CHAPTER-I

OVERVIEW

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1.1 INTRODUCTION

With modern era of information technology & with comfort of living, more and more power electronics equipment are used in our life. Most of the power electronics equipment are nonlinear load which creating the power quality issue even though it is known that with advancement in technology these problem will be solved by power electronics control technology. Because of power quality problem the performance of the other equipment connected in the same bus is affected. Moreover electrical quantities are also affected because of power quality issues. This is explained in subsequent section

Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The term *power quality* has become one of the most prolific buzzwords in the power industry since the late 1980s. It is an umbrella concept for a multitude of individual types of power system disturbances. The issues that fall under this umbrella are not necessarily new. What is new is that engineers are now attempting to deal with these issues using a system approach rather than handling them as individual problems. There are four major reasons for the increased concern:

1. Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.

2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.

3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags and switching transients and are challenging the utilities to improve the quality of power delivered.

4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

The common thread running through all these reasons for increased concern about the quality of electric power is the continued push for increasing productivity for all utility customers. Manufacturers want faster, more productive, more efficient machinery. Utilities encourage this effort because it helps their customers become more profitable and also helps defer large investments in substations and generation by using more efficient load equipment. Interestingly, the equipment installed to increase the productivity is also often the equipment that suffers the most from common power disruptions. And the equipment is sometimes the source of additional power quality problems. When entire processes are automated, the efficient operation of machines and their controls becomes increasingly dependent on quality power.

1. Throughout the world, many governments have revised their laws regulating electric utilities with the intent of achieving more cost-competitive sources of electric energy. Deregulation of utilities has complicated the power quality problem. In many geographic areas there is no longer tightly coordinated control of the power from generation through end-use load. While regulatory agencies can change the laws regarding the flow of money, the physical laws of power flow cannot be altered. In order to avoid deterioration of the quality of power supplied to customers, regulators are going to have to expand their thinking beyond traditional reliability indices

and address the need for power quality reporting and incentives for the transmission and distribution companies.

2. There has been a substantial increase of interest in distributed generation (DG), that is, generation of power dispersed throughout the power system. There are a number of important power quality issues that must be addressed as part of the overall interconnection evaluation for DG.

3. The globalization of industry has heightened awareness of deficiencies in power quality around the world. Companies building factories in new areas are suddenly faced with unanticipated problems with the electricity supply due to weaker systems or a different climate. There have been several efforts to benchmark power quality in one part of the world against other areas.

4. Indices have been developed to help benchmark the various aspects of power quality. Regulatory agencies have become involved in performance-based rate-making (PBR), which addresses a particular aspect, reliability, which is associated with interruptions. Some customers have established contracts with utilities for meeting a certain quality of power delivery.

1.2 WHAT IS POWER QUALITY?

There can be completely different definitions for power quality, depending on one's frame of reference. For example, a utility may define power quality as reliability and show statistics demonstrating that its system is 99.98 percent reliable. Criteria established by regulatory agencies are usually in this vein. A manufacturer of load equipment may define power quality as those characteristics of the power supply that enable the equipment to work properly. These characteristics can be very different for different criteria.

Power quality is ultimately a consumer-driven issue, and the end user's point of reference takes precedence. Therefore, the following definition of a power quality problem is used in this thesis:

"Any power problem manifested in voltage, current, or frequency deviations that result in failure or mis-operation of customer equipment."

There are many misunderstandings regarding the causes of power quality problems. The charts in Figure 1.2-1 show the results of one survey conducted by the Georgia Power Company in which both utility personnel and customers were polled about what causes power quality problems. While surveys of other market sectors might indicate different splits between the categories, these charts clearly illustrate one common theme that arises repeatedly in such surveys: The utility's and customer's perspectives are often much different. While both tend to blame about two-thirds of the events on natural phenomena (e.g., lightning), customers, much more frequently than utility personnel, think that the utility is at fault. When there is a power problem with a piece of equipment, end users may be quick to complain to the utility of an "outage" or "glitch" that has caused the problem. However, the utility records may indicate no abnormal events on the feed to the customer. It must be realized that there are many events resulting in end-user problems that never show up in the utility statistics. One example is capacitor switching, which is quite common and normal on the utility system, but can cause transient overvoltage that disrupt manufacturing machinery. Another example is a momentary fault elsewhere in the system that causes the voltage to sag briefly at the location of the customer in question. This might because an adjustable-speed drive or a distributed generator to trip off, but the utility will have no indication that anything was amiss on the feeder unless it has a power quality monitor installed.

In addition to real power quality problems, there are also perceived power quality problems that may actually be related to hardware, software, or control system malfunctions. Electronic components can degrade over time due to repeated transient voltages and eventually fail due to a relatively low magnitude event. Thus, it is sometimes difficult to associate a failure with a specific cause. It is becoming more common that designers of control software for microprocessor-based equipment have an incomplete knowledge of how power systems operate and do not anticipate all types of malfunction events. Thus, a device can misbehave because of a deficiency in the embedded software. This is particularly common with early versions of new computer-controlled load equipment.

In response to this growing concern for power quality, electric utilities have programs that help them respond to customer concerns. The philosophy of these programs ranges from reactive, where the utility responds to customer complaints, to proactive, where the utility is involved in educating the customer and promoting services that can help to develop solutions to power quality problems. The regulatory issues facing utilities may play an important role in how their programs are structured. Since power quality problems often involve interactions between the supply system and the customer facility and equipment, regulators should make sure that distribution companies have incentives to work with customers and help customers solve these problems.

The economics involved in solving a power quality problem must also be included in the analysis. It is not always economical to eliminate power quality variations on the supply side. In many cases, the optimal solution to a problem may involve making a particular piece of sensitive equipment less sensitive to power quality variations. The level of power quality required is that level which will result in proper operation of the equipment at a particular facility.

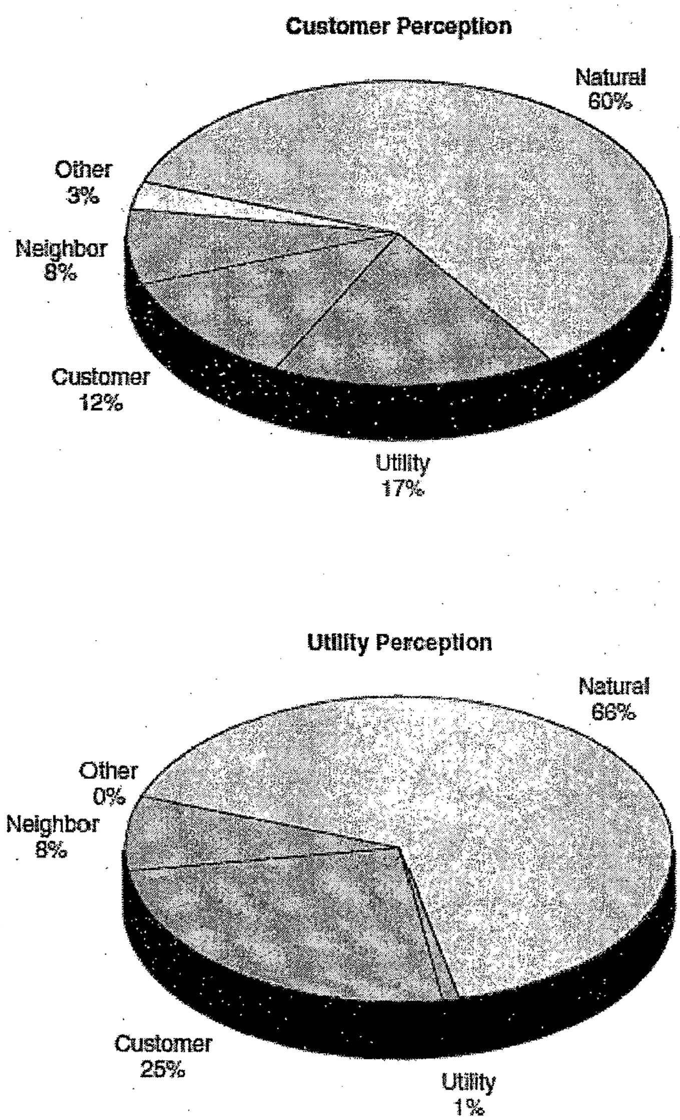

Figure 1.2-1: Results of a survey on the causes of power quality problems (Courtesy of Georgia Power Co.).

Power quality, like quality in other goods and services, is difficult to quantify. There is no single accepted definition of quality power. There are standards for voltage and other technical criteria that may be measured, but the ultimate measure of power quality is determined by the performance and productivity of end-user equipment. If the electric power is inadequate for those needs, then the "quality" is lacking. Perhaps nothing has been more symbolic of a mismatch in the power delivery system and consumer technology than the "blinking clock" phenomenon. Clock designers created the blinking display of a digital clock to warn of possible incorrect time after loss of power and inadvertently created one of the first power quality monitors. It has made the homeowner aware that there are numerous minor disturbances occurring throughout the power delivery system that may have no ill effects other than to be detected by a clock. Many appliances now have a built-in clock, so the average household may have about a dozen clocks that must be reset when there is a brief interruption. Older-technology motor-driven clocks would simply lose a few seconds during minor disturbances and then promptly come back into synchronism.

1.3 POWER QUALITY = VOLTAGE QUALITY

In most of the cases the terms power quality is nothing but it is actually the quality of the voltage that is being addressed in most cases. Power is the rate of energy delivery and is proportional to the product of the voltage and current. It would be difficult to define the quality of this quantity in any meaningful manner. The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits. AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem. Of course, there is always a close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sine-wave voltage, the current passing through the impedance of the system can cause a variety of disturbances to the voltage. For example,

1. *The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.*
2. *Currents from lightning strokes passing through the power system cause high-impulse voltages that frequently flash over insulation and lead to other phenomena, such as short circuits.*
3. *Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Thus a distorted voltage is presented to other end users. Therefore, ultimately the voltage is more concerned. Hence the phenomena in the current to understand the basis of many power quality problems must be addressed.*

1.4 POWER SYSTEM QUANTITIES UNDER NONSINUSOIDAL CONDITIONS

Traditional power system quantities such as rms, power (reactive, active, apparent), power factor, and phase sequences are defined for the fundamental frequency context in a pure sinusoidal condition. In the presence of harmonic distortion the power system no longer operates in a sinusoidal condition, and unfortunately,many of the simplifications power engineers use for the fundamental frequency analysis do not apply.

1.4.1 ACTIVE, REACTIVE, AND APPARENT POWER

There are three standard quantities associated with power:

■ *Apparent power S* [*voltampere* (VA)]. The product of the rms voltage and current.

■ *Active power P* [*watt* (W)]. The average rate of delivery of energy.

■ *Reactive power Q* [*voltampere-reactive*] (VAr)]. The portion of the apparent power that is out of phase, or in quadrature, with the active power.

The apparent power *S* applies to both sinusoidal and nonsinusoidal conditions. The apparent power can be written as follows:

$$S = V_{rms}\, X\, I_{rms} \tag{1.4.1-1}$$

where V_{rms} and I_{rms} are the rms values of the voltage and current. In a sinusoidal condition both the voltage and current waveforms contain only the fundamental frequency component; thus the rms values can be expressed simply as

$$V_{rms} = \frac{1}{\sqrt{2}} V_1 \quad and \quad I_{rms} = \frac{1}{\sqrt{2}} I_1 \tag{1.4.1-2}$$

where V_1 and I_1 are the amplitude of voltage and current waveforms, respectively. The subscript "1" denotes quantities in the fundamental frequency. In a nonsinusoidal condition a harmonically distorted waveform is made up of sinusoids of harmonic frequencies with different amplitudes as shown in Figure 1.4.1-1. The rms values of the waveforms are computed as the square root of the sum of rms squares of all individual components, i.e.

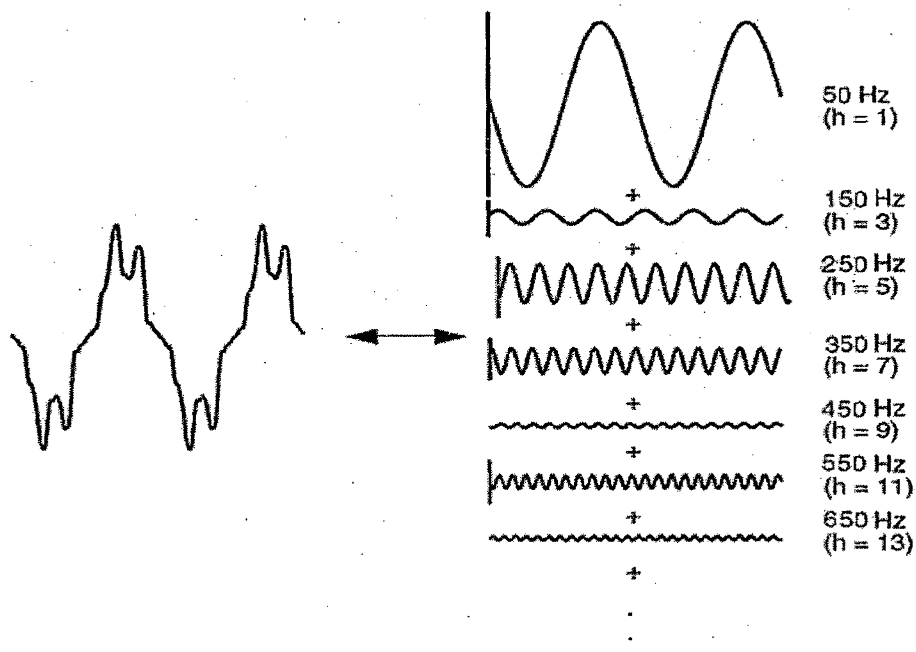

Figure 1.4.1-1: Fourier series representation of distorted waveform

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left(\frac{1}{\sqrt{2}} V_h\right)^2} = \frac{1}{\sqrt{2}} \sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots + V_{h_{max}}^2} \quad (1.4.1\text{-}3)$$

$$I_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left(\frac{1}{\sqrt{2}} I_h\right)^2} = \frac{1}{\sqrt{2}} \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots + I_{h_{max}}^2} \quad (1.4.1\text{-}4)$$

where V_h and I_h are the amplitude of a waveform at the harmonic component h. In the sinusoidal condition, harmonic components of V_h and I_h are all zero, and only $V1$ and $I1$ remain. Equations (1.4.1-3) and (1.4.1-4) simplify to Equation (1.4.1-2). The active power P is also commonly referred to as the average power, real power, or true power. It represents useful power expended by loads to perform real work, i.e., to convert electric energy to other forms of energy. Real work performed by an incandescent light bulb is to convert electric energy into light and heat. In electric power, real work is performed for the portion of the current that is in phase with the voltage. No real work will result from the portion where the current is not in phase with the voltage. The active power is the rate at which energy is expended, dissipated, or consumed by the load and is measured in units of watts. *P* can be computed by averaging the product of the instantaneous voltage and current, i.e.

$$P = \frac{1}{T} \int_0^T v(t)\, i(t)\, dt \qquad (1.4.1\text{-}5)$$

Equation (1.4.1-5) is valid for both sinusoidal and nonsinusoidal conditions.

For the sinusoidal condition, *P* resolves to the familiar form,

$$P = \frac{V_1 I_1}{2} \cos\theta_1 = V_{1rms}\, I_{1rms} \cos\theta_1 = S \cos\theta_1 \qquad (1.4.1\text{-}6)$$

where θ_1 is the phase angle between voltage and current at the fundamental frequency. Equation (1.4.1-6) indicates that the average active power is a function only of the fundamental frequency quantities. In the nonsinusoidal case, the computation of the active power must include contributions from all harmonic components; thus it is the sum of active power at each harmonic. Furthermore, because the voltage distortion is generally very low on power systems (less than 5 percent), Equation (1.4.1-6) is a good approximation regardless of how distorted the current is. This approximation cannot be applied when computing the apparent and reactive power. These two quantities are greatly influenced by the distortion. The apparent power *S* is a measure of the potential impact of the load on the thermal capability of the system. It is proportional to the rms of the distorted current, and its computation is straightforward, although slightly more complicated than the sinusoidal case. Also, many current probes can now directly report the true rms value of a distorted waveform. The reactive power is a type of power that does no real work and is generally associated with reactive elements (inductors and capacitors).

For example, the inductance of a load such as a motor causes the load current to lag behind the voltage. Power appearing across the inductance sloshes back and forth between the inductance itself and the power system source, producing no net effective work. For this reason it is called imaginary or reactive power since no power is dissipated or expended. It is expressed in units of vars. In the sinusoidal case, the reactive power is simply defined as

$$Q = \frac{V_1 I_1}{2} \sin\theta_1 = V_{1rms}\, I_{1rms}\, \sin\theta_1 = S\, \sin\theta_1 \qquad (1.4.1\text{-}7)$$

Which is the portion of power in quadrature with the active power shown in Equation (1.4.1-6). Figure 1.4.1-2 summarizes the relationship between *P, Q,* and *S* in sinusoidal condition.

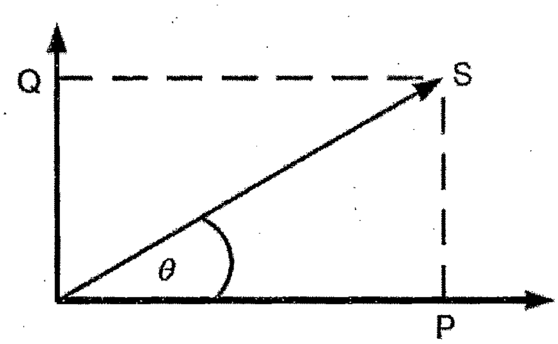

Figure 1.4.1-2: Relationship between P, Q and S in sinusoidal condition

There is some disagreement among harmonics analysts on how to define *Q* in the presence of harmonic distortion. If it were not for the fact that many utilities measure *Q* and compute demand billing from the power factor computed by *Q,* it might be a moot point. It is more important to determine *P* and *S*; *P* defines how much active power is being consumed, while *S* defines the capacity of the power system required to deliver *P*. *Q* is not actually very useful by itself. However, $Q1$, the traditional reactive power component at fundamental frequency, may be used to size shunt capacitors.

The reactive power when distortion is present has another interesting peculiarity. In fact, it may not be appropriate to call it reactive *power.* The concept of VAr flow in the power system is deeply ingrained in the minds of most power engineers. What many do not realize is that this concept is valid only in the sinusoidal steady state. When distortion is present, the component of S that remains after P is taken out is not conserved—that is, it does not sum to zero at a node. Power quantities are presumed to flow around the system in a conservative manner.

This does not imply that P is not conserved or that current is not conserved because the conservation of energy and Kirchhoff's current laws are still applicable for any waveform. The reactive components actually sum in quadrature (square root of the sum of the squares). This has prompted some analysts to propose that Q be used to denote the reactive components that are conserved and introduce a new quantity for the components that are not. Many call this quantity D, for *distortion power* or, simply, *distortion voltamperes.* It has units of voltamperes, but it may not be strictly appropriate to refer to this quantity as *power,* because it does not flow through the system as power is assumed to do. In this concept, Q consists of the sum of the traditional reactive power values at each frequency. D represents all cross products of voltage and current at different frequencies, which yield "NO AVERAGE POWER". P, Q, D, and S are related as follows, using the definitions for S and P previously given in Equation (1.4.1-1) and Equation (1.4.1-5) as a starting point:

$$S = \sqrt{P^2 + Q^2 + D^2} \qquad (1.4.1\text{-}8\text{-a})$$

$$Q = \sum_k V_k I_k \sin\theta_k \qquad (1.4.1\text{-}8\text{-b})$$

Therefore, D can be determined after S, P, and Q by

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{1.4.1-9}$$

Some prefer to use a three-dimensional vector chart to demonstrate the relationships of the components as shown in Figure 1.4.2-1. P and Q contribute the traditional sinusoidal components to S, while D represents the additional contribution to the apparent power by the harmonics.

1.4.2 POWER FACTOR: DISPLACEMENT AND TRUE

Power factor (PF) is a ratio of useful power to perform real work (active power) to the power supplied by a utility (apparent power), i.e.

$$\mathrm{PF} = \frac{P}{S} \tag{1.4.2-1}$$

In other words, the power factor ratio measures the percentage of power expended for its intended use. Power factor ranges from zero to unity. A load with a power factor of 0.9 lagging denotes that the load can effectively expend 90 percent of the apparent power supplied (voltamperes) and convert it to perform useful work (watts). The term *lagging* denotes that the fundamental current lags behind the fundamental voltage by 25.84°. In the sinusoidal case there is only one phase angle between the voltage and the current (since only the fundamental frequency is present; the power factor can be computed as the cosine of the phase angle and is commonly referred as the *displacement power factor:*

$$\mathrm{PF} = \frac{P}{S} = \cos\theta \tag{1.4.2-2}$$

In the nonsinusoidal case the power factor cannot be defined as the cosine of the phase angle as in Equation (1.4.2-2). The power factor that takes into account the contribution from all active power, including both fundamental and harmonic frequencies, is known as the *true power factor*. The true power factor is simply the ratio of total active power for all frequencies to the apparent power delivered by the utility as shown in Equation (1.4.2-1).

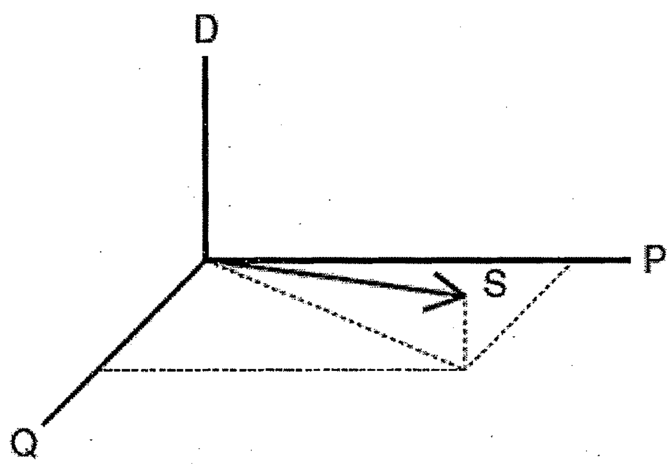

Figure 1.4.2-1: Relationship of components of the apparent power

Power quality monitoring instruments now commonly report both displacement and true power factors. Many devices such as switch- mode power supplies and PWM adjustable-speed drives have a near unity displacement power factor, but the true power factor may be 0.5 to 0.6. An ac-side capacitor will do little to improve the true power factor in this case because *Q*1 is zero.

In fact, if it results in resonance, the distortion may increase, causing the power factor to degrade. The true power factor indicates how large the power delivery system must be built to supply a given load. In this example, using only the displacement power factor would give a false sense of security that all is well. The bottom line is that distortion results in additional current components flowing in the system that do not yield any net energy except that they cause losses in the power system elements they pass through. This requires the system to be built to a slightly larger capacity to deliver the power to the load than if no distortion were present.

1.4.3 HARMONIC PHASE SEQUENCES

Power engineers have traditionally used symmetrical components to help describe three-phase system behavior. The three-phase system is transformed into three single-phase systems that are much simpler to analyze. The method of symmetrical components can be employed for analysis of the system's response to harmonic currents provided care is taken not to violate the fundamental assumptions of the method. The method allows any unbalanced set of phase currents (or voltages) to be transformed into three balanced sets. The *positive-sequence* set contains three sinusoids displaced 120° from each other, with the normal A-B-C phase rotation (e.g., 0°, -120°, 120°). The sinusoids of the *negative-sequence* set are also displaced 120°, but have opposite phase rotation (A-C-B, e.g., 0°, 120°, -120°). The sinusoids of the *zero sequence* are in phase with each other (e.g., 0°, 0°, 0°).

In a perfect balanced three-phase system, the harmonic phase sequence can be determined by multiplying the harmonic number *h* with the normal positive-sequence phase rotation. For example, for the second harmonic, h=2, hence 2 is multiplied with normal phase rotation i.e. 2 x (0, -120°, 120°) or (0°, 120°, -120°), which is the negative sequence. For the third harmonic, h = 3, hence 3 is multiplied with normal phase rotation i.e. 3 x (0°, -120°, 120°) or (0°, 0°, 0°), which is the zero sequence. Phase sequences for all other harmonic orders can be determined in the same fashion. Since a distorted waveform in power systems contains only odd-harmonic components (see Sec. 5.1), only odd-harmonic phase sequence rotations are summarized here:

- Harmonics of order h = 1, 7, 13,... are generally positive sequence.
- Harmonics of order h = 5, 11, 17,... are generally negative sequence.
- Triplens (h = 3, 9, 15,...) are generally zero sequence. Impacts of sequence harmonics on various power system components are detailed in Sec. 1.9.

1.5 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.

1.5.1 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:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1} \qquad (1.5.1\text{-}1)$$

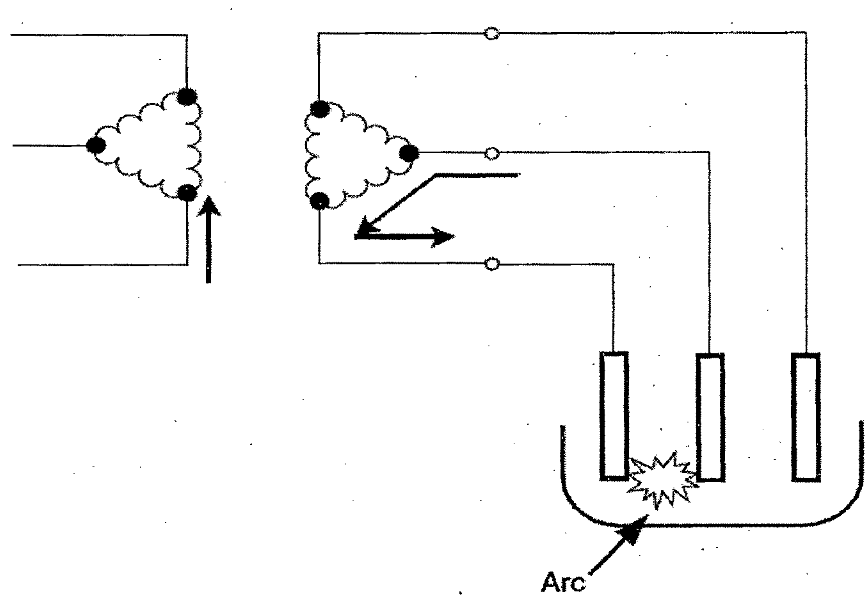

Figure 1.5.1-1: Arc furnace operation in an unbalanced mode allows triplen harmonics to reach the power system despite a delta connected transformer.

where M_h 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 Equation (1.4.1-3) and (1.4.1-4). The THD is related to the rms value of the waveform as follows:

$$RMS = \sqrt{\sum_{h=1}^{h_{max}} M_h^2} = M_1 \sqrt{1 + THD^2} \tag{1.5.1-2}$$

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.

1.5.2 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:

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L} \tag{1.5.2-1}$$

IL 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 *IL*. 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, *IL* has to be estimated based on the predicted load profiles.

1.6 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.

1.6.1 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.

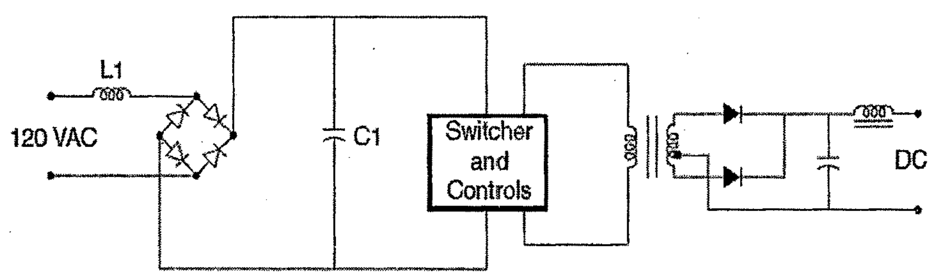

Figure 1.6.1-1: Switch-mode power supply.

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 Figure 1.6.1-1) use dc-to-dc conversion techniques to achieve a smooth dc output with small, lightweight components.

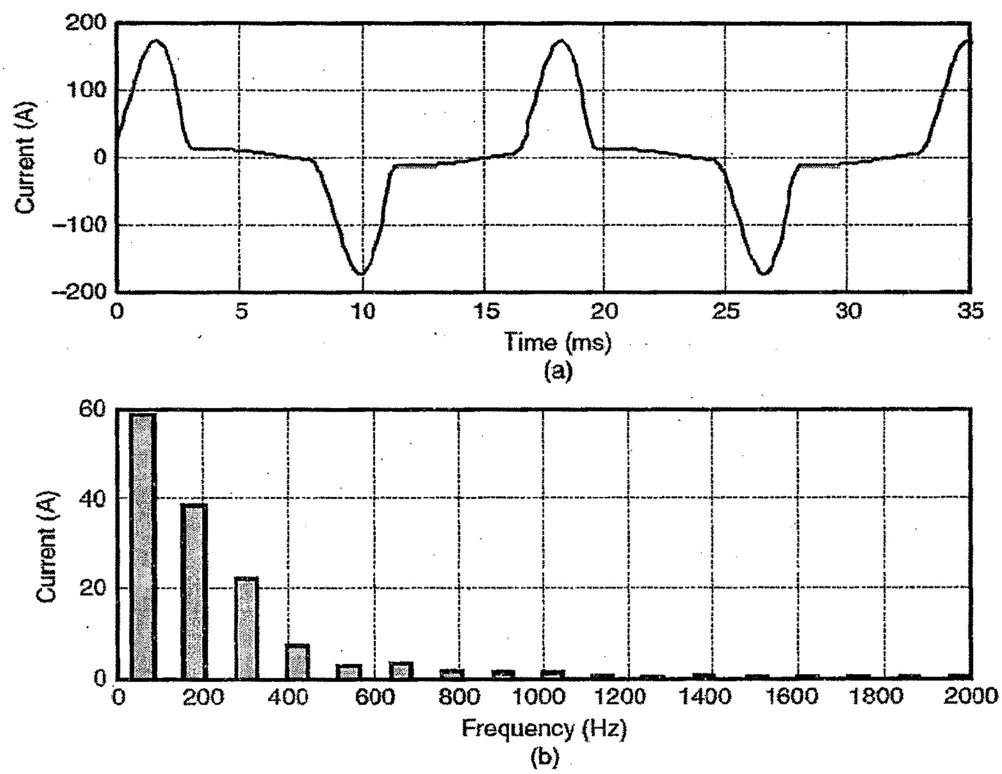

Figure 1.6.1-2: SMPS current and harmonic spectrum.

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 1.6.1-2 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.

1.6.2 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, ballast is also a current-limiting device in lighting applications.

There are two types of ballasts, magnetic and electronic. Standard magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. Single magnetic ballast can drive one or two fluorescent lamps, and it operates 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 electronic ballast.

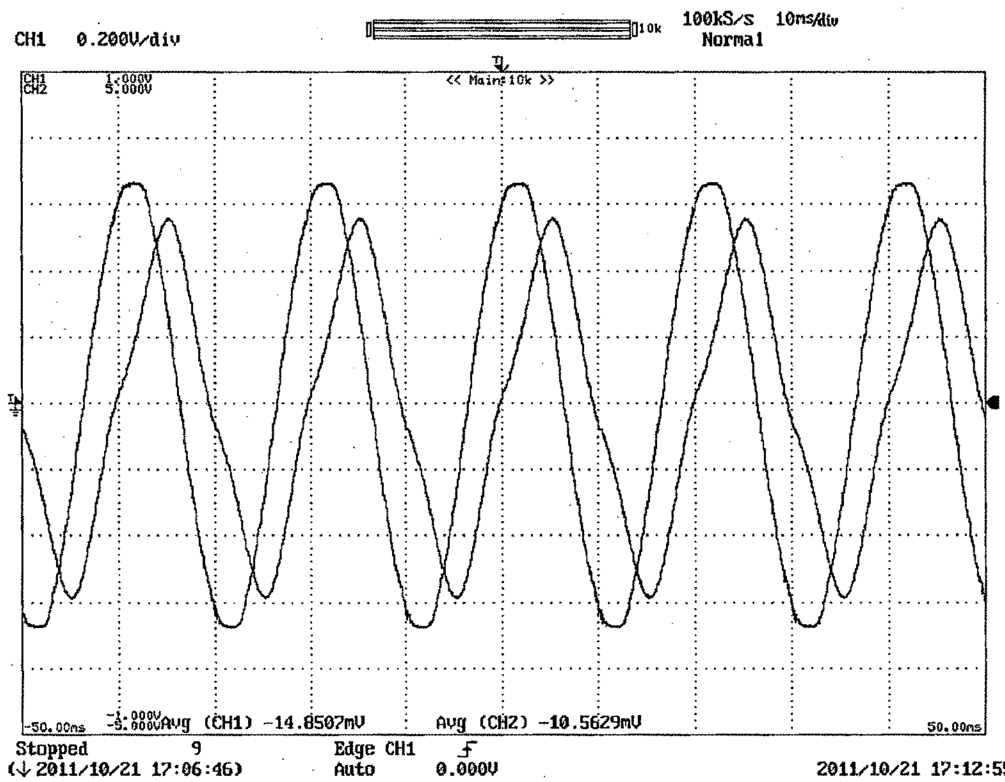

Figure 1.6.2-1: Input current & voltage waveform for fluorescent lamp with magnetic ballast

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.

Table 1.6.2-1: Input current & voltage harmonic spectrum for fluorescent lamp with magnetic ballast

Harm No.	Current IR in %	Current IR in Amps	Voltage VRY in %
1	100.00	0.34	100.00
2	2.37	0.01	0.00
3	13.65	0.05	1.49
4	0.00	0.00	0.00
5	0.92	0.00	0.62
6	0.00	0.00	0.00
7	0.56	0.00	0.71
8	0.00	0.00	0.00
9	0.24	0.00	0.46
10	0.00	0.00	0.00
11	0.15	0.00	0.33
12	0.00	0.00	0.00
13	0.06	0.00	0.04
14	0.00	0.00	0.04
15	0.06	0.00	0.25
16	0.00	0.00	0.04
17	0.03	0.00	0.08
18	0.00	0.00	0.00
19	0.00	0.00	0.04
20	0.00	0.00	0.00
21	0.03	0.00	0.08
22	0.00	0.00	0.00
23	0.00	0.00	0.00
24	0.00	0.00	0.00
25	0.00	0.00	0.00
THD %	13.90		1.87
Parameter measured Amp/Volt	0.34		241.14

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 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 1.6.2-1 & table 1.6.2-1 shows a measured fluorescent lamp input current & voltage waveform and their harmonic spectrum respectively. 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 1.6.2-2 shows a fluorescent lamp with electronic ballast that has a current THD of 144.

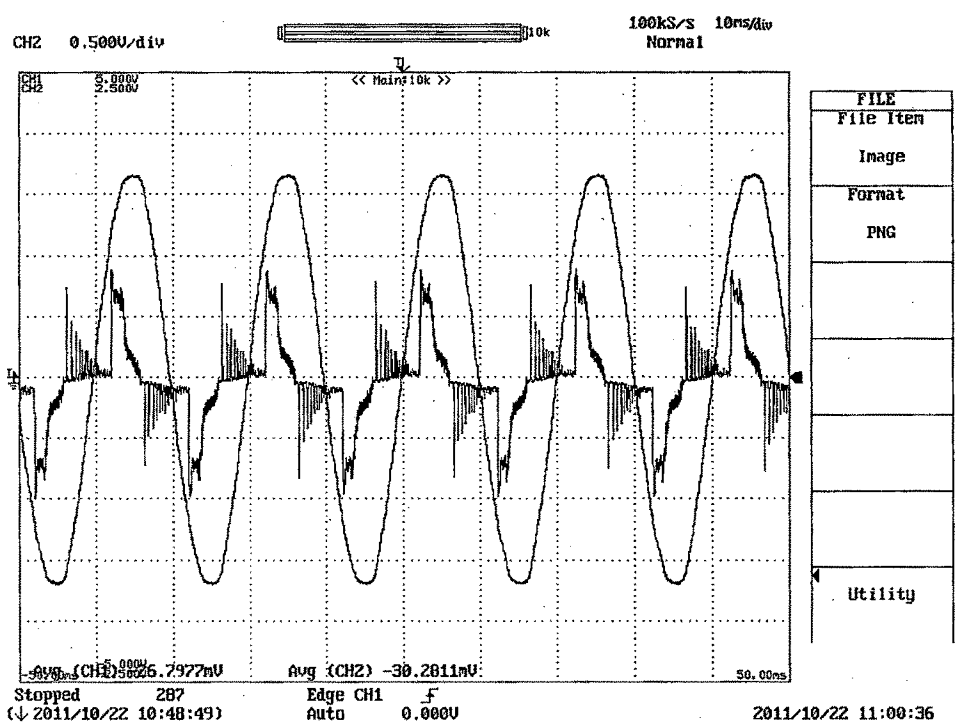

Figure 1.6.2-2: Input current & voltage waveform for fluorescent lamp with electronic ballast

Table 1.6.2-2: Input current & voltage harmonic spectrum for fluorescent lamp with electronic ballast.

Harm No.	Current I_R in %	Current I_R in Amps	Voltage V_{RY} in %
1	100.00	0.23	100.00
2	0.00	0.00	0.83
3	62.50	0.15	1.67
4	0.00	0.00	0.00
5	34.91	0.08	0.50
6	0.43	0.00	0.00
7	26.72	0.06	0.67
8	0.43	0.00	0.00
9	17.24	0.04	0.46
10	0.43	0.00	0.08
11	4.31	0.01	0.25
12	0.00	0.00	0.00
13	9.05	0.02	0.21
14	0.00	0.00	0.00
15	7.33	0.02	0.21
16	0.43	0.00	0.04
17	9.48	0.02	0.13
18	0.43	0.00	0.00
19	9.05	0.02	0.13
20	0.43	0.00	0.00
21	4.74	0.01	0.08
22	0.43	0.00	0.00
23	5.17	0.01	0.04
24	0.43	0.00	0.00
25	1.72	0.00	0.04
THD %	80.72		2.14
Parameter measured Amp/Volt	0.30		239.95

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.

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. However, it should be noted that the common wye-wye supply transformers will not impede the flow of triplen harmonics regardless of how well balanced the phases are to match the application requirement such as slowing a pump or fan. ASDs also find many applications in industrial loads.

1.6.3 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

1.7 HARMONIC 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 mis-operation of sensitive electronic equipment. Nonlinear industrial loads can generally be grouped into three categories: three-phase power converters, arcing devices, and saturable devices. Sections 1.7.1 to 1.7.3 detail the industrial load characteristics.

1.7.1 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 Figure 1.7.1-1. This is a typical current source type of adjustable-speed drive. The harmonic spectrum given in Figure 1.7.1-1 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 Figure 1.7.1-2.

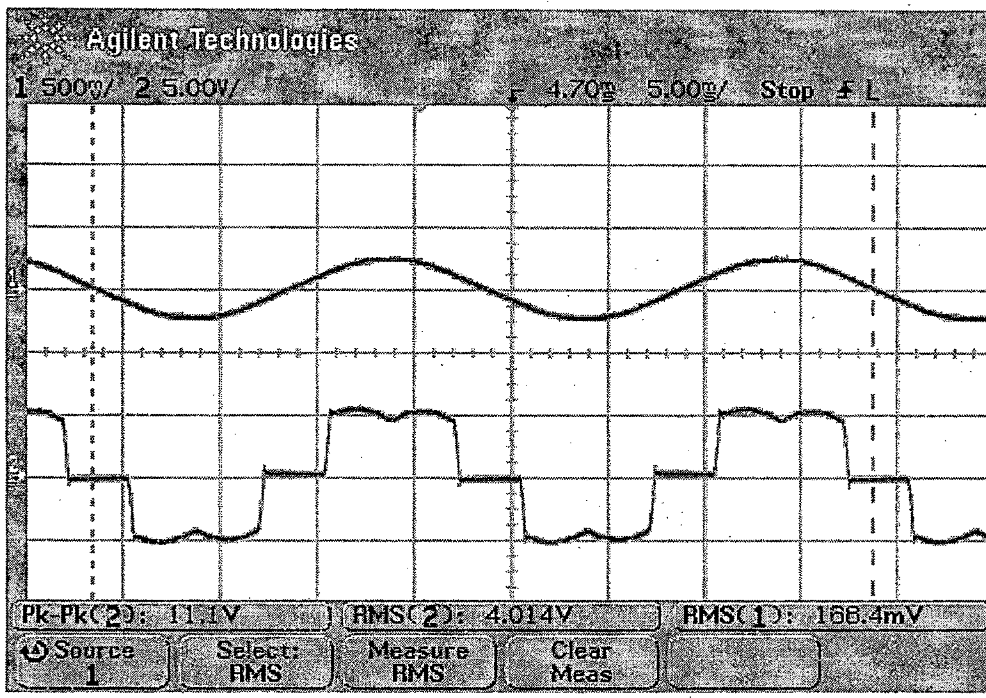

Figure 1.7.1-1: Voltage &Current and waveform for CSI-type ASD.

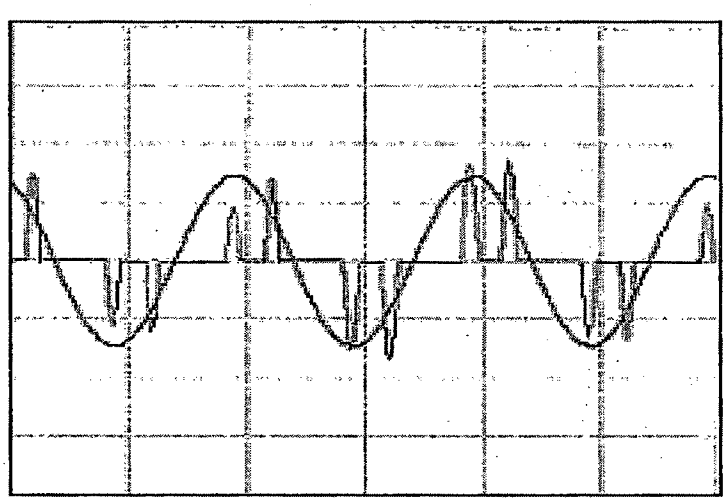

Figure 1.7.1-2: Voltage & current waveform for PWM-type ASD.

Table 1.7.1-2 Harmonic analysis of current & voltage waveform for PWM-type ASD as shown in Figure 1.7.1-2.

Harm No.	Current I_R in %	Current I_R in Amps	Voltage V_{RY} in %	Current I_Y in %	Current I_Y in Amps	Voltage V_{YB} in %	Current I_B in %	Current I_B in Amps	Voltage V_{BR} in %
1	100.00	3.39	100.00	100.00	3.37	100.00	100.00	3.14	100.00
2	2.06	0.07	0.00	3.86	0.13	0.00	1.27	0.04	0.00
3	5.60	0.19	0.00	2.37	0.08	0.24	3.82	0.12	0.27
4	2.06	0.07	0.00	6.53	0.22	0.00	2.23	0.07	0.00
5	84.66	2.87	0.24	90.50	3.05	0.00	91.72	2.88	0.27
6	1.18	0.04	0.00	6.53	0.22	0.00	1.59	0.05	0.00
7	79.06	2.68	0.24	77.74	2.62	0.48	79.30	2.49	0.48
8	1.47	0.05	0.00	0.00	0.00	0.00	1.59	0.05	0.00
9	7.67	0.26	0.24	4.75	0.16	0.00	4.78	0.15	0.12
10	1.47	0.05	0.00	5.04	0.17	0.00	2.87	0.09	0.00
11	46.31	1.57	0.24	56.97	1.92	0.24	59.55	1.87	0.24
12	0.88	0.03	0.00	5.04	0.17	0.00	1.91	0.06	0.00
13	38.94	1.32	0.24	40.65	1.37	0.24	43.31	1.36	0.46
14	0.59	0.02	0.00	2.37	0.08	0.00	1.91	0.06	0.00
15	5.01	0.17	0.00	4.45	0.15	0.00	3.50	0.11	0.00
16	0.59	0.02	0.00	1.78	0.06	0.00	2.23	0.07	0.00
17	13.27	0.45	0.00	21.07	0.71	0.24	24.20	0.76	0.22
18	0.59	0.02	0.00	3.26	0.11	0.00	0.96	0.03	0.00
19	7.96	0.27	0.00	11.28	0.38	0.00	13.06	0.41	0.00
20	0.29	0.01	0.00	1.78	0.06	0.00	1.59	0.05	0.00
21	1.18	0.04	0.00	2.08	0.07	0.00	1.27	0.04	0.00
22	0.00	0.00	0.00	1.19	0.04	0.00	1.27	0.04	0.00
23	1.47	0.05	0.00	1.78	0.06	0.00	2.87	0.09	0.00
24	0.29	0.01	0.00	2.08	0.07	0.00	0.32	0.01	0.00
25	2.65	0.09	0.00	3.26	0.11	0.00	0.96	0.03	0.00
THD %	132.17		0.55	141.34		0.68	144.91		0.84
Parameter measured	5.62 A		410.01 V	5.83 A		414.01 V	5.53 A		413.01 V

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.

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 speed and torque characteristics of the dc motor. Most dc drives use the six-pulse rectifier shown in Figure 1.7.1-3. 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.

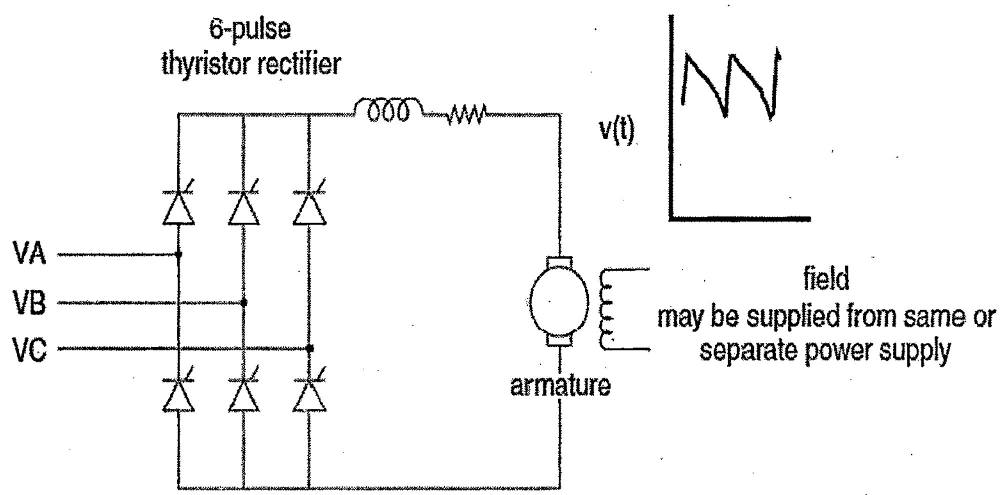

Figure 1.7.1-3: Six-pulse dc ASD.

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 Figure 1.7.1-4).

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.

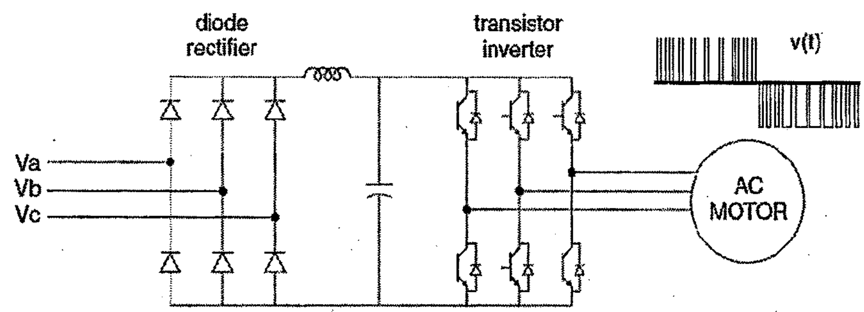

Figure 1.7.1-4: PWM ASD

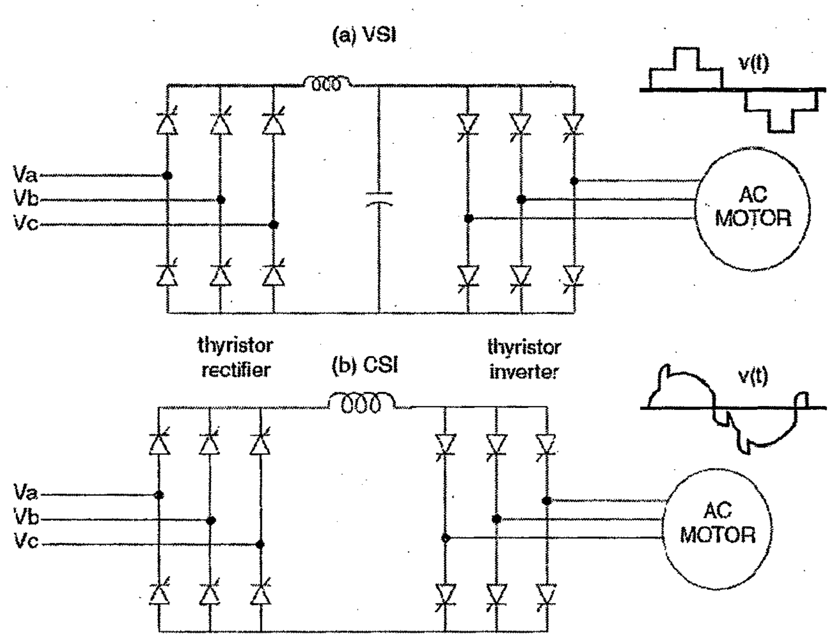

Figure 1.7.1-5: Large ac ASDs

Very high power drives employ SCRs and inverters. These may be 6- pulse, as shown in Figure 1.7.1-5, or like large dc drives, 12-pulse. VSI drives (Figure 1.7.1-5 a) are limited to applications that do not require rapid changes in speed. CSI drives (Figure 1.7.1-5 *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.

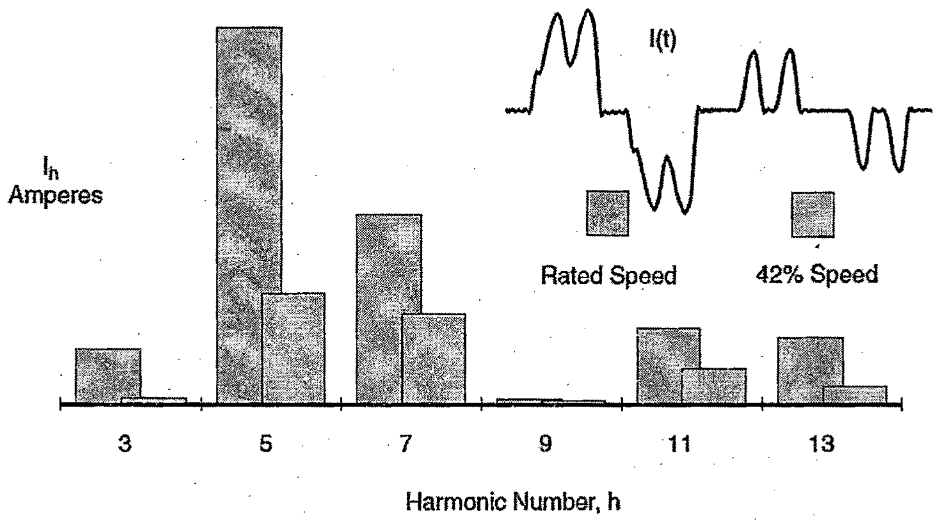

Figure 1.7.1-6: Effect of PWM ASD speed on ac current harmonics.

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 1.7.1-6 shows two operating conditions for a PWM adjustable speed 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.

1.7.2 ARCING DEVICES

This category includes arc furnaces, arc welders, and discharge-type lighting (fluorescent, sodium vapor, mercury vapor) with magnetic (rather than electronic) ballasts. As shown in Figure 1.7.2-1, 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.

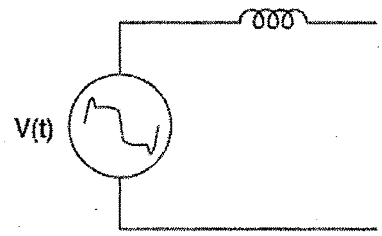

Figure 1.7.2-1: Equivalent circuit for an arcing device.

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 Amp 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. The harmonic content of an arc furnace load and other arcing devices is similar to that of the magnetic ballast shown in Figure 1.6.2-1. Three phase arcing devices can be arranged to cancel the triplen harmonics through the transformer connection. However, this cancellation may not work in three-phase arc furnaces because of the frequent unbalanced operation during the melting phase. During the refining stage when the arc is more constant, the cancellation is better.

1.7.3 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 Figure 1.7.3-1). 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.

Although transformer exciting current is rich in harmonics at normal operating voltage (see Figure 1.7.3-2a & Figure 1.7.3-2b), 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.

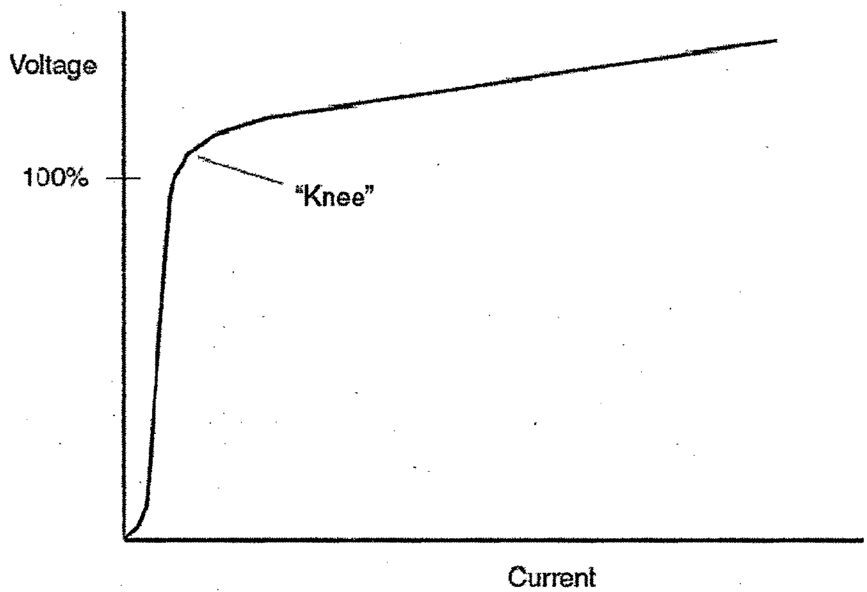

Figure 1.7.3-1: Transformer magnetizing characteristic

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 150 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. The waveform shown in see Figure 1.7.3-2 is for single-phase or wye grounded three-phase transformers. The current obviously contains a large amount of third harmonic. Delta connections and ungrounded wye connections prevent the flow of zero-sequence harmonic, which triplens tend to be. Thus, the line current will be void of these harmonics unless there is an imbalance in the system.

Table 1.7.3-2: FFT Analysis of Transformer magnetizing current.

Harm No.	Current I_R in %	Current I_R in Amps	Voltage V_{RY} in %
1	100.00	2.59	100.00
2	0.31	0.01	0.11
3	11.27	0.29	2.70
4	0.39	0.01	0.06
5	26.77	0.69	7.89
6	0.08	0.00	0.00
7	6.33	0.16	3.70
8	0.00	0.00	0.00
9	0.85	0.02	0.66
10	0.00	0.00	0.00
11	1.47	0.04	0.83
12	0.00	0.00	0.00
13	1.00	0.03	0.61
14	0.00	0.00	0.00
15	0.54	0.01	0.33
16	0.00	0.00	0.00
17	0.39	0.01	0.28
18	0.00	0.00	0.00
19	0.23	0.01	0.17
20	0.00	0.00	0.00
21	0.15	0.00	0.17
22	0.00	0.00	0.00
23	0.08	0.00	0.06
24	0.00	0.00	0.00
25	0.00	0.00	0.00
THD %	29.81		9.22
Parameter measured	2.70 A		36.39 kV

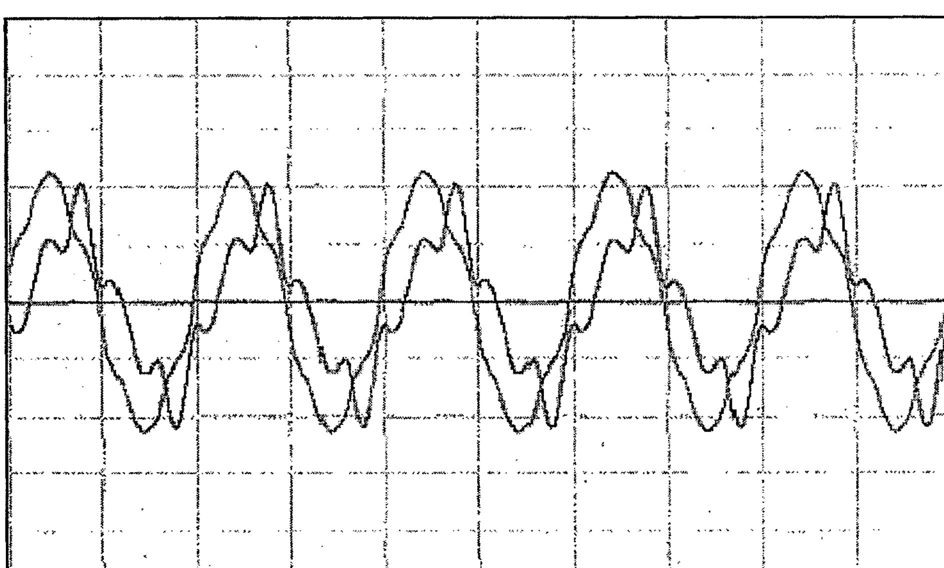

Figure 1.7.3-2a: Transformer magnetizing current waveforms and applied Voltage

1.8 SYSTEM RESPONSE CHARACTERISTICS

In power systems, the response of the system is equally as important as the sources of harmonics. In fact, power systems are quite tolerant of the currents injected by harmonic-producing loads unless there is some adverse interaction with the impedance of the system. Identifying the sources is only half the job of harmonic analysis. The response of the power system at each harmonic frequency determines the true impact of the nonlinear load on harmonic voltage distortion. There are three primary variables affecting the system response characteristics, i.e., the system impedance, the presence of a capacitor bank, and the amount of resistive loads in the system. Sections 1.8.1 through 1.8.4 detail these variables.

1.8.1 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 MegaVoltAmpere (MVA) or the short-circuit current as follows:

$$Z_{SC} = R_{SC} + jX_{SC} = \frac{kV^2}{MVA_{SC}} = \frac{kV\ X\ 1000}{\sqrt{3}\, I_{SC}} \qquad (1.8.1\text{-}1)$$

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:

$$X_h = hX_1 \tag{1.8.1-2}$$

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 X_{SC} may be based on the impedance of the service entrance transformer only:

$$X_{SC} \equiv X_{tr} \tag{1.8.1-3}$$

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 Z_{tx} found on the nameplate by

$$X_{tr} = \left(\frac{kV^2}{MVA_{3\emptyset}}\right) Z_{tr}\ (\%) \tag{1.8.1-4}$$

where $MVA_{3\emptyset}$ is the kVA rating of the transformer in MVA.

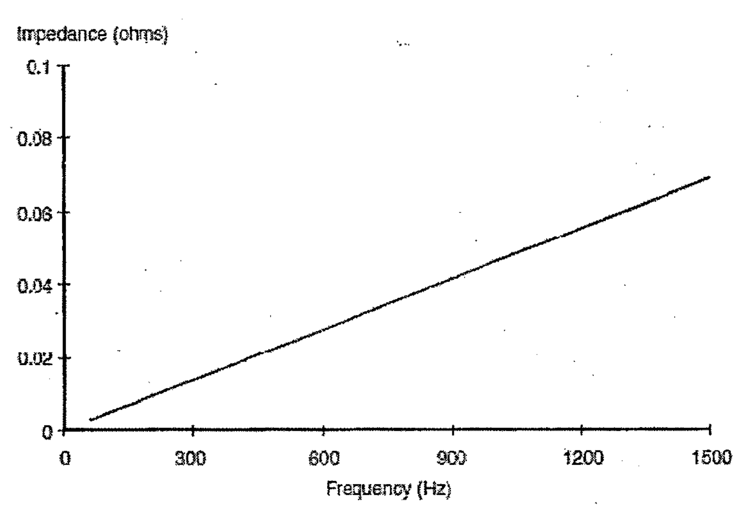

Figure 1.8.2-1: Impedance versus frequency for inductive system.

This assumes that the impedance is predominantly reactive. For example for a 1500-kVA, 6 percent transformer, the equivalent impedance on the 440-V side is A plot of impedance versus frequency for an inductive system (no capacitors installed) would look like Figure 1.8.2-1. This simple model neglects capacitance, which cannot be done for harmonic analysis.

1.8.2 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:

$$X_C = \frac{1}{2f\Pi C} \tag{1.8.2-1}$$

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

$$X_C = \frac{kV^2}{Mvar} \tag{1.8.2-2}$$

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

$$X_C = \frac{kV^2}{Mvar} = \frac{13.8^2}{1.2} = 158.7\Omega \tag{1.8.2-3}$$

1.8.3 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 1.8.3-1 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 Figure 1.8.3-2 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:

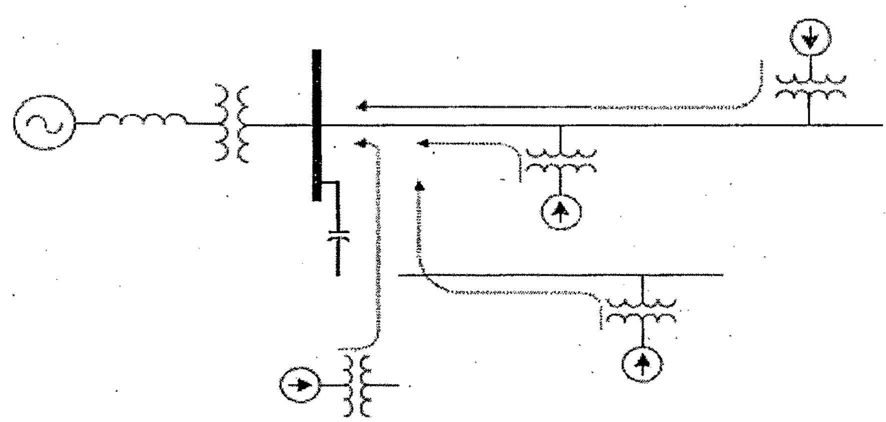

Figure 1.8.3-1: System with parallel resonance problem

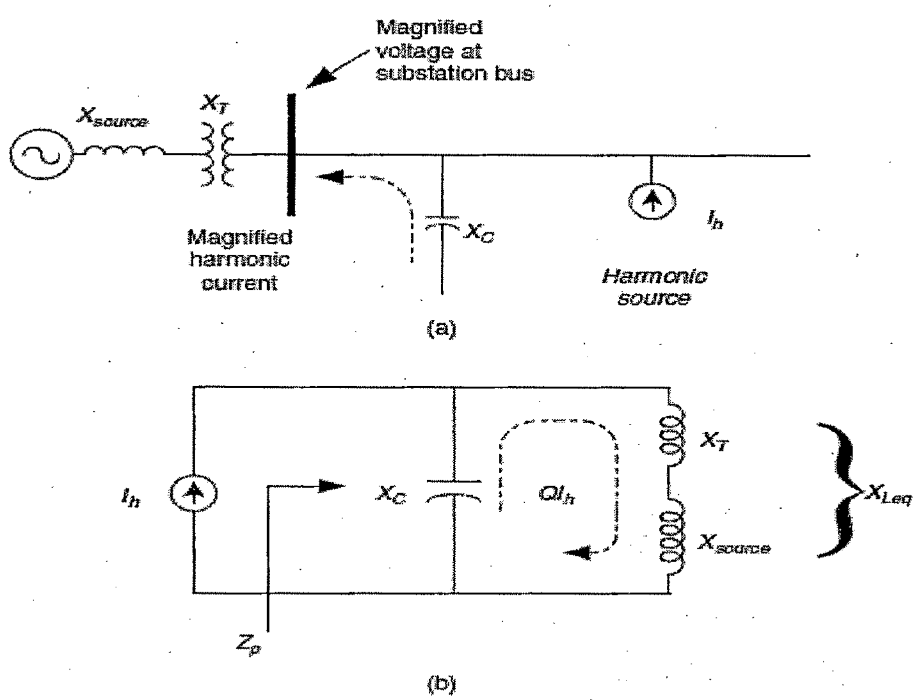

Figure 1.8.3-2: At harmonic frequencies, the shunt capacitor bank appears in parallel with the system inductance. (*a*) Simplified distribution circuit; (*b*) parallel resonant circuit as seen from the harmonic source

$$f_p = \frac{1}{2\Pi}\sqrt{\frac{1}{L_{eq}\,C} - \frac{R^2}{4L_{eq}^2}} \cong \frac{1}{2\Pi}\sqrt{\frac{1}{L_{eq}\,C}} \qquad (1.8.3\text{-}1)$$

where R = resistance of combined equivalent source and transformer (not shown in Figure 1.8.3-2)

L_{eq} = inductance of combined equivalent source and transformer

C = capacitance of capacitor bank

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, i.e.,

$$Z_p = \frac{X_C\,(X_{Leq}+R)}{X_C + X_{Leq} + R} = \frac{X_C\,(X_{Leq}+R)}{R}$$

$$\cong \frac{X_{Leq}^2}{R} = \frac{X_C^2}{R} = QX_{Leq} = QX_C \qquad (1.8.3\text{-}2)$$

where $Q = XL/R = XC/R$ and $R << X_{L\text{Equation}}$ Keep in mind that the reactance in this equation is 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 Equation (1.8.3-2), it is clear that during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance, i.e., $V_p = Q\, X_{Leq}\, I_h$. 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,

$$I_{resonance} = \frac{V_p}{X_C} = \frac{QX_C I_h}{X_C} = QI_h \qquad (1.8.3\text{-}3\text{-}a)$$

or

$$I_{resonance} = \frac{V_p}{X_{Leq}} = \frac{QX_{Leq} I_h}{X_{Leq}} = QI_h \qquad (1.8.3\text{-}3\text{-}b)$$

From Equation (1.8.3-3), 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. These phenomenon will likely cause capacitor failure, fuse blowing, or transformer overheating.

The extent of voltage and current magnification is determined by the size of the shunt capacitor bank. Figure 1.8.3-3 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.

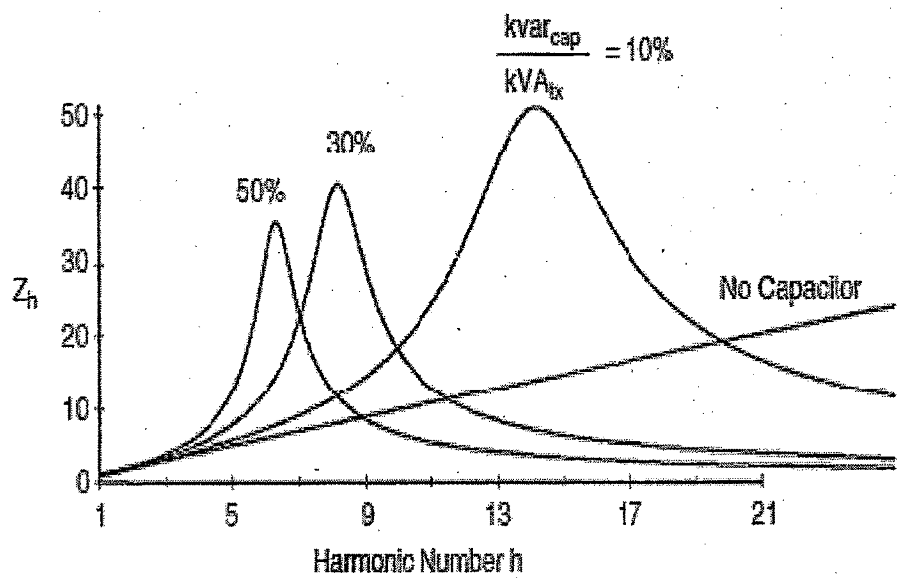

Figure 1.8.3-3: System frequency response as capacitor size is varied in relation to transformer

They commonly compute the resonant harmonic *hr* based on fundamental frequency impedances and ratings using one of the following:

$$h_r = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{MVA_{SC}}{Mvar_{cap}}} \equiv \sqrt{\frac{kVA_{tx}\ X\ 100}{kvar_{cap}\ X\ Z_{tx}\ (\%)}} \qquad (1.8.3\text{-}4)$$

where h_r = resonant harmonic

X_C = capacitor reactance

X_{SC} = system short-circuit reactance

MVA_{SC} = system short-circuit MVA

MVA_{cap} = MVAr rating of capacitor bank

kVA_{tx} = kVA rating of step-down transformer

Z_{tx} = step-down transformer impedance

$kVAr_{cap}$ = 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

$$h_r \equiv \sqrt{\frac{kVA_{tx}\,X\,100}{kVAr_{cap}\,X\,Z_{tx}\,(\%)}} = \sqrt{\frac{1500\,X\,100}{500\,X\,6}} = 7.07 \qquad (1.8.3\text{-}5)$$

1.8.4 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 Figure 1.8.4-1.

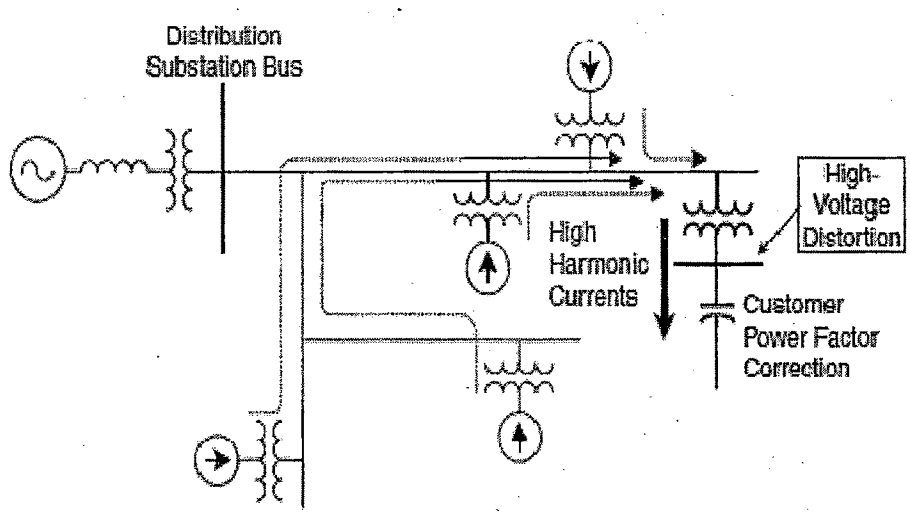

Figure 1.8.4-1: System with potential series resonance problems

During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources. The simplified circuit is shown in Figure 1.8.4-2. 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:

$$V_s\,(at\ power\ factor\ capacitor\ bank) = \frac{X_C}{X_T + X_C + R}\,V_h \equiv \frac{X_C}{R}\,V_h \qquad (1.8.4\text{-}1)$$

where V_h and V_s are the harmonic voltage corresponding to the harmonic current I_h and the voltage at the power factor capacitor bank, respectively. The resistance R of the series resonant circuit is not shown in Figure 1.8.4-2, and it is small compared to the reactance. The negligible impedance of the series resonant circuit can be exploited to absorb desired harmonic currents.

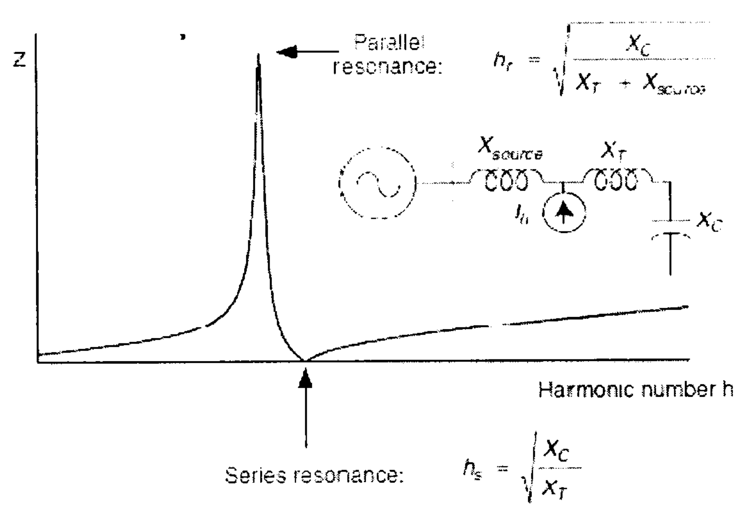

Figure 1.8.4-2: Frequency response of a circuit with series resonance

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 Figure 1.8.4-2 where the parallel resonance is formed by the parallel combination between X_{source} and a series between X_T and X_C. The resulting parallel resonant frequency is always smaller than its series resonant.

$$h_r = \sqrt{\frac{X_C}{X_T + X_{source}}} \qquad (1.8.4\text{-}2)$$

1.8.5 EFFECTS OF RESISTANCE AND RESISTIVE LOAD

Determining that the resonant harmonic aligns with a common harmonic source is not always cause for alarm. The damping provided by resistance in the system is often sufficient to prevent catastrophic voltages and currents. Figure 1.8.5-1 shows the parallel resonant circuit impedance characteristic for various amounts of resistive load in parallel with the capacitance. As little as 10 percent resistive loading can have a significant beneficial impact on peak impedance.

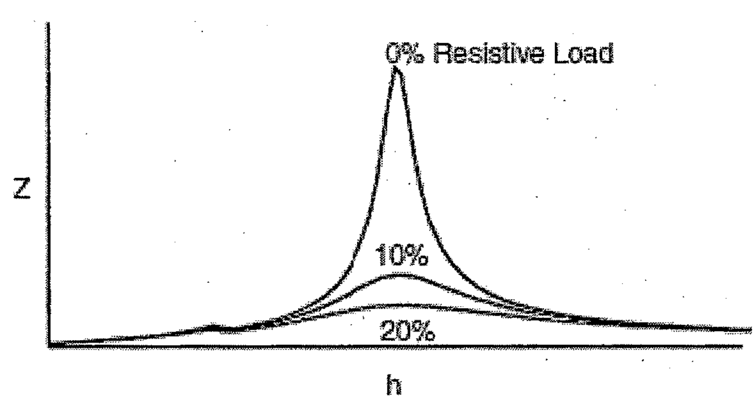

Figure 1.8.5-1: Effect of resistive loads on parallel resonance

Likewise, if there is a significant length of lines or cables between the capacitor bus and the nearest up line transformer, the resonance will be suppressed. Lines and cables can add a significant amount of the resistance to the equivalent circuit. Loads and line resistances are the reasons why catastrophic harmonic problems from capacitors on utility distribution feeders are seldom seen. That is not to say that there will not be any harmonic problems due to resonance, but the problems will generally not cause physical damage to the electrical system components. The most troublesome resonant conditions occur when capacitors are installed on substation buses, either utility substations or in industrial facilities. In these cases, where the transformer dominates the system impedance and has a high X/R ratio, the relative resistance is low and the corresponding parallel resonant impedance peak is very sharp and high. This is a common cause of capacitor, transformer, or load equipment failure.

While utility distribution engineers may be able to place feeder banks with little concern about resonance, studies should always be performed for industrial capacitor applications and for utility substation applications. Utility engineers familiar with the problems indicate that about 20 percent of industrial installations for which no studies are performed have major operating disruptions or equipment failure due to resonance. In fact, selecting capacitor sizes from manufacturers' tables to correct the power factor based on average monthly billing data tends to result in a combination that tunes the system near the fifth harmonic. This is one of the worst harmonics to which to be tuned because it is the largest frequency component in the system.

It is a misconception that resistive loads damp harmonics because in the absence of resonance, loads of any kind will have little impact on the harmonic currents and resulting voltage distortion. Most of the current will flow back into the power source. However, it is very appropriate to say that resistive loads will damp *resonance,* which will lead to a significant reduction in the harmonic distortion.

Motor loads are primarily inductive and provide little damping. In fact, they may increase distortion by shifting the system resonant frequency closer to a significant harmonic. Small, fractional-horsepower motors may contribute significantly to damping because their apparent X/R ratio is lower than that of large three-phase motors.

1.9 EFFECTS OF HARMONIC DISTORTION

Harmonic currents produced by nonlinear loads are injected back into the supply systems. These currents can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interference with telecommunication lines and errors in power metering. Sections 1.9.1 through 1.9.5 discuss impacts of harmonic distortion on various power system components.

1.9.1 IMPACT ON CAPACITORS

Problems involving harmonics often show up at capacitor banks first. As discussed in Sections. 1.8.3 & 1.8.4, a capacitor bank experiences high voltage distortion during resonance. The current flowing in the capacitor bank is also significantly large and rich in a monotonic harmonic. Figure 1.9.1-1 shows a current waveform of a capacitor bank in resonance with the system at the 11th harmonic. The harmonic current shows up distinctly, resulting in a waveform that is essentially the 11th harmonic riding on top of the fundamental frequency. This current waveform typically indicates that the system is in resonance and a capacitor bank is involved. In such a resonance condition, the rms current is typically higher than the capacitor rms current rating.

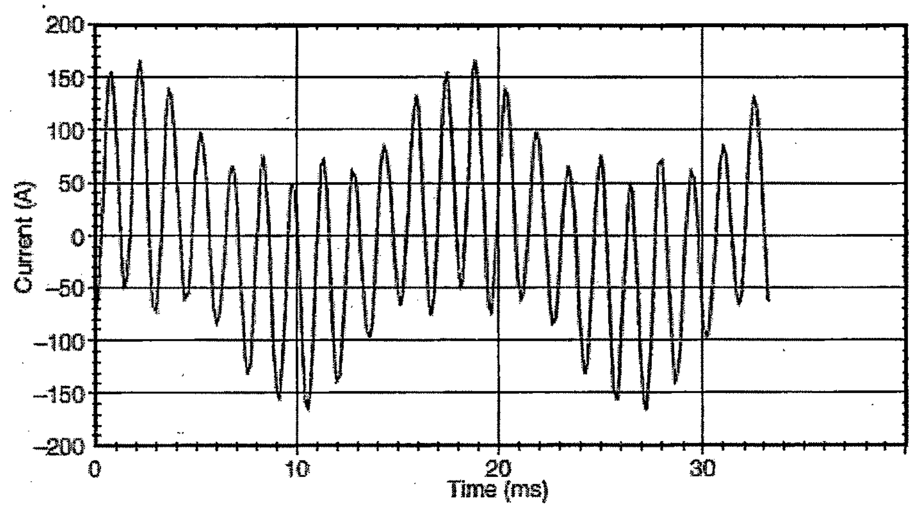

Figure 1.9.1-1: Typical capacitor current from a system in 11th-harmonic resonance.

IEEE Standard for Shunt Power Capacitors (IEEE Standard 18-1992) specifies the following continuous capacitor ratings:

■ 135 percent of nameplate kVAr

■ 110 percent of rated rms voltage (including harmonics but excluding transients)

■ 180 percent of rated rms current (including fundamental and harmonic current)

■ 120 percent of peak voltage (including harmonics)

Table 1.9.2-1 summarizes an example capacitor evaluation using a computer spreadsheet that is designed to help evaluate the various capacitor duties against the standards. The fundamental full-load current for the 1200-kvar capacitor bank is determined from

$$I_C = \frac{kvar_{3\emptyset}}{\sqrt{3}\, X\, kV_{LL}} = \frac{1200}{\sqrt{3}\, X\, 11.0} = 62.98\, A$$

The capacitor is subjected principally to two harmonics: the fifth and the seventh. The voltage distortion consists of 5 percent fifth and 4 percent seventh. This results in 25 percent fifth harmonic current and 28 percent seventh harmonic current. The resultant values all come out well below standard limits in this case, as shown in the box at the bottom of Table 1.9.1-1.

Table 1.9.1-1: Example Capacitor Evaluation

Recommended Practice for Establishing Capacitor Capabilities when Supplied by Nonsinusoidal Voltage
IEEE Std 18-2002

Capacitor Bank Data:

Bank Rating:	1200	kVAr
Voltage Rating:	11000	V (L-L)
Operating Voltage:	11000	V (L-L)
Supplied Compensation:	1200	kVAr
Fundamental Current Rating:	62.98	Amps
Fundamental Frequency:	50	Hz
Capacitive Reactance:	100.8	Ohm

Harmonic Distribution of Bus Voltage:

Harmonic Number	Frequency (Hz)	Voltage Mag. Vh (% of Fund.)	Voltage Mag. Vh (Volts)	Line Current Ih (% of Fund.)	Line Current Ih (Amp)
1	50	100.00	6198.0	100.0	61.47
3	150	0.00	0.0	0.0	0.00
5	250	5.00	310.0	25.0	15.37
7	350	4.00	248.0	28.0	17.22
9	450	0.00	0.0	0.0	0.00
11	550	0.00	0.0	0.0	0.00
13	650	0.00	0.0	0.0	0.00
15	750	0.00	0.0	0.0	0.00
17	850	0.00	0.0	0.0	0.00
19	950	0.00	0.0	0.0	0.00
21	1050	0.00	0.0	0.0	0.00
23	1150	0.00	0.0	0.0	0.00
25	1250	0.00	0.0	0.0	0.00

Voltage Distortion (THD):	6.41	%
RMS Capacitor Voltage:	6210.70	Volts
Capacitor Current Distortion:	37.55	%
RMS Capacitor Current:	65.66	Amps

Capacitor Bank Data:

	Calculated	Limit	Exceeds Limits
Peak Voltage:	101.0 %	120%	No
RMSVoltage:	97.8 %	110%	No
RMS Current:	104.2 %	180%	No
kVAr:	101.95 %	135%	No

1.9.2 IMPACT ON TRANSFORMERS

Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Harmonic distortion of the current, in particular, as well as of the voltage will contribute significantly to additional heating. To design a transformer to accommodate higher frequencies, designers make different design choices such as using continuously transposed cable instead of solid conductor and putting in more cooling ducts. As a general rule, a transformer in which the current distortion exceeds 5 percent is a candidate for derating for harmonics. The effect of Harmonics on transformer losses is given in Annexure-I-A

There are three effects that result in increased transformer heating when the load current includes harmonic components:

1. *RMS current.* If the transformer is sized only for the kVA requirements of the load, harmonic currents may result in the transformer rms current being higher than its capacity. The increased total rms current results in increased conductor losses.
2. *Eddy current losses. These are induced currents in a transformer caused by the magnetic fluxes. These induced currents flow in the windings, in the core, and in other conducting bodies subjected to the magnetic field of the transformer and cause additional heating. This component of the transformer losses increases with the square of the frequency of the current causing the eddy currents. Therefore, this becomes a very important component of transformer losses for harmonic heating.*
3. *Core losses. The increase in core losses in the presence of harmonics will be dependent on the effect of the harmonics on the applied voltage and the design of the transformer core. Increasing the voltage distortion may increase the eddy currents in the core laminations. The net impact that this will have depends on the thickness of the core laminations and*

the quality of the core steel. The increase in these losses due to harmonics is generally not as critical as the previous two.

Exceptions: There are often cases with transformers that do not appear to have a harmonics problem from the criteria given in Table 1.9.2-1, yet are running hot or failing due to what appears to be overload. One common case found with grounded-wye transformers is that the line currents contain about 8 percent third harmonic, which is relatively low, and the transformer is overheating at less than rated load. Why would this transformer pass the heat run test in the factory and perhaps, an overload test also, and fail to perform as expected in practice? Discounting mechanical cooling problems, chances are good that there is some conducting element in the magnetic field that is being affected by the harmonic fluxes. Three of several possibilities are as follows:

■ Zero-sequence fluxes will "escape" the core on three-legged core designs (the most popular design for utility distribution substation transformers). This is illustrated in Figure 1.9.2-1. The 3d, 9th, 15th, etc., harmonics are predominantly zero-sequence. Therefore, if the winding connections are proper to allow zero-sequence current flow, these harmonic fluxes can cause additional heating in the tanks, core clamps, etc., that would not necessarily be found under balanced three-phase or single-phase tests. The 8 percent line current previously mentioned translates to a neutral third-harmonic current of 24 percent of the phase current. This could add considerably to the leakage flux in the tank and in the oil and air space. Two indicators are charred or bubbled paint on the tank and evidence of heating on the end of a bayonet fuse tube (without blowing the fuse) or bushing end.

DC offsets in the current can also cause flux to "escape" the confines of the core. The core will become slightly saturated on, for example, the positive half cycle while remaining normal for the negative half cycle. There are a number of electronic power converters that produce current waveforms that are nonsymmetrical either by accident or by design. This can result in a small dc offset on the load side of the transformer (it can't be measured from the source side). Only a small amount of dc offset is required to cause problems with most power transformers.

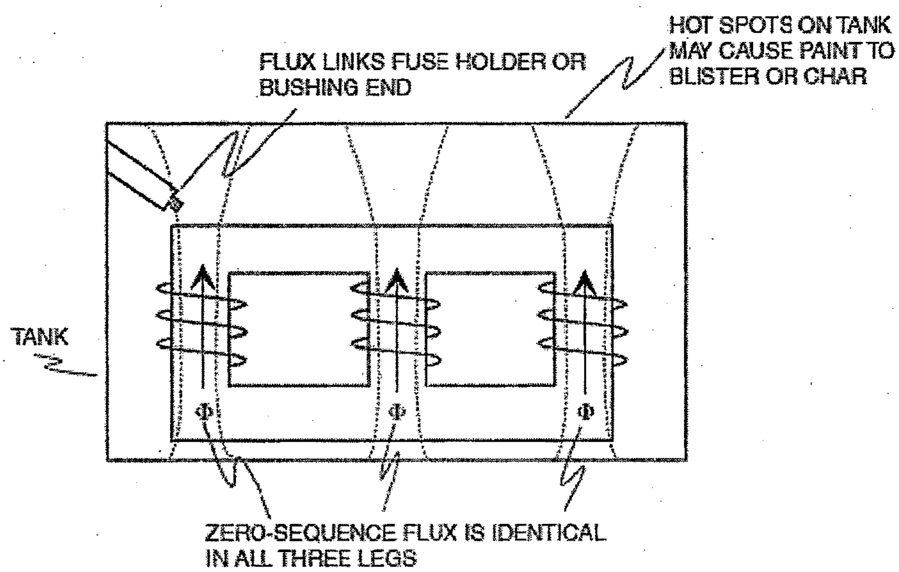

Figure 1.9.2-1: Zero Sequence flux in three legged core transformers enters the tank and the air and oil space

■ There may be a clamping structure, bushing end, or some other conducting element too close to the magnetic field. It may be sufficiently small in size that there is no notable effect in stray losses at fundamental frequency but may produce a hot spot when subjected to harmonic fluxes.

1.10 POWER IN DISTORTED AC NETWORKS

The active and reactive power components for electric circuits with sinusoidal and linear loads are well established. In the case of non-linear loads, however the use of the reactive and the harmonic power is an actual necessity for accomplishing reactive power compensation and/or harmonic filtering. The components of the electric power are shown in Figure 1.10-1 assuming a sinusoidal voltage supply and a non-linear load [8]. In this case, the power factor *($cos\Phi$)* is the product of the distortion factor *($I_1/I= cos\gamma$)* by displacement factor *($cos\Phi_I$)* :

Power Factor = Distortion factor **x** Displacement Factor

The displacement factor corresponds to the power factor of systems without harmonics. This factor may be called fundamental power factor, as it depends only on the current fundamental component. On the other hand, the power factor, as defined above, may be called total power factor, as it depends on fundamental and al1 harmonic components. Hence, harmonics cause lower power factor. The power components in distorted networks are represented in power tetrahedron, instead of the triangle as in the linear case, is shown in Figure 1.10-2.

From Figure 1.10-1 and Figure 1.10-2, various important factors are determined on the use of reactive power and harmonic compensation:

(i) The reactive component is dependent only on the current component at fundamental frequency. The reactive component can be eliminated by using a conveniently chosen capacitor or inductor. The connection of an inductor or a capacitor component in parallel with load allows the generation of a current at fundamental frequency that absorbs or generates the reactive power required by the load;

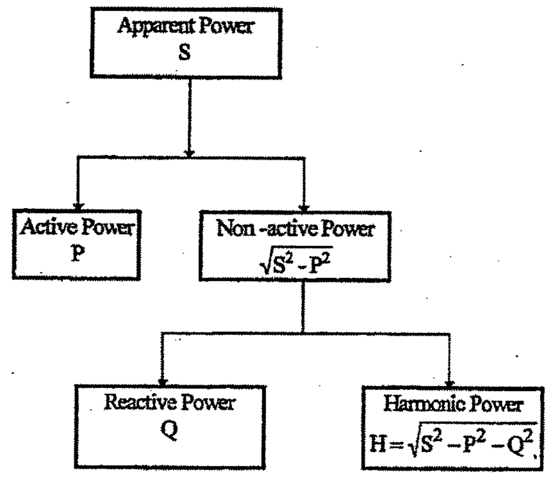

Figure 1.10-1: Components of electric power

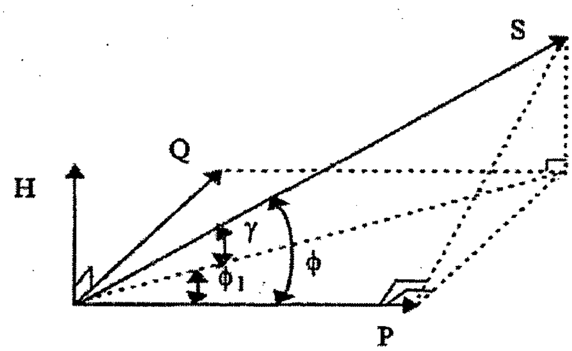

Figure 1.10-2: Power Tetrahedron.

(ii) Harmonic power is reactive power. There will be real power due to harmonics also this is included in "P". The distorting power is dependent on the current components with frequencies different from fundamental frequency (harmonics) and cannot be eliminated by a single capacitor or inductor. The elimination of harmonic power depends on filters that work as short-circuit for the harmonic current generated by the load.

1.11 HARMONIC STANDARDS AND RECOMMENDED PRACTICES.

In view of the proliferation of the power electronic equipment connected to the utility distribution system, various international agencies have proposed limits on the magnitude of harmonic current injected into the supply to maintain acceptable power quality. The resulting guidelines and standards specify limits on the magnitudes of harmonic currents and harmonic voltage distortion at various harmonic frequencies.

The most widely known are the IEEE-519 guidelines [2] in North America and the IEC-61000 Standard (formerly IEC 555) [3] prepared by the International Electrical Commission (in effect since 1996). However, the approach taken in these documents is drastically different. The IEC Standard imposes limits on individual equipment (up to 15 A, 220 V) connected to the supply, whereas the IEEE Recommended Practice addresses the issue of harmonic distortion at the point of common of coupling (PCC). Complying with the IEC Standard usually requires special design of the equipment itself *[5]* [6] [7]. However, meeting the IEEE guidelines can be achieved by means of filter, particularly active filters. Therefore, reference in this work will only be made to the IEEE guideline. IEEE 519 proposes to designers of industrial plants harmonic limits as given in Table 1.11-1 and 1.11-2. For existing installations, harmonic mitigation techniques may have to be used to reduce distortion to the specified limits.

Table 1.11-1: IEEE-519 Voltage distortions limits

Bus Voltage @PCC	HDv(%)	THDv(%)
69 KV and below	3.0	5.0

HDv=Individual harmonic voltage distortion.

Table 1.11-2: IEEE-519 Maximum odd-harmonic current distortions.

% Limits of Harmonic Currents (Bus voltage @ PCC<69 KV)

I_{SC}/I_1	h<11	11<h<17	17<h<23	23<h<35	35<h	THD
<20	4.0	2.0	1.5	0.3	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

I_{sc} is the maximum short-circuit current @PCC.

I_1 is the maximum fundamental frequency load current @PCC.

1.12 LITERATURE SURVEY

Most of the research work in the three-phase power converter area was for balanced three-phase systems, such as motor drive applications, where three-legged power converters are used. When the neutral connection is needed, typically split DC link capacitors are used. The first four-legged current source thyristor inverter was presented in [E2] in 1979, where the fourth leg was used for commutation of thyristors. A four-legged power inverter was also proposed in [B19] to eliminate the common mode noise. The first voltage source four-legged inverter used for an aircraft power generation application was presented in [E1] in 1993 to provide the neutral connection and to handle the neutral current. Since it is a resonant DC link inverter (RDCL inverter), it is controlled with a pulse density modulation scheme. The same topology was proposed in [G2] in 1992 for active filter applications to deal with a zero-sequence component in a power system. The current source four-legged inverter was also proposed for active filter applications in [G3] in the same year to handle a zero-sequence component. Another variation of four-legged inverter was proposed in [G23], where the neutral point is still provided by two split capacitors, and the fourth leg is really an active filter independent from the three phase legs. The fourth leg is controlled to nullify the zero-sequence current due to unbalanced load or nonlinear load so that the neutral current does not flow through the DC link capacitors. This approach allows a smaller DC link capacitance to be used for the same voltage ripple; however, it still suffers from insufficient utilization of the DC link voltage. In all the previous research, there are no space vector modulation schemes proposed for four-legged power converters, nor are the modeling and control aspects of four-legged power converters discussed.

Pulse width modulation (PWM) techniques have been widely used in the field since 1960s. With intensive research activities over the last decades, many PWM schemes have been proposed for single-phase and three-phase applications, including sinusoidal PWM, harmonic elimination or optimal PWM [B24-B25], hysteresis and bang-bang type modulation [B28-B32], random modulation [B33-B35], and space vector modulation [B2-B17]. Space vector modulation was first proposed in [B2] in 1982 and became more and more popular due to its merits of high utilization of the DC link voltage, possible optimized output distortion and switching losses, and compatibility with a digital controller. It has been widely used for high performance three-phase drive systems [B3-B7] and PFC rectifiers [B8] with success. Several research focuses for space vector modulation can be identified:

(1) optimized space vector modulation schemes in terms of harmonic distortion [B13-B14] and switching losses [B10-B12];

(2) digital implementation of space vector modulation schemes [B4, B14, B16];

(3) over modulation operation [B9]; and [B4] adaptive sequencing schemes for varying modulation index and load power factor [B15, B17].

All the existing space vector modulation schemes are implemented in a two-dimensional space, and are therefore unable to deal with the zero sequence component caused by unbalanced or nonlinear loads.

Unbalanced source and load have been analyzed extensively in power systems. The symmetrical component representation was proposed by C. L. Fortescue in 1918, and became a textbook method when analyzing unbalance in power systems. By decomposing an arbitrarily unbalanced three-phase variable into three sets of balanced three-phase variables, namely, positive-sequence, negative-sequence and zero-sequence, not only is the analysis greatly simplified, but also more physical meaning can be obtained from the unbalanced conditions. In power systems, there are several passive means to correct the negative-sequence and zero-sequence components caused by unbalanced load, such as zero-sequence trap [A4], zigzag transformer [A5], and passive balancing network [A6]. In a power electronics system, there are three ways to correct the negative-sequence component caused by a unbalanced load:

(1) Large passive filter to reduce the 2w ripple;

(2) High bandwidth feedback control so that the disturbance caused by the 2w ripple can be suppressed;

(3) Feed forward control to counterbalance the disturbance of the 2w ripple; or combination of (2) and (3).

Using three-legged power converters to deal with unbalanced source has been addressed in [F1-F3]. By engaging a feed forward control, the negative-sequence component caused by an unbalanced source can be canceled out so that the input power becomes a constant and the DC link voltage is free of low frequency even harmonic ripples. The same concept was used for active power filter application in [G1]. However, a three-legged power converter is incapable of dealing with zero-sequence unbalance. To solve the limitation, normally split DC link capacitors are used. The zero-sequence current path is provided by tying the neutral point to the middle point of the two DC link capacitors. [G1] presented a scheme using split DC link capacitors to handle the zero-sequence for active power filter application. The drawback of this scheme is that excessively large DC link capacitors are needed; therefore cost is high especially for high voltage applications. To handle the zero-sequence component, the four-legged inverter proposed in [E1] can substantially reduce the DC link capacitance. Since it is a soft-switching inverter, the correction of unbalance is achieved by a fast feedback control loop with a high switching frequency.

Modeling of three-phase three-legged power converters was presented in [H2] by representing the switching networks with controlled voltage and current sources. The "inplace" circuit averaging method was adopted to derive the average circuit model directly from the switching circuit model. Large-signal and small-signal models are derived in d-q rotating coordinate. The models are convenient for direct analysis and simulation with circuit simulation software. Effects of circuit parasitic are also discussed in [H2]. Due to three-legged topologies, the zero-sequence component is not revealed in the models. Small-signal models of PWM modulators are also presented in [H1]. It has been shown that a PWM modulator will add additional time delay, and the gain of the PWM modulator could change with respect to the modulation index and the vector position. Both the gain and phase delay of the PWM modulator cannot be expressed in a simple closed form.

Control of three-phase three-legged power converters has been extensively investigated. As with DC/DC converters, control for three-phase power converters can also be classified into voltage mode control and current mode control. Current mode control has been used widely for PFC rectifier, motor drive applications and high performance UPS due to its fast dynamic response and inherent current protection capability. Three independent hysteresis current controllers can provide fast current regulation. However, in unbalanced cases, the performance is degraded due to a continuous fight among the three independent hysteresis controllers. Deadbeat control was proposed to make the controlled variable equal to the reference at the end of each switching cycle so that a response within one discretigation time is obtained. Deadbeat control was used for both single-phase applications [H5] and three-phase applications [H6-H8]. It can be applied to both the current control loop and voltage control loop [H7-H8].

For hard-switching power converters, a dead time needs to be added for each switching commutation to prevent shoot-through problem. The dead time will cause duty ratio loss, and thus lead to an inaccurate control. The control inaccuracy may greatly degrade performance especially when the ratio of the dead time to the switching period is large. [H14] proposed a method to compensate the duty ratio loss caused by the dead time. It adjusts the pulse width by the amount of dead time according to the load current direction.

As Digital Signal Processor (DSP), microcontroller, and other peripherals such as A/D conversion and D/A conversion become faster and faster, the digital controller becomes more and more popular in power electronics [H9-H13] [H22]. A digital controller can easily realize a complicated control algorithm. It is insensible to parameter changes and temperature variations, and thus more robust. The drawback with a digital controller is an additional time delay caused by sensing, sampling and computation, which is a major limitation for extending control bandwidth. Predictive current control may help to reduce the delay to some extent [B1].

To achieve a high performance with nonlinear load, a low output impedance is needed. The output impedance may be reduced by (1) parallel power converters, or (2) a high control bandwidth. The parallel power converters have to deal with current sharing problem [D5-D14]. A high control bandwidth is always desired to achieve a compact and high performance system. The control bandwidth can be extended with a high switching frequency. Soft-switching power converters [C1-C14] enable the use of a high switching frequency by reducing switching losses. However, there is a trade-off in using soft switching power converters. A control inaccuracy may occur due to duty ratio losses caused by interventions of a soft-switching network.

Active filters were investigated in the past decades to deal with nonlinear loads in power systems. The basic principle was first proposed in [G5] in 1971, and was generalized in [G6] in 1976. Active filters can be classified into two categories: shunt (parallel) active filter and series active filter [G7]. Parallel active filters are controlled to be a current source, and used to deal with nonlinear loads with a harmonic current source characteristic; a series active filter is controlled to be a voltage source, and used to deal with nonlinear loads with a harmonic voltage source characteristic [G8]. Active filters can be used not only to handle the harmonics caused by nonlinear loads, but also to handle reactive power [G9-G10]. Design aspects of hard switching active filters were discussed in [G14-G16], while an example of a soft switching active filter was given in [G17].

There were three hybrid approaches in the active filter applications aiming at a high performance and cost-effective solution. First, a hybrid of a shunt active filter with a passive filter. The shunt active filter compensates low-order harmonic currents, and the passive filter compensates high-order harmonic currents [G7]; second, hybrid of a series active filter with a passive filter [G7], [G1-G12]. The series active filter does not compensate harmonic currents, it only isolates the harmonics for the passive filter to handle. This approach can eliminate the sensitivity of the passive filter to the power source impedance, and results in a low cost system; third, a hybrid of a shunt active filter with a series active filter. The so-called universal active can deal with nonlinear loads with both harmonic current and voltage source characteristics [G13].

Harmonic current detection is the major focus in designing an active power filter. Instantaneous reactive power theory was developed in [G19] to extract harmonic currents. Both three-phase voltage and current are sensed. If the three-phase voltage is known, instantaneous reactive power theory is the same as applying d-q transformation to the load current to extract the harmonic currents. Instantaneous reactive power theory is more appropriate for a balanced source. When three-phase systems are unbalanced, [G20] proposed three methods to calculate the current references by using a synchronous detection technique. Under an unbalanced source voltage, the current reference for the active power filter can be given to realize either of the following three: (1) equal power among phases; (2) equal current among phases; (3) equal resistance among phases. The source could be not only unbalanced, it could also be distorted due to heavy nonlinear loads, that makes the harmonic current detection even more difficult. It was also argued in [G21] that when the source voltage is heavily distorted under a heavy nonlinear load, the instantaneous reactive power theory does not give satisfactory results. It could even make the harmonic currents larger. A compensation strategy, which aims at making the nonlinear load/active filter system a constant linear resistor, is concluded to be a better choice in this situation. Another compensation concept suitable for nonlinear voltage and current can be found in [G22], where fictitious power was defined to include reactive power, effect of harmonic voltage and current and sub harmonic voltage and current. However, the computation is more complicated.

With the ever faster evolution of power electronics technologies, power converters tend to be connected to form a power converter system. Series and parallel connected power converters are the two basic forms of power converter systems. A series connected AC/DC PFC rectifier and a DC/AC inverter can provide a high performance motor drive system. Multiple power converters in parallel can provide high power capacity and N+1 redundancy. In recent years, more sophisticated power converter systems have been proposed. Among them, multi-functional power converters, passive circuit combined with active power converter, and active power converter combined with active power converter can be found. One example of a multi-functional power converter was given in [D17], where a three-phase voltage source inverter, used in a battery energy storage system and connected to a utility line, can perform charger, inverter and active filter functions. Hybrid approaches are mostly found in power conditioning applications. A combined system with a shunt passive filter and series active filter was presented in [G11-G12] to compensate harmonic currents in power systems. The series active filter isolates the harmonic currents from the power source so that the passive filter can be effective for harmonic currents. The passive-active hybrid system is more effective than a passive filter and practical due to its low cost. An active-active hybrid approach can be found in [G13], where a shunt active filter is combined with a series active filter. Since a shunt active filter is effective in dealing with nonlinear load with harmonic current source characteristics, and a series active filter is effective in dealing with nonlinear loads with a harmonic voltage source characteristics, the hybrid system renders an overall better performance. This kind of active-active power converter system is a hybrid of power converters for different loads. Another kind of active-active power converter system is presented in [D18-G20], which partitions the energy flow into two distinguished parts: high-power/low-frequency and low-power/high-frequency, and then handles them separately by two power converters. [D18] presented a high-power magnet power supply, where a low-frequency thyristor rectifier is used to handle the main output power, while a high-frequency PWM converter is in series with the thyristor rectifier to cancel harmonics and compensate for errors. [D19] presented a hybrid system with a similar concept for active power filter application. A GTO high-power low frequency inverter is combined with a low-power high-frequency IGBT inverter. [D20] was also for power conditioning applications. A high-power multi-step inverter was adopted to handle reactive power, and PWM inverters are adopted for harmonic compensation. The common essential aspect of a power converter system is the control strategy it employs. Since more than one power converter and/or loads are involved, the analysis and control design of the whole system can be extremely difficult. In designing a power converter system, special attention should also be paid to the circulating current at switching frequency [D1-D2] and grounding issue [D16].

Using power converters to perform active damping function was suggested in [H20] and [H21]. A distributed UPS system was presented in [H20]. The loop formed by UPS output filter capacitors and the interconnecting line inductance is highly under damped. The derivative of the interconnecting current was used as a current reference for each UPS to serve a damping purpose. No active power is processed to perform the damping function since only harmonic currents were included in the derivative. Simulation results showed that active damping can suppress the sub harmonic oscillation on the line. However, this approach is noise sensitive due to the derivative. A current type PWM rectifier was presented in [H21] with active damping function. The motivation was to damp harmonic currents amplified by the LC filter of the current type rectifier. There is no prior research on using active damping function for the purpose of extending the control bandwidth of the other power converter.

Large-scale power electronic systems have been analyzed for solar power systems and parallel UPS systems. System stability is of a major concern when many power converters are connected together. The forbidden region concept was developed for test of small-signal stability margin. A large-scale DC distribution power system with PFC rectifier, motor drive, utility power supply, and other power converters, has not been investigated before. There is no large-signal stability issue discussed for this large-scale power electronics system.

1.13 MOTIVATION FOR THE THESIS

The study for power quality problems highlights that the shunt active filter can compensate for current harmonics, improve power factor & control the reactive power flow from system to the load. The study also shows that the combined active filter systems have the same objectives as the independent series and shunt active filters. That is, the series active filter isolates the utility voltage disturbances and the shunt active filter provides compensation for reactive power, harmonies current, and unbalance in load. But elimination of voltage harmonics for low rating having imported linear load which is connected to same bus is not reported in the literature.

In addition, the study finds the following unresolved issues

The shunt active filter alone provides the load reactive power compensation, harmonics compensation so that bus voltage does not distort and affect other small but important linear load for this its ratings are very high.

Online as well as instantaneous detection of voltage harmonics so that it can be used as reference for VSI to compensate voltage harmonics

Online as well as instantaneous detection of voltage unbalance (negative sequence as well as zero sequence) so that it can be used as reference for VSI to compensate unbalance.

The motivation for the thesis stems from the fact that there is a need for a novel power quality tool to solve the problem of voltage harmonics & compensate negative sequence and zero sequence voltage which is the normal power quality issue in real world to reduce the ratings of the shunt active filter.

In this thesis, a series active filter, negative and zero sequence voltage compensator using Instantaneous Active Reactive power Theory (IARP Theory) is presented. Instantaneous Active Reactive power Theory (IARP Theory) is used for shunt active filter for current harmonics elimination & reactive power compensation but in this thesis IARP theory is modified in such a way so that it can detect online, instantaneous voltage harmonics, negative sequence and zero sequence voltage.

1.14 ORGANIZATION OF THE THESIS

The thesis is organized into six chapters. The outlines of these chapters are as follows:

Chapter 1 gives overview on power quality & its effect.

Chapter 2 is devoted to the different tools or methods for improvement of power quality. In this chapter different methods along with control theory for improvement of power quality are discussed

For improving reliability & quality of power following methods are discussed.

a) Different type of passive filter & its analysis along with its advantage & disadvantage
b) Different type of shunt active filter, their control, simulation as well as experimental results
c) Unity power factor boost converter along with control, simulation & experimental results

Chapter 3 deals with series active filter which not only isolate the linear load from distortion but also improve the voltage profile of the bus. Instantaneous Active Reactive power Theory (IARP Theory) which is used for detection of current is modified so that it can be used to detect the voltage harmonic of the system. Extensive simulation results along with experimental results were presented.

Main contribution of this chapter is

a) Active series filter to eliminate voltage harmonics for linear load using modified IARP theory.
b) Extensive simulation results along with experimental results were presented. Experiments were done at 415 volts, 3 phase systems.
c) Experiments were done at 415 volts, 3 phase systems
d) Analogue based control systems was discussed along with it power circuit.

Chapter 4 illustrated new techniques to detect negative sequence & zero sequence voltage and compensate the same so that load experience the balance voltage profile. Same Instantaneous Active Reactive power Theory (IARP Theory) is used in different manner so that desired quantity i.e. negative sequence as well as zero sequence can be detected. This signal will be used as reference signal for SPWM inverter so that it will compensate the system voltage profile for unbalance. Main contributions of this chapter are:

a) Novel technique for online, instantaneous detection of negative sequence & zero sequence components
b) Using this techniques a novel power quality improvement tool which can compensate for unbalance in the systems bus voltage

Chapter 5 describe about combine harmonic & negative sequence compensator which is useful where for unbalance voltage having distortion. In this chapter, with slide modification in IARP theory used for series active filter this novel combine series compensator is simulated & simulation results are presented.

Chapter 6 lists the important contributions of this thesis work and identifies the future challenges that need to be addressed.

1.15 PROBLEM STATEMENTS

The system impedance plays an important role in distorting the bus voltages due to presence of harmonics in the line currents. As the system impedance increases, there are more chances of generating distortion in the voltage bus. It is observed in practice that the bus voltages get distorted due to present of current harmonics. Sensitive load being fed from such a distorted bus are liable to malfunction. One of the examples, being the railways signaling load, where in the signaling is affected due to the bus distortion which is generated by rectifier load connected on same bus. This signaling load is of fraction capacity compared to total load on the bus. In such cases it is economical to use a series active filter to filter out the bus voltages feeding a sensitive load instead of the eliminating current harmonics in the bus.

Due to unbalance loads connected to the bus having higher impedance, there is unbalance generated in bus voltages. This unbalance results in generation of zero and negative sequence voltages. 80% of the industrial loads are motor loads. These negative sequence voltages generate negative torque which in turn decreases the effective output torque of the motor and hence the efficiency of the drive system. The zero sequence voltages produce heat loss in the motor.

The work presented here deals with a voltage source converter, configured as a series active filter, which not only eliminates the voltage harmonics but also compensates for the negative sequence voltages and the zero sequence voltages of the bus. It also improves the voltage profile of the system.