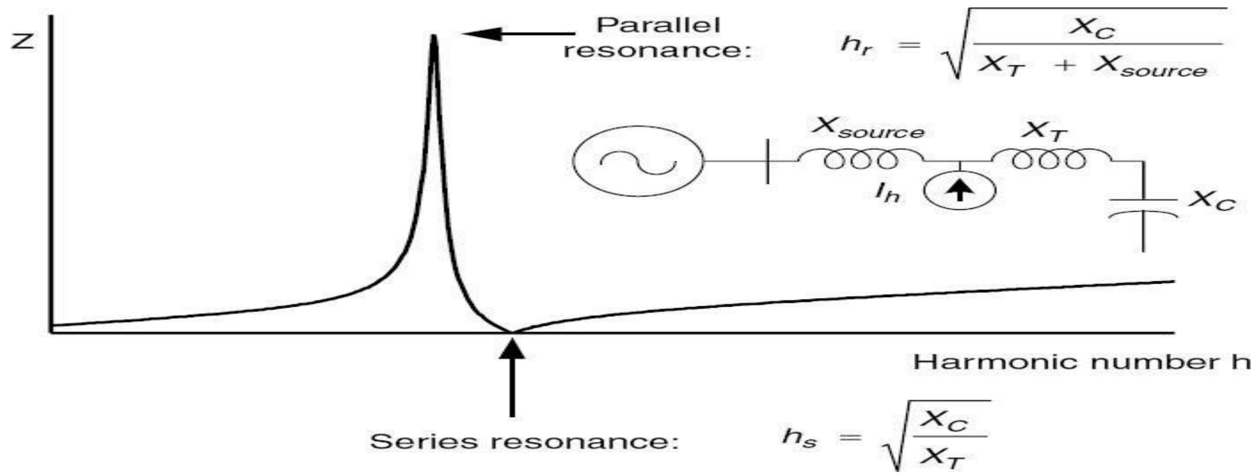


Figure 4.24 Frequency response of a circuit with series resonance.

Effects of Harmonics:

Introduction

Harmonics in electrical system result in waveform distortion. The are periodic disturbance in voltage and current. Any noon sinusoidal periodic waveforms can be considered as combination of sine waveform of certain frequency, amplitude and phase angle. Generally these are individual multiple of fundamental frequency. Hence 3rd order frequency has got frequency of 150 Hz, and the 5th order harmonic has 250 frequency and so on. The amplitude and phase angle of individual components will vary depending on the nature of distorted waveform.

THD is defined as the ratio of the root mean square value of the harmonic content to root mean square value of the fundamental quantity, expressed as percent of the fundamental. It is measured of effective value of harmonic distortion.

The total harmonic value of distortion (THD) is the value used to describe the characteristics of distorted waveform. The THD is a measured of how badly the waveform is distorted from pure sinusoidal the THD is 0%. IEEE standard 519 recommends that for most system, the THD of the bus voltage should be less than 5% with maximum of 3% with any individual components.

Harmonic Distortion

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. Figure 4.1 illustrates this concept by the case of a sinusoidal voltage applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape. This is the source of most harmonic distortion in a power system.

Figure 4.2 illustrates that any periodic, distorted waveform can be expressed as a sum of sinusoids. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a *harmonic* of the fundamental, hence the name of this subject matter. The sum of sinusoids is referred to as a *Fourier series,* named after the great mathematician who discovered the concept.

Because of the above property, the Fourier series concept is universally applied in analyzing harmonic problems. The system can now be analyzed separately at each harmonic. In addition, finding the system response of a sinusoid of each harmonic individually is much more straightforward compared to that with the entire distorted waveforms. The outputs at each frequency are then combined to form a new Fourier series, from which the output waveform may be computed, if desired. Often, only the magnitudes of the harmonics are of interest.

When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only *odd* harmonics. This offers a further simplification for most power system studies because most common harmonic-producing devices look the same to both polarities. In fact, the presence of even harmonics is often a clue that there is something wrong—either with the load equipment or with the transducer used to make the measurement. There are notable exceptions to this such as half-wave rectifiers and arc furnaces when the arc is random.

Usually, the higher-order harmonics (above the range of the 25th to 50th, depending on the system) are negligible for power system analysis. While they may cause interference with low-power electronic devices, they are usually not damaging to the power system. It is also difficult to collect sufficiently accurate data to model power systems at these frequencies.

A common exception to this occurs when there are system resonances in the range of frequencies. These resonances can be excited by notching or switching transients in electronic power converters. This causes voltage waveforms with multiple zero crossings which disrupt timing circuits. These resonances generally occur on systems with underground cable but no power factor correction capacitors.

If the power system is depicted as series and shunt elements, as is the conventional practice, the vast majority of the nonlinearities in the system are found in *shunt* elements (i.e., loads). The series impedance of the power delivery system (i.e., the short-circuit impedance between the source and the load) is remarkably linear. In transformers, also, the source of harmonics is the shunt branch (magnetizing impedance) of the common "T" model; the leakage impedance is linear. Thus, the main sources of harmonic distortion will ultimately be end-user loads. This is not to say that all end users who experience harmonic distortion will themselves have significant sources of harmonics, but that the harmonic distortion generally originates with some end-user's load or combination of loads.

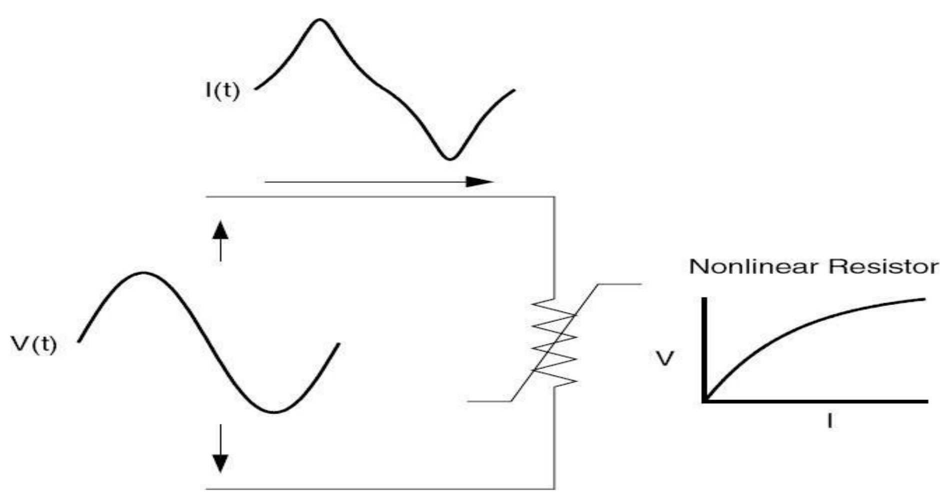


Fig 2.1 Current distortion caused by nonlinear resistance.

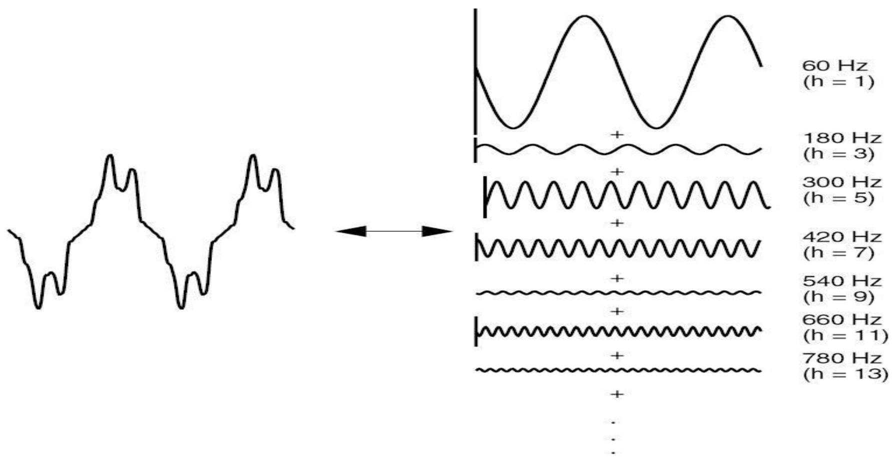


Fig 2.2 Fourier series representation of a distorted waveform.

Voltage versus Current Distortion

The word harmonics is often used by itself without further qualification. For example, it is common to hear that an adjustable-speed drive or an induction furnace can't operate properly because of harmonics. What does that mean? Generally, it could mean one of the following

Three things:

1. The harmonic voltages are too great (the voltage too distorted) for the control to properly determine firing angles.
2. The harmonic currents are too great for the capacity of some device in the power supply system such as a transformer, and the machine must be operated at a lower than rated power.
3. The harmonic voltages are too great because the harmonic currents produced by the device are too great for the given system condition.

As suggested by this list, there are separate causes and effects for voltages and currents as well as some relationship between them. Thus, the term harmonics by itself is inadequate to definitively describe a problem.

Nonlinear loads appear to be sources of harmonic current in shunt with and injecting harmonic currents into the power system. For nearly all analyses, it is sufficient to treat these harmonic-producing loads simply as current sources. There are exceptions to this as will be described later.

As Fig. 4.3 shows, voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system, although, assuming that the source bus is ultimately a pure sinusoid, there is a nonlinear load that draws a distorted current. The harmonic currents passing through the impedance of the systemcause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. The amount of voltage distortion depends on the impedance and the current. Assuming the load bus distortion stays within reasonable limits (e.g., less than 5 percent), the amount of harmonic current produced by the load is generally constant.

While the load current harmonics ultimately cause the voltage distortion, it should be noted that load has no control over the voltage distortion. The same load put in two different locations on the power system will result in two different voltage distortion values. Recognition of this fact is the basis for the division of responsibilities for harmonic control that are found in standards such as IEEE Standard 519-1992, *Recommended Practices and Requirements for* Harmonic Control in Electrical Power Systems:

1. The control over the amount of harmonic current injected into the system takes place at the end-use application.

2. Assuming the harmonic current injection is within reasonable limits, the control over the voltage distortion is exercised by the entity having control over the system impedance, which is often the utility.

One must be careful when describing harmonic phenomena to understand that there are distinct differences between the causes and effects of harmonic voltages and currents. The use of the term harmonics should be qualified accordingly. By popular convention in the power industry, the majority of times when the term is used by itself to refer to the load apparatus, the speaker is referring to the harmonic currents. When referring to the utility system, the voltages are generally the subject. To be safe, make a habit of asking for clarification.

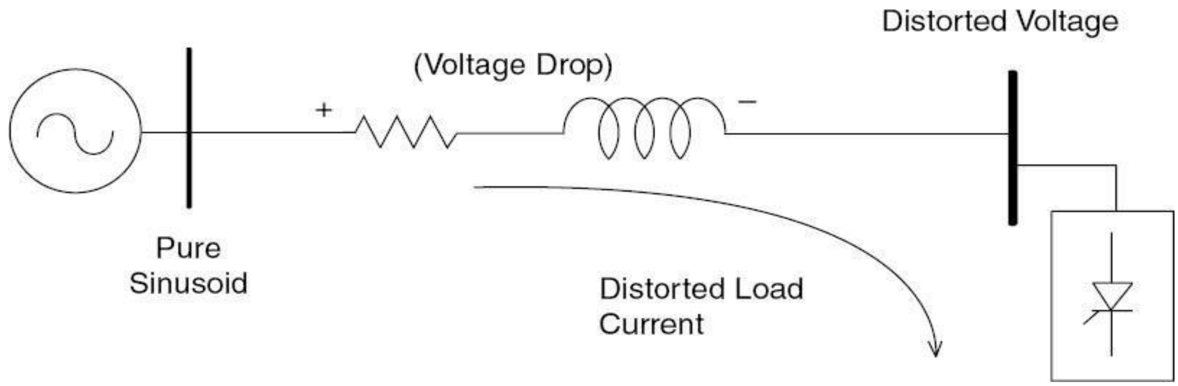


Fig 2.3 Harmonic currents flowing through the system impedance result in harmonic voltages at the load.

Harmonic Indices:

The two most commonly used indices for measuring the harmonic content of a waveform are the total harmonic distortion and the total demand distortion. Both are measures of the effective value of a waveform and may be applied to either voltage or current.

Total harmonic distortion

The THD is a measure of the *effective value* of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental. This index can be calculated for either voltage or current:

$$\mathrm{THD} = \frac{\sqrt{\sum_{h>1}^{h_{\max}} M_h^{\,2}}}{M_1} \qquad (4.1)$$

where *Mh* is the rms value of harmonic component *h* of the quantity *M*.

The rms value of a distorted waveform is the square root of the sum of the squares as shown in Eqs. (4.1) and (4.2). The THD is related to the rms value of the waveform as follows:

$$\mathrm{RMS} = \sqrt{\sum_{h=1}^{h_{\max}} M_h^{\,2}} = M_1\sqrt{1+\mathrm{THD}^2} \qquad (4.2)$$

The THD is a very useful quantity for many applications, but its limitations must be realized. It can provide a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load. Likewise, it can give an indication of the additional losses caused by the current flowing through a conductor. However, it is not a good indicator of the voltage stress within a capacitor because that is related to the peak value of the voltage waveform, not its heating value.

The THD index is most often used to describe voltage harmonic distortion. Harmonic voltages are almost always referenced to the fundamental value of the waveform at the time of the sample. Because fundamental voltage varies by only a few percent, the voltage THD is nearly always a meaningful number. Variations in the THD over a period of time often follow a distinct pattern representing nonlinear load activities in the system. Figure 4.4 shows the voltage THD variation over a 1-week period where a daily cyclical pattern is obvious. The voltage THD shown in Fig. 4.4 was taken at a 13.2-kV distribution substation supplying a residential load. High-voltage THD occurs at night and during the early morning hours since the nonlinear loads are relatively high compared to the amount of linear load during these hours. A 1-week observation period is often required to come up with a meaningful THD pattern since it is usually the shortest period to obtain representative and reproducible measurement results.

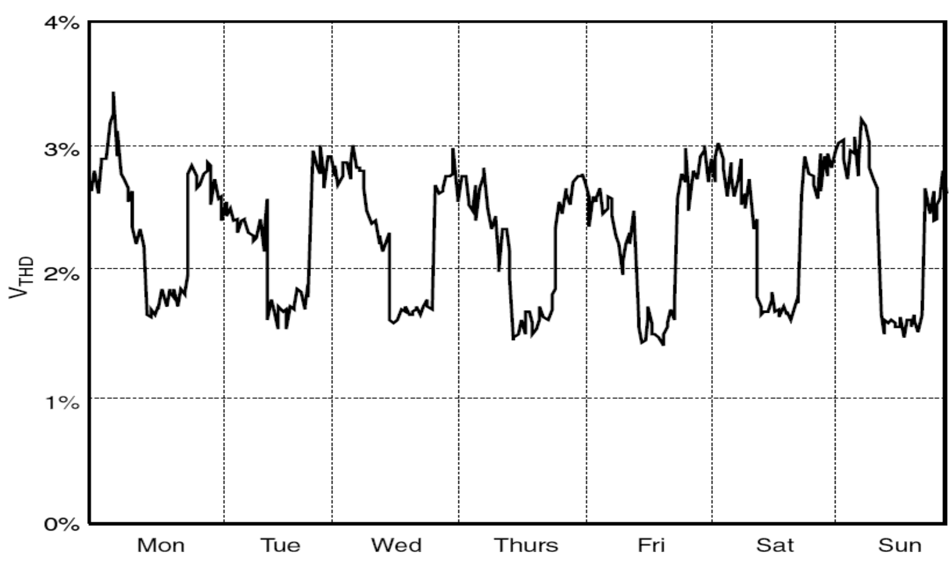


Fig 2.4 Variation of the voltage THD over a 1-week period.

Total demand distortion

Current distortion levels can be characterized by a THD value, as has been described, but this can often be misleading. A small current may have a high THD but not be a significant threat to the system. For example, many adjustable-speed drives will exhibit high THD values for the input current when they are operating at very light loads. This is not necessarily a significant concern because the magnitude of harmonic current is low, even though its relative current distortion is high.

Some analysts have attempted to avoid this difficulty by referring THD to the fundamental of the peak demand load current rather than the fundamental of the present sample. This is called total demand distortion and serves as the basis for the guidelines in IEEE Standard

519-1992, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.* It is defined as follows:

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} I_h{}^2}}{I_L} \tag{4.1}$$

I_L is the peak, or maximum, demand load current at the fundamental frequency component measured at the point of common coupling (PCC). There are two ways to measure I_L. With a load already in the system, it can be calculated as the average of the maximum demand current for the preceding 12 months. The calculation can simply be done by averaging the 12-month peak demand readings. For a new facility, I_L has to be estimated based on the predicted load profiles.

Harmonic Distortion Evaluation:

The interaction often gives rise to voltage and current harmonic distortion observed in many places in the system. Therefore, to limit both voltage and current harmonic distortion, IEEE Standard 519-19922 proposes to limit harmonic current injection from end users so that harmonic voltage levels on the overall power system will be acceptable if the power system does not inordinately accentuate the harmonic currents. This approach requires participation from both end users and utilities.1–3

1. End users. For individual end users, IEEE Standard 519-1992 limits the level of harmonic current injection at the point of common coupling (PCC). This is the quantity end users have control over. Recommended limits are provided for both individual harmonic components and the total demand distortion. The concept of PCC is illustrated in Fig. 4.25. These limits are expressed in terms of a percentage of the end user's maximum demand current level, rather than as a percentage of the fundamental. This is intended to provide a common basis for evaluation over time.

2. The utility. Since the harmonic voltage distortion on the utility system arises from the interaction between distorted load currents and the utility system impedance, the utility is mainly responsible for limiting the voltage distortion at the PCC. The limits are given for the maximum individual harmonic components and for the total harmonic distortion (THD). These values are expressed as the percentage of the fundamental voltage. For systems below 69 kV, the THD should be less than 5 percent. Sometimes the utility system impedance at harmonic frequencies is determined by the resonance of power factor correction capacitor banks. This results in a very high impedance and high harmonic voltages. Therefore, compliance with IEEE Standard 519- 1992 often means that the utility must ensure that system resonances do not coincide with harmonic frequencies present in the load currents. Thus, in principle, end users and utilities share responsibility for limiting harmonic current injections and voltage distortion at the PCC. Since there are two parties involved in limiting harmonic distortions, the evaluation of harmonic distortion is divided into two parts: measurements of the currents being injected by the load and calculations of the frequency response of the system impedance. Measurements should be taken continuously over a sufficient period of time so that time variations and statistical characteristics of the harmonic distortion can be accurately represented. Sporadic measurements should be avoided since they do not represent harmonic characteristics accurately given that harmonics are a continuous phenomenon. The minimum measurement period is usually 1 week since this provides a representative loading cycle for most industrial and commercial loads.

Concept of point of common coupling

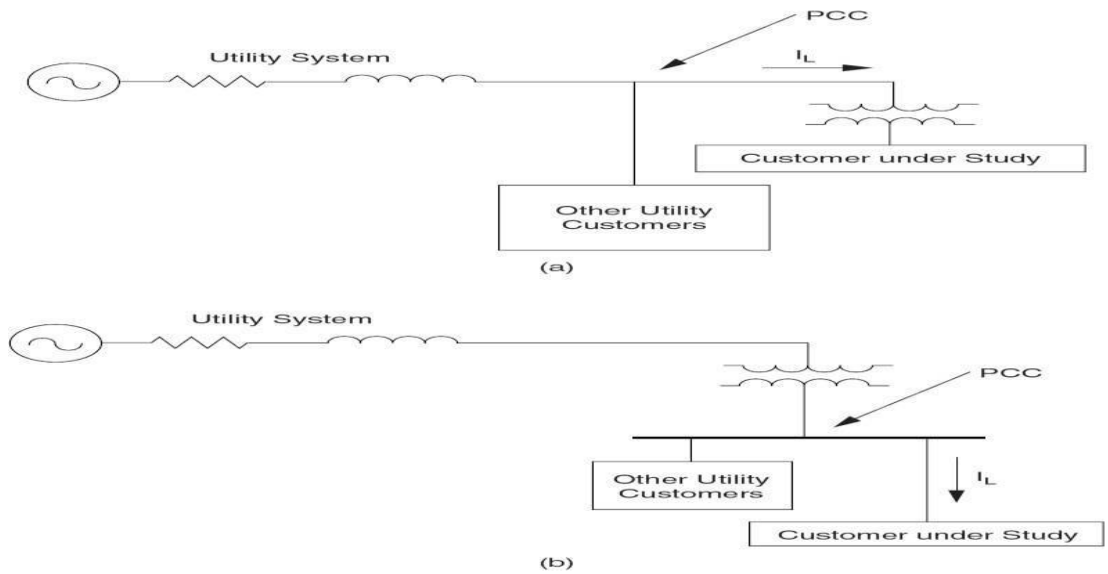


Figure 2.25 PCC selection depends on where multiple customers are served. (*a*) PCC at the transformer primary where multiple customers are served. (*b*) PCC at the transformer secondary where multiple customers are served.

Evaluations of harmonic distortion are usually performed at a point between the end user or customer and the utility system where another customer can be served. This point is known as the point of common coupling.1

The PCC can be located at either the primary side or the secondary side of the service transformer depending on whether or not multiple customers are supplied from the transformer. In other words, if multiple customers are served from the primary of the transformer, the PCC is then located at the primary. On the other hand, if multiple customers are served from the secondary of the transformer, the PCC is located at the secondary. Figure 2.25 illustrates these two possibilities.

Note that when the primary of the transformer is the PCC, current measurements for verification can still be performed at the transformer secondary. The measurement results should be referred to the transformer high side by the turns ratio of the transformer, and the effect of transformer connection on the zero-sequence components must be taken into account. For instance, a delta-wye connected transformer will not allow zero-sequence current components to flow from the secondary to the primary system. These secondary components will be trapped in the primary delta winding. Therefore, zero-sequence components (which are balanced triplen harmonic components) measured on the secondary side would not be included in the evaluation for a PCC on the primary side.

Harmonic evaluations on the utility system

Harmonic evaluations on the utility system involve procedures to determine the acceptability of the voltage distortion for all customers. Should the voltage distortion exceed the recommended limits, corrective actions will be taken to reduce the distortion to a level within limits. IEEE Standard 519-1992 provides guidelines for acceptable levels of voltage distortion on the utility system. These are summarized in Table 4.1. Note that the recommended limits are specified for the maximum individual harmonic component and for the THD.

Note that the definition of the total harmonic distortion in Table 4.1 is slightly different than the conventional definition. The THD value in this table is expressed as a function of the nominal system rms voltage rather than of the fundamental frequency voltage magnitude at the time of the measurement. The definition used here allows the evaluation of the voltage distortion with respect to fixed limits rather than limits that fluctuate with the system voltage. A similar concept is applied for the current limits.

There are two important components for limiting voltage distortion levels on the overall utility system:

1. Harmonic currents injected from individual end users on the system must be limited. These currents propagate toward the supply source through the system impedance, creating voltage distortion. Thus by limiting the amount of injected harmonic currents, the voltage distortion can be limited as well. This is indeed the basic method of controlling the overall distortion levels proposed by IEEE Standard 519- 1992.

2. The overall voltage distortion levels can be excessively high even if the harmonic current injections are within limits. This condition occurs primarily when one of the harmonic current frequencies is close to a system resonance frequency. This can result in unacceptable voltage distortion levels at some system locations. The highest voltage distortion will generally occur at a capacitor bank that participates in the resonance. This location can be remote from the point of injection.

Table 4.1 Harmonic Voltage Distortion Limits in Percent of

Nominal Fundamental Frequency Voltage

Bus voltage at PCC, V_n (kV)	Individual harmonic voltage distortion (%)	Total voltage distortion, THD_{V_n} (%)
$V_n \leq 69$	3.0	5.0
$69 < V_n \leq 161$	1.5	2.5
$V_n > 161$	1.0	1.5

SOURCE: IEEE Standard 519-1992, table 11.1.

Voltage limits evaluation procedure:

The overall procedure for utility system harmonic evaluation is described here. This procedure is applicable to both existing and planned installations. Figure 4.26 shows a flowchart of the evaluation procedure.

1. ***Characterization of harmonic sources***. Characteristics of harmonic sources on the system are best determined with measurements for existing installations. These measurements should be performed at facilities suspected of having offending nonlinear loads. The duration of measurements is usually at least 1 week so that all the cyclical load variations can be captured. For new or planned installations, harmonic characteristics provided by manufacturers may suffice.

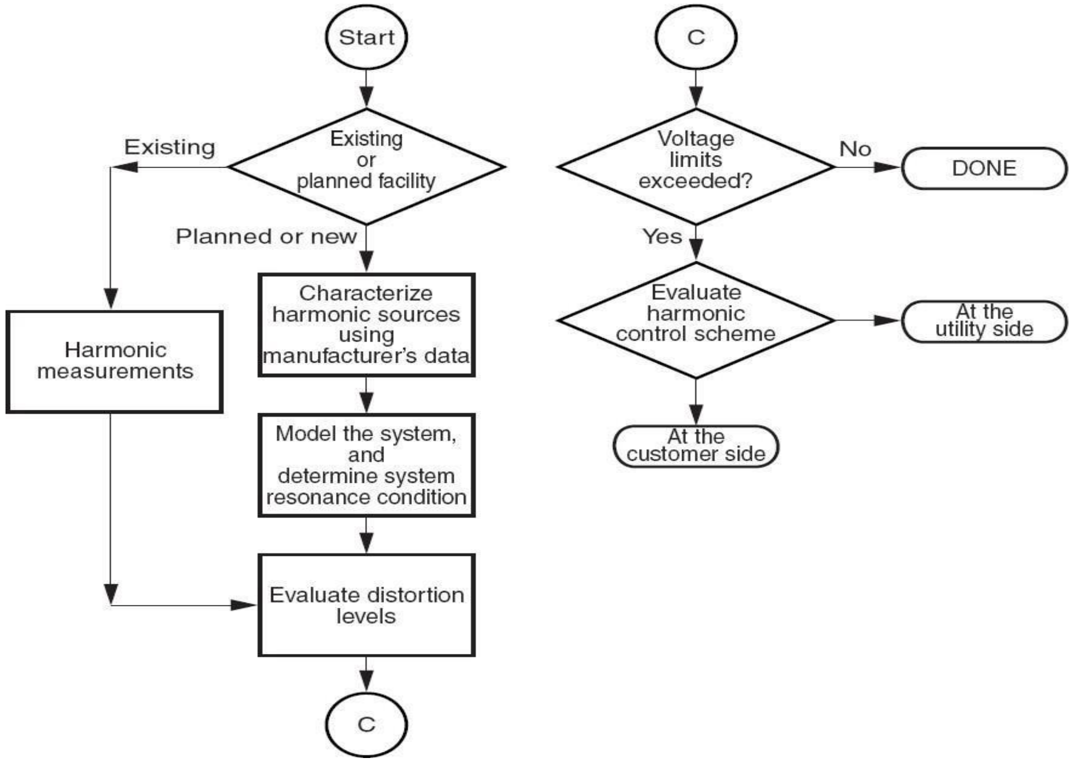


Fig 2.26 Voltage limit evaluation procedure

2. **System modeling.** The system response to the harmonic currents injected at end-user locations or by nonlinear devices on the power system is determined by developing a computer model of the system.

3. **System frequency response**. Possible system resonances should be determined by a frequency scan of the entire power delivery system. Frequency scans are performed for all capacitor bank configurations of interest since capacitor configuration is the main variable that will affect the resonant frequencies.

4. ***Evaluate expected distortion levels***. Even with system resonance close to characteristic harmonics, the voltage distortion levels around the system may be acceptable. On distribution systems, most resonances are significantly damped by the resistances on the system, which reduces magnification of the harmonic currents. The estimated harmonic sources are used with the system configuration yielding the worst-case frequency-response characteristics to compute

the highest expected harmonic distortion. This will indicate whether or not harmonic mitigation measures are necessary.

5. Evaluate harmonic control scheme. Harmonic control options consist of controlling the harmonic injection from nonlinear loads, changing the system frequency-response characteristics, or blocking the flow of harmonic currents by applying harmonic filters. Design of Passive filters for some systems can be difficult because the system characteristics are constantly changing as loads vary and capacitor banks are switched.

Harmonic evaluation for end-user facilities:

Harmonic problems are more common at end-user facilities than on the utility supply system. Most nonlinear loads are located within end-user facilities, and the highest voltage distortion levels occur close to harmonic sources. The most significant problems occur when there are nonlinear loads and power factor correction capacitors that result in resonant conditions. IEEE Standard 519-1992 establishes harmonic current distortion limits at the PCC. The limits, summarized in Table 4.2, are dependent on the customer load in relation to the system short-circuit capacity at the PCC.

The variables and additional restrictions to the limits given in Table 4.2 are:

I_{SC}/I_L	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
$V_n \le 69$ kV						
<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
69 kV $< V_n \le$ 161 kV						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_n > 161$ kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

*All power generation equipment applications are limited to these values of current distortion regard less of the actual short-circuit current ratio I_{SC}/I_L.
SOURCE: IEEE Standard 519-1992, tables 10.3, 10.4, 10.5.

- ✓ Ih is the magnitude of individual harmonic components (rms amps).
- ✓ *I*SC is the short-circuit current at the PCC.

- ✓ *IL* is the fundamental component of the maximum demand load current at the PCC. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated.
- ✓ The individual harmonic component limits apply to the odd-harmonic components. Even-harmonic components are limited to 25 percent of the limits.
- ✓ Current distortion which results in a dc offset at the PCC is not allowed.
- ✓ The total demand distortion (TDD) is expressed in terms of the maximum demand load current, i.e.,

$$\mathrm{TDD} = \frac{\sqrt{\sum_{2} I_h^2}}{I_L} \times 100\% \tag{4.11}$$

- ✓ If the harmonic-producing loads consist of power converters with pulse number *q* higher than 6, the limits indicated in Table 6.2 are increased by a factor equal to √ q/6 .

In computing the short-circuit current at the PCC, the normal system conditions that result in minimum short-circuit capacity at the PCC should be used since this condition results in the most severe system impacts.

A procedure to determine the short-circuit ratio is as follows:

- ✓ Determine the three-phase short-circuits duty *I*SC at the PCC. This value may be obtained directly from the utility and expressed in amperes. If the short-circuit duty is given in mega volt amperes, convert it to an amperage value using the following expression:

$$\mathrm{I_{SC}} = \frac{1000 \times \mathrm{MVA}}{\sqrt{3}\,\mathrm{kV}} \quad \mathrm{A}$$

- ✓ Find the load average kilowatt demand P_D over the most recent 12months. This can be found from billing information.
- ✓ Convert the average kilowatt demand to the average demand currentin amperes using the following expression:

$$I_L = \frac{\text{kW}}{\text{PF} \ \sqrt{3} \ \text{kV}} \qquad \text{A}$$

where *PF* is the average billed power factor.

- ✓ The short-circuit ratio is now determined by:

$$\text{Short-circuit ratio} = \frac{I_{SC}}{I_L}$$

This is the short-circuit ratio used to determine the limits on harmonic currents in IEEE Standard 519-1992.

In some instances, the average of the maximum demand load current at the PCC for the previous 12 months is not available. In such circumstances, this value must be estimated based on the predicted load profiles. For seasonal loads, the average should be over the maximum loads only.

Devices for Controlling Harmonic Distortion

There are a number of devices available to control harmonic distortion. They can be as simple as a capacitor bank or a line reactor, or as complex as an active filter.

PASSIVE FILTERS:

Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. They are commonly used and are relatively inexpensive compared with other means for eliminating harmonic distortion. However, they have the disadvantage of potentially interacting adversely with the power system, and it is important to check all possible system interactions when they are designed. They are employed either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected frequency. Figure 4.27 shows several types of common filter arrangements.

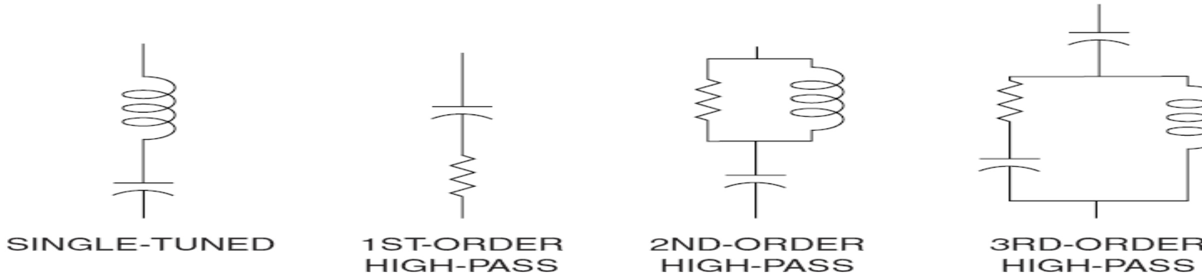


Figure 2.27 Common passive filter configurations.

SHUNT PASSIVE FILTERS:

The most common type of passive filter is the single tuned "notch" filter. This is the most economical type and is frequently sufficient for the application. The notch filter is series-tuned to present low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter. Notch filters can provide power factor correction in addition to harmonic suppression. In fact, power factor correction capacitors may be used to make notch filters. The dry-type iron- core reactor is positioned atop the capacitors, which are connected in a wye, or star, configuration with the other phases (not shown). Each capacitor can is fused with a current- limiting fuse to minimize damage in case of a can failure. In outdoor installations it is often more economical to use air-core reactors.

Iron-core reactors may also be oil-insulated. Here the reactors are placed on top of the cabinet housing the capacitors and switchgear. An example of a common 480-V filter arrangement is illustrated in Fig. 4.28. The figure shows a delta-connected low-voltage capacitor bank converted into a filter by adding an inductance in series with the phases. In this case, the notch harmonic h_{notch} is related to the fundamental frequency reactances by

$$h_{\text{notch}} = \sqrt{\frac{X_C}{3X_F}} \qquad (4.12)$$

Note that *XC* in this case is the reactance of one leg of the delta rather than the equivalent line-to-neutral capacitive reactance.

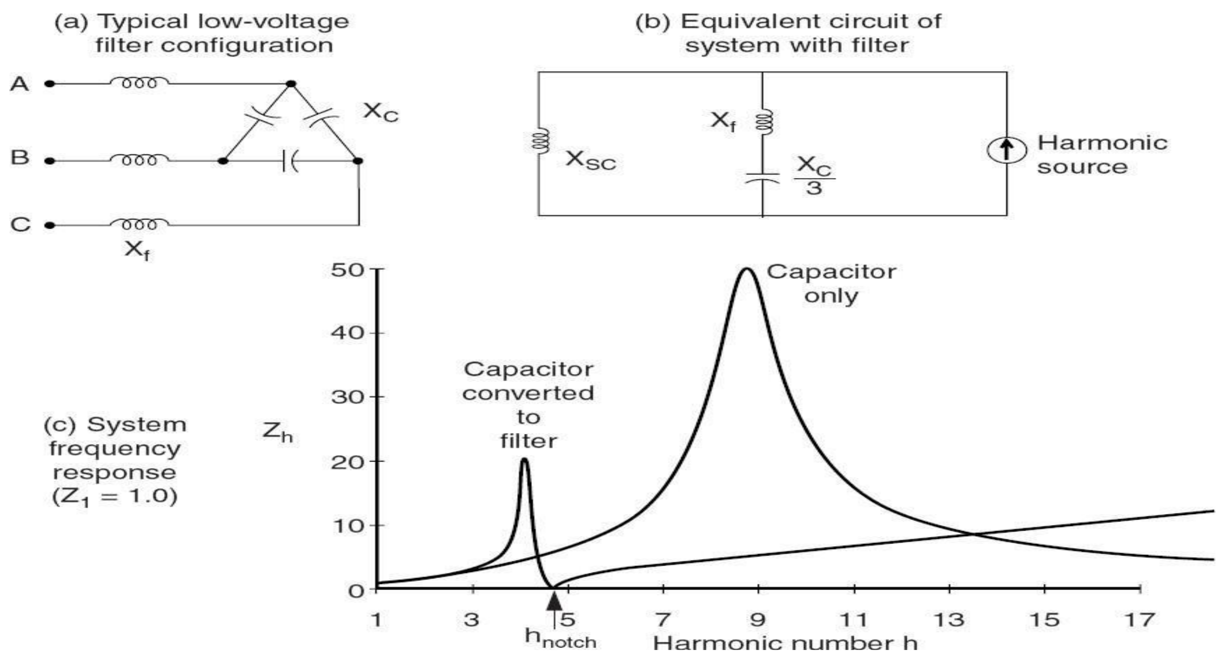


Figure 2.28 creating a fifth-harmonic notch filter and its effect on system response.

SERIES PASSIVE FILTERS:

Unlike a notch filter which is connected in shunt with the power system, a series passive filter is connected in series with the load. The inductance and capacitance are connected in parallel and are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic currents at the tuned frequency only. At fundamental frequency, the filter would be designed to yield low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses. Fig 4.29. Shows a typical series filter arrangement. Series filters are used to block a single harmonic current (such as the third harmonic) and are especially useful in a single-phase circuit where it is not possible to take advantage of zero-sequence characteristics. The use of the series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequency.

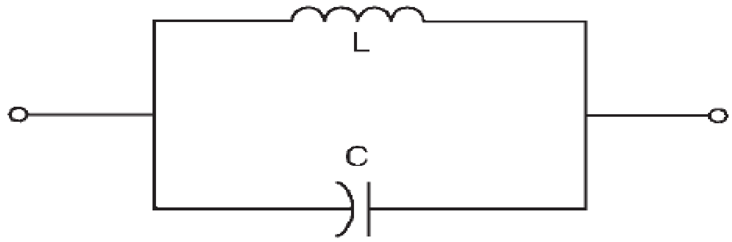


Figure 2.29 A series passive filter.

LOW-PASS BROADBAND FILTERS:

Multiple stages of both series and shunt filters are often required in practical applications. For example, in shunt filter applications, a filter for blocking a seventh-harmonic frequency would typically require two stages of shunt filters, the seventh-harmonic filter itself and the lower fifth-harmonic filter. Similarly, in series filter applications, each frequency requires a series filter of its own; thus, multiple stages of filters are needed to block multiple frequencies. In numerous power system conditions, harmonics can appear not only in a single frequency but can spread over a wide range of frequencies. A six-pulse converter generates characteristic harmonics of 5th, 7th, 11th, 13th, etc. Electronic powers converters can essentially generate time-varying inter harmonics covering a wide range of frequencies.

Designing a shunt or series filter to eliminate or reduce these widespread and time- varying harmonics would be very difficult using shunt filters. Therefore, an alternative harmonic filter must be devised. A low-pass broadband filter is an ideal application to block multiple or widespread harmonic frequencies. Current with frequency components below the filter cutoff frequency can pass; however, current with frequency components above the cutoff frequency is filtered out. Since this type of low-pass filter is typically designed to achieve a low cutoff frequency, it is then called a low-pass broadband filter. A typical configuration of a low-pass broadband filter is shown in Fig. 2.30.

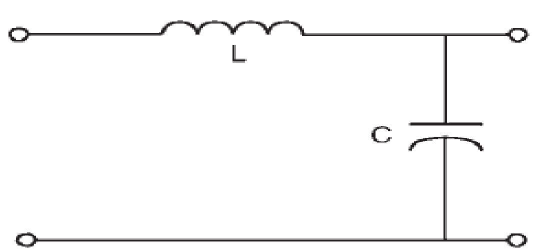


Figure 2.30 a low-pass broadband filter configuration.

C FILTERS:

C filters are an alternative to low-pass broadband filters in reducing multiple harmonic frequencies simultaneously in industrial and utility systems. They can attenuate a wide range of steady state and time-varying harmonic and inter harmonic frequencies generated by electronic converters, induction furnaces, cyclo converters, and the like.

ACTIVE FILTERS:

Active filters are relatively new types of devices for eliminating harmonics. They are based on sophisticated power electronics and are much more expensive than passive filters. However, they have the distinct advantage that they do not resonate with the system. Active filters can work independently of the system impedance characteristics. Thus, they can be used in very difficult circumstances where passive filters cannot operate successfully because of parallel resonance problems. They can also address more than one harmonic at a time and combat other power quality problems such as flicker. They are particularly useful for large, distorting loads fed from relatively weak points on the power system.

The basic idea is to replace the portion of the sine wave that is missing in the current in a nonlinear load. Figure 2.31 illustrates the concept. An electronic control monitors the line voltage and/or current, switching the power electronics very precisely to track the load current or voltage and force it to be sinusoidal. As shown, there are two fundamental approaches: one that uses an inductor to store current to be injected into the system at the appropriate instant and one that uses a capacitor. Therefore, while the load current is distorted to the extent demanded by the nonlinear load, the current seen by the system is much more sinusoidal.

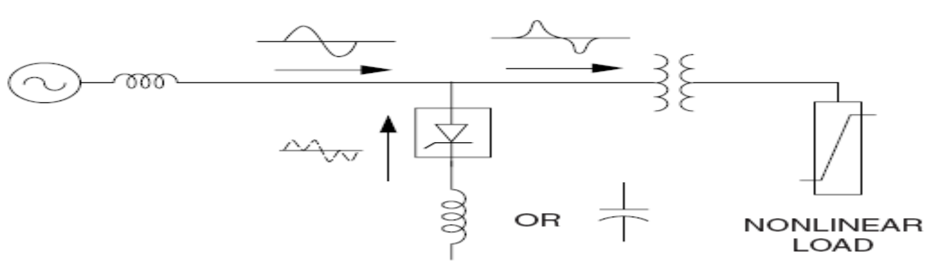


Figure 2.31 Application of an active filter at a load.

IEEE and IEC Standards:

It should be emphasized that the philosophy behind this standard seeks to limit the harmonic injection from individual customers so that they do not create unacceptable voltage distortion under normal system characteristics and to limit the overall harmonic distortion in the voltage supplied by the utility. The voltage and current distortion limits should be used as system design values for the worst case of normal operating conditions lasting more than 1 h. For shorter periods, such as during start-ups, the limits may be exceeded by 50 percent.

This standard divides the responsibility for limiting harmonics between both end users and the utility. End users will be responsible for limiting the harmonic current injections, while the utility will be primarily responsible for limiting voltage distortion in the supply system.

The harmonic current and voltage limits are applied at the PCC. This is the point where other customers share the same bus or where new customers may be connected in the future. The standard seeks a fair approach to allocating a harmonic limit quota for each customer. The standard allocates current injection limits based on the size of the load with respect to the size of the power system, which is defined by its short-circuit capacity. The short-circuit ratio is defined as the ratio of the maximum short-circuit current at the PCC to the maxi mum demand load current (fundamental frequency component) at the PCC as well.

The basis for limiting harmonic injections from individual customers is to avoid unacceptable levels of voltage distortions. Thus the current limits are developed so that the total harmonic injections from an individual customer do not exceed the maximum voltage distortion shown in Table 2.8. Table 2.8 shows harmonic current limits for various system voltages. Smaller loads (typically larger short-circuit ratio values) are allowed a higher percentage of harmonic currents than larger loads with smaller short-circuit ratio values. Larger loads have to meet more stringent limits since they occupy a larger portion of system load capacity. The current limits take into account the diversity of harmonic currents in which some harmonics tend to cancel out while others are additive. The harmonic current limits at the PCC are developed to limit individual voltage distortion and voltage THD to the values shown in Table 2.1. Since voltage distortion is dependent on the system impedance, the key to controlling voltage distortion is to control the impedance.

The two main conditions that result in high impedance are when the system is too weak to supply the load adequately or the system is in resonance. The latter is more common. Therefore, keeping the voltage distortion low usually means keeping the system out of resonance. Occasionally, new transformers and lines will have to be added to increase the system strength. IEEE Standard 519-1992 represents a consensus of guidelines and recommended practices by the utilities and their customers in minimizing and controlling the impact of harmonics generated by nonlinear loads.

Table 2.8 Basis for Harmonic Current Limits

Short-circuit ratio at PCC	Maximum individual frequency voltage harmonic (%)	Related assumption
10	2.5–3.0	Dedicated system
20	2.0–2.5	1–2 large customers
50	1.0–1.5	A few relatively large customers
100	0.5–1.0	5–20 medium-size customers
1000	0.05–0.10	Many small customers

Overview of IEC standards on harmonics

The International Electro technical Commission (IEC), currently with headquarters in Geneva, Switzerland, has defined a category of electromagnetic compatibility (EMC) standards that deal with power quality issues. The term electromagnetic compatibility includes concerns for both radiated and conducted interference with end-use equipment. The IEC standards are broken down into six parts:

- *Part 1: General.* These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms. Their designation number is IEC 61000-1-x.

- *Part 2: Environment.* These standards define characteristics of the environment where equipment will be applied, the classification of such environment, and its compatibility levels. Their designation number is IEC 61000-2-x.

- *Part 3: Limits.* These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits. Their designation number is IEC 61000-3-x.

- *Part 4: Testing and measurement techniques.* These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards. Their designation number is IEC 61000-4-x.

- *Part 5: Installation and mitigation guidelines.* These standards provide guidelines in application of equipment such as ear thing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions. They are designated with IEC 61000-5- x.

- *Part 6: Miscellaneous.* These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

Their designation number is IEC 61000-6-x. IEC standards relating to harmonics generally fall in parts 2 and 3. Unlike the IEEE standards on harmonics where there is only a single publication covering all issues related to harmonics, IEC standards on harmonics are separated into several publications. There are standards dealing with environments and limits which are further broken down based on the voltage and current levels. These key standards are as follows:

- IEC 61000-2-2 (1993): *Electromagnetic Compatibility (EMC).* Part 2: Environment. Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Low-Voltage Power Supply Systems.

- IEC 61000-3-2 (2000): *Electromagnetic Compatibility (EMC).* Part 3: Limits. Section 2: Limits for Harmonic Current Emissions (Equipment Input Current Up to and Including 16 A per Phase).

- IEC 61000-3-4 (1998): *Electromagnetic Compatibility (EMC).* Part 3: Limits. Section 4: Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Greater Than 16 A.

- IEC 61000-3-6 (1996): *Electromagnetic Compatibility (EMC).* Part 3: Limits. Section 6: Assessment of Emission Limits for Distorting Loads in MV and HV Power Systems. Basic EMC publication. Prior to 1997, these standards were designated by a 1000 series numbering scheme. For example, IEC 61000-2-2 was known as IEC 1000-2- 2. These standards on harmonics are generally adopted by the European Community (CENELEC); thus, they are also designated with the EN 61000 series. For example, IEC 61000-3-2 is also known as EN 61000-3-2.

4.9.2. IEC 61000-2-2

IEC 61000-2-2 defines compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems such as 50- or 60-Hz single- and three-phase systems with nominal voltage up 240 and 415 V, respectively. Compatibility levels are defined empirically such that they reduce the number of complaints of mis operation to an acceptable level.15 these levels are not rigid and can be exceeded in a few exceptional conditions. Compatibility levels for individual harmonic voltages in the low-voltage network are shown in Table 6.7. They are given in percentage of the fundamental voltage.

4.9.3. IEC 61000-3-2 and IEC 61000-3-4

Both IEC 61000-3-2 and 61000-3-4 define limits for harmonic current emission from equipment drawing input current of up to and including 16 Aper phase and larger than 16 Aper phase, respectively. These standards are aimed at limiting harmonic emissions from equipment connected to the low-voltage public network so that compliance with the limits ensures that the voltage in the public network satisfies the compatibility limits defined in IEC 61000-2-2. The IEC 61000-3-2 is an outgrowth from IEC 555-2 (EN 60555-2). The standard classifies equipment into four categories:

- Class A: Balanced three-phase equipment and all other equipment not belonging to classes B, C, and D
- Class B: Portable tools.
- Class C: Lighting equipment including dimming devices

■ Class D: Equipment having an input current with a “special wave shape” and an active input power of less than 600 W

Figure 2.32 can be used for classifying equipment in IEC 61000-3-2. It should be noted that equipment in classes B and C and provisionally motor-driven equipment are not considered class D equipment regardless of their input current wave shapes. The half-cycle wave shape of class D equipment input current should be within the envelope of the inverted T-shape shown in Fig. 2.33 for at least 95 percent of the time. The center line at /2 lines up with the peak value of the input current *I*pk. Maximum permissible harmonic currents for classes A, B, C, and D are given in actual amperage measured at the input current of the equipment. Note that harmonic current limits for class B equipment are 150 percent of those in class A. Harmonic current limits according to IEC 61000-3-2 are shown in Tables 6.8 through 6.10. Note that harmonic current limits for class D equipment are specified in absolute numbers and in values relative to active power. The limits only apply to equipment operating at input power up to 600 W. IEC 61000-3-4 limits emissions from equipment drawing input current larger than 16 A and up to 75 A. Connections of this type of equipment do not require consent from the utility. Harmonic current limits based on this standard are shown in Table 2.3.

Table 2.3 Harmonic Current Limits According to IEC 61000-3-4

Harmonic order h	Max. permissible harmonic current* (%)	Harmonic order h	Max. permissible harmonic current* (%)
3	21.6	19	1.1
5	10.7	21	0.6
7	7.2	23	0.9
9	3.8	25	0.8
11	3.1	27	0.6
13	2	29	0.7
15	0.7	31	0.7
17	1.2	33	0.6

*Percent of the fundamental input current.

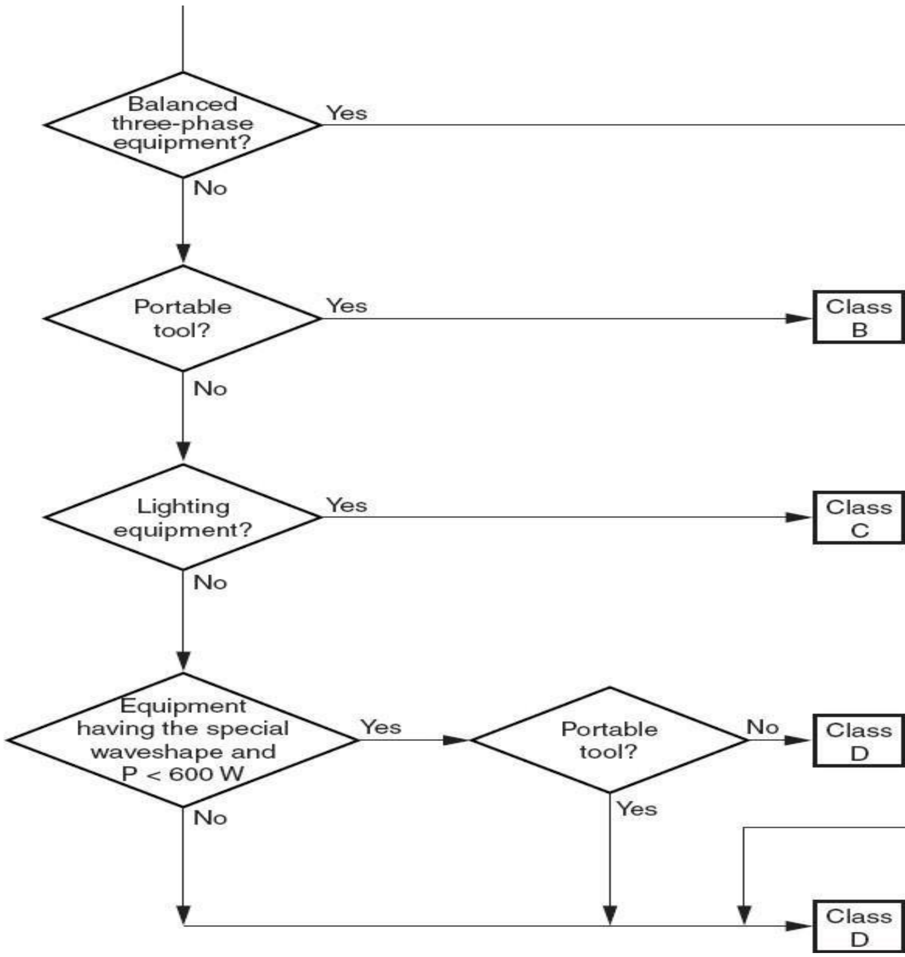


Figure 2.32 Flowchart for classifying equipment according to IEC 61000-3-2.