POWER QUALITY
COURSE MATERIAL

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SREE VIDYANIKETHAN ENGINEERING COLLEGE

(AUTONOMOUS)

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Department of Electrical and Electronics Engineering

Program Educational Objectives - B.Tech Electrical and Electronics Engineering:

PEO1: be enrolled in academic programs in the disciplines of electrical engineering or other disciplines.

PEO2: be employed as productive and valued engineers in reputed organizations.

PEO3: assume increasingly responsible positions and use the technical skills and analytical acumen to address professional values, ethics, and leadership and team skills for execution of complex technological solutions.

Program outcomes - B.Tech Electrical and Electronics Engineering:

On successful completion of the program, engineering graduates will be able to:

1. Apply the knowledge of mathematics, science, engineering fundamentals, and concepts of engineering to the solution of complex engineering problems. (Engineering knowledge)
2. Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences. (Problem analysis)
3. Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations. (Design/development of solutions)
4. Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions. (Conduct investigations of complex problems)
5. Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations. (Modern tool usage)
6. Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice. (The engineer and society)
7. Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of and need for sustainable development. (Environment and sustainability)
8. Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice. (Ethics)
9. Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings. (Individual and team work)
10. Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions. (Communication)

11. Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments. (Project management and finance)
12. Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change. (Life-long learning)

PROGRAM SPECIFIC OUTCOMES

On successful completion of the program, engineering graduates will

PSO1: Demonstrate knowledge of Electrical and Electronic circuits, Electrical Machines, Power Systems, Control Systems, and Power Electronics for solving problems in electrical and electronics engineering.

PSO2: Analyze, design, test and maintain electrical systems to meet the specific needs of the Industry and society.

PSO3: Conduct investigations to address complex engineering problems in the areas of Electrical Machines, Power Systems, Control Systems and Power Electronics.

PSO4: Apply appropriate techniques, resources and modern tools to provide solutions for problems related to electrical and electronics engineering

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UNIT–I

INTRODUCTION TO POWER QUALITY

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1.1 Introduction

The term electric power quality (PQ) is generally used to assess and to maintain the good quality of power at the level of generation, transmission, distribution and utilization of AC electrical power. Since the pollution of electric power supply systems is much severe at the utilization level, it is important to study at the terminals of end users in distribution systems. There are a number of reasons for the pollution of the AC supply systems, including natural ones such as lightening, flashover, equipment failure and faults (around 60%) and forced ones such as voltage distortions and notches (about 40%). A number of customer's equipment also pollute the supply system as they draw non-sinusoidal current and behave as nonlinear loads. Therefore, power quality is quantified in terms of voltage, current or frequency deviation of the supply system, which may result in failure or mal-operation of customer's equipment. Typically, some power quality problems related to the voltage at the point of common coupling (PCC) where various loads are connected are the presence of voltage harmonics, surge, spikes, notches, sag/dip, swell, unbalance, fluctuations, glitches, flickers, outages and so on. These problems are present in the supply system due to various disturbances in the system or due to the presence of various nonlinear loads such as furnaces, uninterruptible power supplies (UPSs) and adjustable speed drives (ASDs). However, some power quality problems related to the current drawn from the AC mains are poor power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in poly-phase systems due to unbalancing and harmonic currents generated by some nonlinear loads.

These power quality problems cause failure of capacitor banks, increased losses in the distribution system and electric machines, noise, vibrations, over voltages and excessive current due to resonance, negative sequence currents in generators and motors, especially rotor heating, de-rating of cables, dielectric breakdown, interference with communication systems, signal interference and relay and breaker malfunctions, false metering, interferences to the motor controllers and digital controllers, and so on.

These power quality problems have become much more serious with the use of solid-state controllers, which cannot be dispensed due to benefits of the cost and size reduction, energy conservation, ease of control, low wear and tear, and other reduced maintenance requirements in the modern electric equipment. Unfortunately, the electronically controlled energy-efficient industrial and commercial electrical loads are most sensitive to power quality problems and they themselves generate power quality problems due to the use of solid-state controllers in them.

Because of these problems, power quality has become an important area of study in electrical engineering, especially in electric distribution and utilization systems. It has created a great challenge to both the electric utilities and the manufacturers. Utilities must supply consumers with good quality power for operating their equipment satisfactorily, and manufacturers must develop their electric equipment either to be immune to such disturbances or to override them. A number of techniques have evolved for the mitigation of these problems either in existing systems or in equipment to be developed in the near future. It has resulted in a new direction of research and development (R&D) activities for the design and development engineers working in the fields of power electronics, power systems, electric drives, digital signal processing, and sensors. It has changed the scenario of power electronics as most of the equipment using power converters at the front end need modifications in view of these newly visualized requirements. Moreover, some of the well-developed converters are becoming obsolete and better substitutes are required. It has created the need for evolving a large number of circuit configurations of front-end converters for very specific and particular applications. Apart from these issues, a number of standards and benchmarks are developed by various organizations such as IEEE (Institute of Electrical and Electronics Engineers) and IEC (International Electro technical Commission), which are enforced on the customers, utilities, and manufacturers to minimize or to eliminate the power quality problems.

The techniques employed for power quality improvements in exiting systems facing power quality problems are classified in a different manner from those used in newly designed and developed equipment. These mitigation techniques are further sub classified for the electrical loads and supply systems, since both of them have somewhat different kinds of power quality problems. In existing nonlinear loads, having the power quality problems of poor power factor, harmonic currents, unbalanced currents, and an excessive neutral current, a series of power filters of various types such as passive, active, and hybrid in shunt, series, or a combination of both configurations are used externally depending upon the nature of loads such as voltage-fed loads, current-fed loads, or a combination of both to mitigate these problems. However, in many situations, the power quality problems may be other than those of harmonics such as in distribution systems, and the custom power devices such as distribution static compensators (DSTATCOMs), dynamic voltage restorers (DVRs) and unified power quality conditioners (UPQCs) are used for mitigating the current, voltage or both types of power quality problems. Power quality improvement techniques used in newly designed and developed systems are based on the modification of the input stage of these systems with power factor corrected (PFC) converters, also known as improved power quality AC–DC converters (IPQCs), multi pulse AC–DC converters, matrix converters for AC–DC or AC–AC conversion, and so on, which inherently mitigate some of the power quality problems in them and in the supply system by drawing clean power from the utility.

1.2 State of the Art on Power Quality

The power quality problems have been present since the inception of electric power. There have been several conventional techniques for mitigating the power quality problems and in many cases even the equipment are designed and developed to operate satisfactorily under some of the power quality problems. However, recently the awareness of the customers toward the power quality problems has increased tremendously because of the following reasons:

- The customer’s equipment have become much more sensitive to power quality problems than these have been earlier due to the use of digital control and power electronic converters, which are highly sensitive to the supply and other disturbances. Moreover, the industries have also become more conscious for loss of production.
- The increased use of solid-state controllers in a number of equipment with other benefits such as decreasing the losses, increasing overall efficiency, and reducing the

cost of production has resulted in the increased harmonic levels, distortion, notches, and other power quality problems. It is achieved, of course, with much more sophisticated control and increased sensitivity of the equipment toward power quality problems. Typical examples are ASDs and energy-saving electronic ballasts, which have substantial energy savings and some other benefits; however, they are the sources of waveform distortion and much more sensitive to the number of power quality disturbances.

- The awareness of power quality problems has increased in the customers due to direct and indirect penalties enforced on them, which are caused by interruptions, loss of production, equipment failure, standards, and so on.
- The disturbances to other important appliances such as telecommunication network, TVs, computers, metering, and protection systems have forced the end users to either reduce or eliminate power quality problems or dispense the use of power polluting devices and equipment.
- The deregulation of the power systems has increased the importance of power quality as consumers are using power quality as performance indicators and it has become difficult to maintain good power quality in the world of liberalization and privatization due to heavy competition at the financial level.
- Distributed generation using renewable energy and other local energy sources has increased power quality problems as it needs, in many situations, solid-state conversion and variations in input power add new problems of voltage quality such as in solar PV generation and wind energy conversion systems.
- Similar to other kinds of pollution such as air, the pollution of power networks with power quality problems has become an environmental issue with other consequences in addition to financial issues.
- Several standards and guidelines are developed and enforced on the customers, manufacturers and utilities as the law and discipline of the land.

In view of these issues and other benefits of improving power quality, an increased emphasis has been given on quantifying, monitoring, awareness, impacts, and evolving the mitigation techniques for power quality problems. A substantial growth is observed in developing the customer’s equipment with improved power quality and improving the utilities’ premises. Starting from conventional techniques used for mitigating power quality problems in the utilities, distribution systems, and customers’ equipment, a substantial literature has appeared in research publications, texts, patents, and manufacturers' manuals for the new techniques of mitigating power quality problems. Most of the technical institutions have even introduced courses on the power quality for teaching and training the forthcoming generation of engineers in this field.

A remarkable growth in research and development work on evolving the mitigation techniques for power quality problems has been observed in the past quarter century. A substantial research on power filters of various types such as passive, active, and hybrid in shunt, series, or a combination of both configurations for single-phase two-wire, three-phase three-wire, and three-phase four-wire systems has appeared for mitigating not only the problems of harmonics but also additional problems of reactive power, excessive neutral current, and balancing of the linear and nonlinear loads. Similar evolution has been seen in custom power devices such as DSTATCOMs for power factor correction, voltage regulation, compensation of excessive neutral current, and load balancing; DVRs and series static synchronous compensators (SSSCs) for mitigating voltage quality problems in transient and steady-state conditions; and UPQCs as a combination of DSTATCOM and DVR for mitigating current and voltage quality problems in a number of applications. These mitigation techniques for power quality problems are considered either for retrofit applications in existing equipment or for the utilities' premises. An exponential growth is also made in devising a number of circuit configurations of input front-end converters providing inherent power quality improvements in the equipment from fraction of watts to MW ratings. The use of various AC–DC and AC–AC converters of buck, boost, buck–boost, multilevel, and multipulse types with unidirectional and bidirectional power flow capability in the input stage of these equipment and providing suitable circuits for specific applications have changed the scenario of power quality improvement techniques and the features of these systems.

1.3 Terms and Definitions

a) ***Power Quality:*** It is any deviation of the voltage or current waveform from its normal sinusoidal wave shape.

b) ***Voltage quality:*** Deviations of the voltage from a sinusoidal waveform.

c) ***Current quality:*** Deviations of the current from a sinusoidal waveform.

d) ***Frequency Deviation:*** An increase or decrease in the power frequency.

e) ***Impulsive transient:*** A sudden, non power frequency change in the steady state condition of voltage or current that is unidirectional in polarity.

f) ***Oscillatory transients:*** A sudden, non power frequency change in the steady state condition of voltage or current that is bidirectional in polarity.

g) ***DC Offset:*** The presence of a DC voltage or current in an AC power system.

h) ***Noises:*** An unwanted electric signal in the power system.

i) ***Long duration Variation:*** A variation of the RMS value of the voltage from nominal voltage for a time greater than 1 min.

j) ***Short Duration Variation:*** A variation of the RMS value of the voltage from nominal voltage for a time less than 1 min.

k) ***Sag:*** A decrease in RMS value of voltage or current for durations of 0.5 cycles to 1 min.

l) ***Swell:*** A Temporary increase in RMS value of voltage or current for durations of 0.5 cycles to 1 min.

m) ***Under voltage:*** 10% below the nominal voltage for a period of time greater than 1 min.

n) ***Over voltage:*** 10% above the nominal voltage for a period of time greater than 1 min.

o) ***Voltage fluctuation:*** A cyclical variation of the voltage that results in flicker of lightning.

p) ***Voltage imbalance:*** Three phase voltages differ in amplitude.

q) ***Harmonic:*** It is a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental power frequency.

r) ***Distortion:*** Any deviation from the normal sine wave for an AC quantity.

s) ***Total Harmonic Distortion:*** The ratio of the root mean square of the harmonic content to the RMS value of the fundamental quantity.

$$\mathrm{THD} = \frac{\sqrt{\sum_{h=1}^{h_{max}} M_h^2}}{M_1}$$

t) ***Interruption:*** The complete loss of voltage on one or more phase conductors for a time greater than 1 min.

1.4 Classification of Power Quality Problems

There are a number of power quality problems in the present-day fast-changing electrical systems. These may be classified on the basis of events such as transient and steady state, the quantity such as current, voltage, and frequency, or the load and supply systems.

The transient types of power quality problems include most of the phenomena occurring in transient nature (e.g., impulsive or oscillatory in nature), such as sag (dip), swell, short-duration voltage variations, power frequency variations, and voltage fluctuations. The steady-state types of power quality problems include long-duration voltage variations, waveform distortions, unbalanced voltages, notches, DC offset, flicker, poor power factor, unbalanced load currents, load harmonic currents, and excessive neutral current.

The second classification can be made on the basis of quantity such as voltage, current, and frequency. For the voltage, these include voltage distortions, flicker, notches, noise, sag, swell, unbalance, under voltage, and overvoltage; similarly for the current, these include reactive power component of current, harmonic currents, unbalanced currents, and excessive neutral current.

The third classification of power quality problems is based on the load or the supply system. Normally, power quality problems due to nature of the load (e.g., fluctuating loads such as furnaces) are load current consisting of harmonics, reactive power component of current, unbalanced currents, neutral current, DC offset, and so on. The power quality problems due to the supply system consist of voltage- and frequency related issues such as notches, voltage distortion, unbalance, sag, swell, flicker, and noise. These may also consist of a combination of both voltage- and current-based power quality problems in the system. The frequency-related power quality problems are frequency variation above or below the desired base value. These affect the performance of a number of loads and other equipment such as transformers in the distribution system.

1.5 Causes of Power Quality Problems

There are a number of power quality problems in the present-day fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightening, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The causes related to the loads are nonlinear loads such as saturating transformers and other electrical machines, or loads with solid-state controllers such as vapor lamp-based lighting systems, ASDs, UPSs, arc furnaces, computer power supplies, and TVs. The causes of power quality problems related to system operations are switching of transformers, capacitors, feeders, and heavy loads.

The natural causes result in power quality problems that are generally transient in nature, such as voltage sag (dip), voltage distortion, swell, and impulsive and oscillatory transients. However, the man made causes result in both transient and steady-state types of power quality problems. Table 1.1 lists some of the power quality problems and their causes.

However, one of the important power quality problems is the presence of harmonics, which may be because of several loads that behave in a nonlinear manner, ranging from classical ones such as transformers, electrical machines, and furnaces to new ones such as power converters in vapor lamps, switched-mode power supplies (SMPS), ASDs using AC–DC converters, cycloconverters, AC voltage controllers, HVDC transmission, static VAR compensators, and so on.

1.6 Effects of Power Quality Problems on Users

The power quality problems affect all concerned utilities, customers, and manufacturers directly or indirectly in terms of major financial losses due to interruption of process, equipment damage, production loss, wastage of raw material, loss of important data, and so on. There are many instances and applications such as automated industrial processes, namely, semiconductor manufacturing, pharmaceutical industries, and banking, where even a small voltage dip/sag causes interruption of process for several hours, wastage of raw material, and so on.

Some power quality problems affect the protection systems and result in mal-operation of protective devices. These interrupt many operations and processes in the industries and other establishments. These also affect many types of measuring instruments and metering of the various quantities such as voltage, current, power, and energy. Moreover, these problems affect the monitoring systems in much critical, important, emergency, vital, and costly equipment.

Harmonic currents increase losses in a number of electrical equipment and distribution systems and cause wastage of energy, poor utilization of utilities’ assets such as transformers and feeders, overloading of power capacitors, noise and vibrations in electrical machines, and disturbance and interference to electronics appliances and communication networks.

Table 1.1 Power Quality Problems Causes and Effects

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Peak, Rise Time and Duration	Lightning Strikes, Transformer energization, Capacitor Switching	Power system resonance
	Oscillatory	Peak Magnitude and frequency components	Line, Capacitor or Load Switching	System resonance
Short Duration Voltage Variation	Sag	Magnitude, Duration	Motor Starting, Single line to ground faults	Protection malfunction, Loss of production
	Swell	Magnitude, Duration	Capacitor switching, large load switching, faults	Protection malfunction, stress on computers and home appliances
	Interruption	Duration	Temporary faults	Loss of production, malfunction of fire alarms
Long Duration Voltage Variation	Sustained Interruption	Duration	Faults	Loss of production
	Under Voltage	Magnitude, Duration	Switching on loads, Capacitor de-energization	Increased losses, heating
	Over Voltage	Magnitude, Duration	Switching off loads, Capacitor energization	Damage to household appliances
Voltage Imbalance Waveform Distortion	DC Offset	Symmetrical Components volts, Amperes	Single-phase load, Single-Phasing, Geomagnetic disturbance, Rectification	Heating of motors, Saturation in transformers
	Harmonics	THD, Harmonic Spectrum	ASDs, Nonlinear Loads	Increased losses, poor power factor
	Inter Harmonics	THD, Harmonic Spectrum	ASDs, Nonlinear Loads	Acoustic noise in power equipment
	Notching	THD, Harmonic Spectrum	Power electronic converters	Damage to capacitive components
	Noise	THD, Harmonic	Arc furnaces,	Capacitor

	Spectrum	arc lamps, power converters	overloading, disturbances to appliances
Voltage Flicker	Frequency of Occurrence, Modulation Frequency	Arc furnaces, arc lamps	Human health, irritation, headache, migraine
Voltage Fluctuations	Intermittent	Load Changes	Protection malfunction, light intensity changes
Power Frequency Variations		Faults, disturbances in isolated customer-owned systems and islanding operations	Damage to generator and turbine shafts

1.7 Concepts of Transients

Transient over voltages in electrical transmission and distribution networks result from the unavoidable effects of lightning strike and network switching operations. Response of an electrical network to a sudden change in network conditions.

Oscillation is an effect caused by a transient response of a circuit or system. It is a momentary event preceding the steady state (electronics) during a sudden change of a circuit. An example of transient oscillation can be found in digital (pulse) signals in computer networks. Each pulse produces two transients, an oscillation resulting from the sudden rise in voltage and another oscillation from the sudden drop in voltage. This is generally considered an undesirable effect as it introduces variations in the high and low voltages of a signal, causing instability.

Types of transient:

1. Impulsive transient
2. Oscillatory transient

1.7.1 Impulse Transient

A sudden, non power frequency change in the steady state condition of voltage or current that is unidirectional in polarity as shown in figure 1.1.

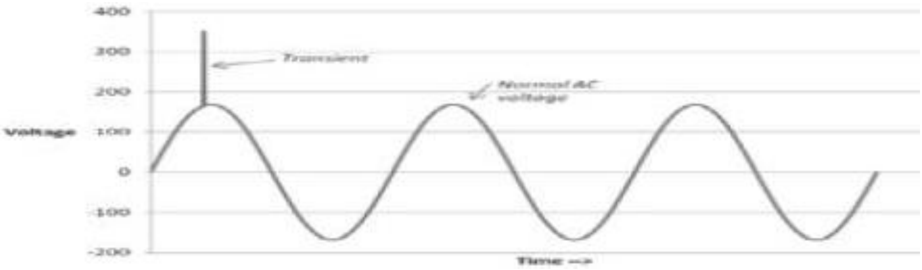


Fig. 1.1 Impulse Transient

1.7.2 Oscillatory Transient

A sudden, non power frequency change in the steady state condition of voltage or current that is bidirectional in polarity as shown in figure 1.2.

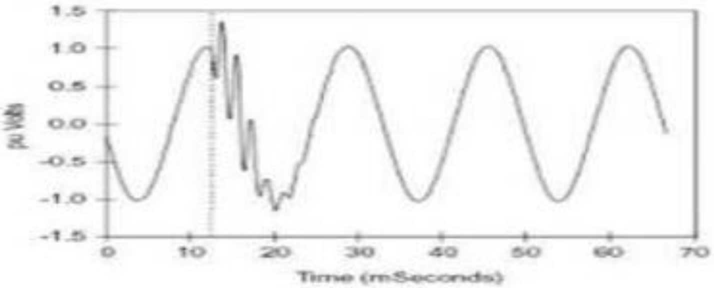


Fig. 1.2 Oscillatory Transient

1.8 Short duration variations – Interruption

The complete loss of voltage on one or more phase conductors for a time less than 1 min as shown in figure 1.3.

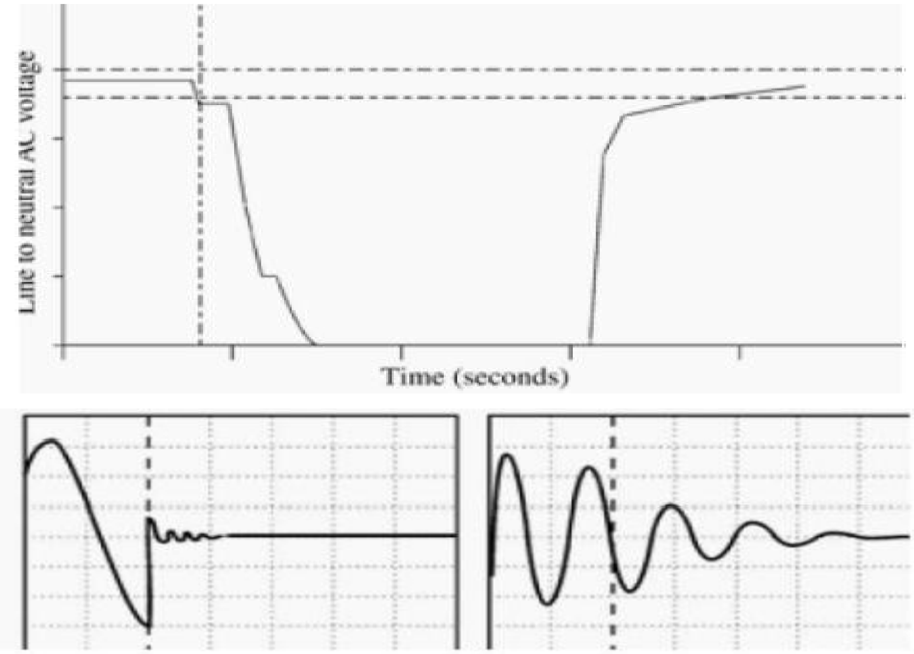


Fig. 1.3 Short Duration Interruption

1.9 Long duration variations – Sustained Interruption

The complete loss of voltage on one or more phase conductors for a time greater than 1 min.

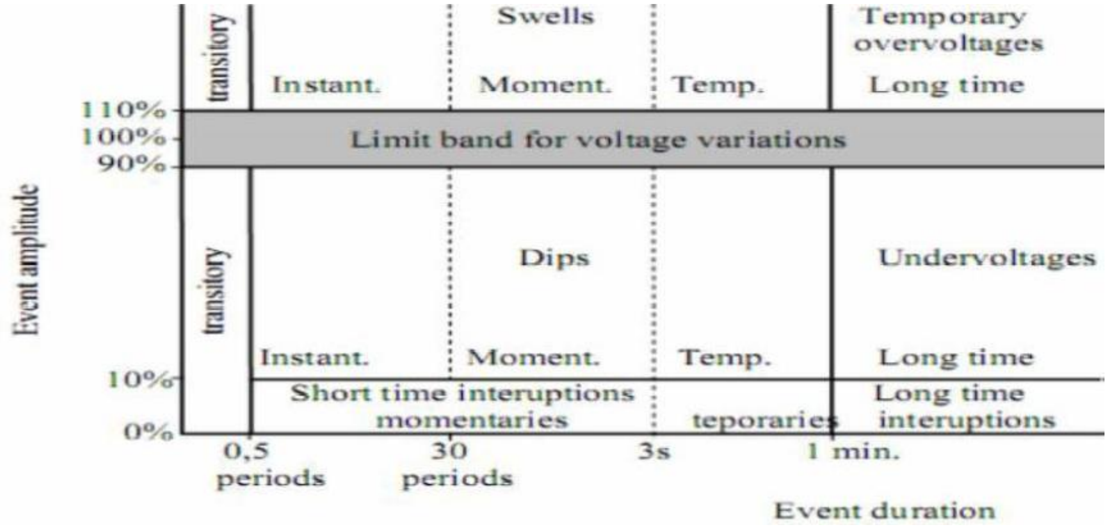


Fig. 1.4 Long Duration Interruption

1.10 Sags and Swells

1.10.1 Voltage Sag

A voltage sag or voltage dip is a short duration reduction in RMS voltage which can be caused by a short circuit, overload or starting of electric motors. Voltage sag happens when the RMS voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute. Some references define the duration of sag for a period of 0.5 cycles to a few seconds, and longer duration of low voltage would be called “sustained sag" as shown in figure 1.5.

There are several factors which cause voltage sag to happen:

- Since the electric motors draw more current when they are starting than when they are running at their rated speed, starting an electric motor can be a reason of voltage sag.
- When a line-to-ground fault occurs, there will be voltage sag until the protective switch gear operates.
- Some accidents in power lines such as lightning or falling an object can be a cause of line-to-ground fault and voltage sag as a result.
- Sudden load changes or excessive loads can cause voltage sag.
- Depending on the transformer connections, transformers energizing could be another reason for happening voltage sags.

- Voltage sags can arrive from the utility but most are caused by in-building equipment. In residential homes, we usually see voltage sags when the refrigerator, air-conditioner or furnace fan starts up.

Fig. 1.5 Voltage Sag

1.10.2 Voltage Swell

Swell - an increase to between 1.1pu and 1.8pu in RMS voltage or current at the power frequency durations from 0.5 to 1 minute. In the case of a voltage swell due to a single line- to-ground (SLG) fault on the system, the result is a temporary voltage rise on the un-faulted phases, which last for the duration of the fault. This is shown in the figure 1.6,

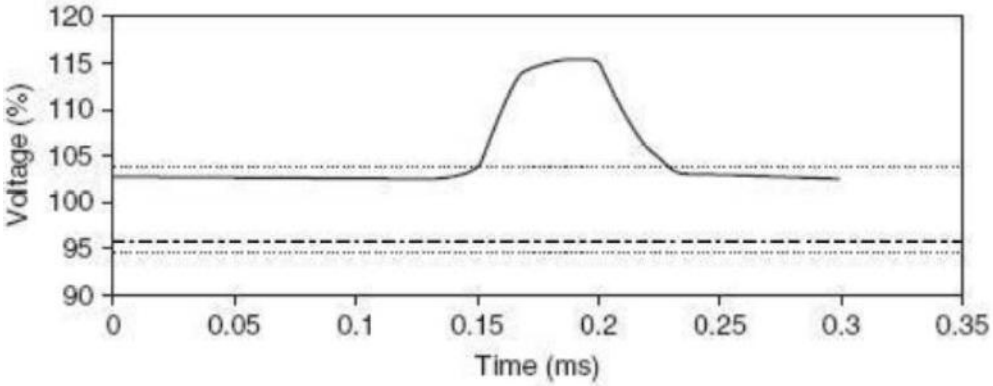


Fig. 1.6 Voltage Swell

Instantaneous Voltage Swell Due to SLG fault

- Voltage swells can also be caused by the deenergization of a very large load.
- It may cause breakdown of components on the power supplies of the equipment, though the effect may be a gradual, accumulative effect. It can cause control problems and hardware failure in the equipment, due to overheating that could eventually result to shutdown. Also, electronics and other sensitive equipment are prone to damage due to voltage swell.

Voltage Swell	Magnitude	Duration
Instantaneous	1.1 to 1.8 PU	0.5 to 30 cycles
Momentary	1.1 to 1.4 PU	30 cycles to 3 sec
Temporary	1.1 to 1.2 PU	3 sec to 1 min

1.10.3 Voltage Imbalance

In a balanced sinusoidal supply system the three line-neutral voltages are equal in magnitude and are phase displaced from each other by 120 degrees as shown in figure 1.7. Any differences that exist in the three voltage magnitudes and/or a shift in the phase separation from 120 degrees is said to give rise to an unbalanced supply as illustrated in Figure 1.8.

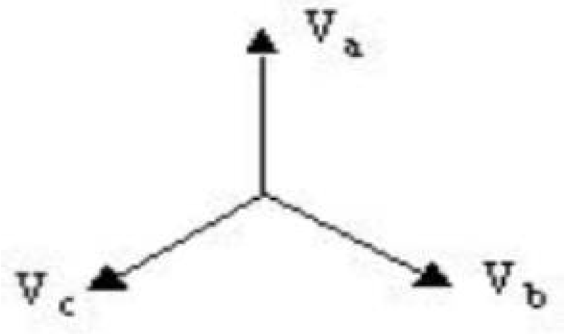


Fig. 1.7 Balanced System

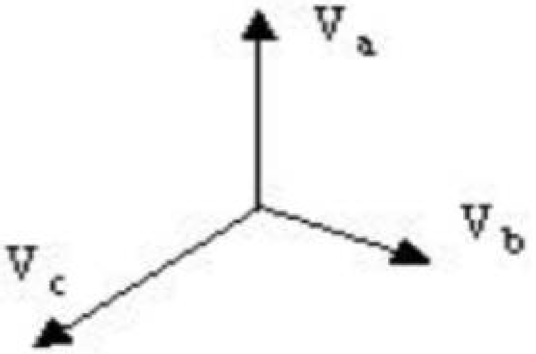
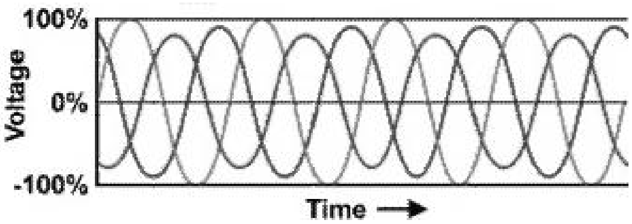


Fig. 1.8 Unbalanced System



The utility can be the source of unbalanced voltages due to malfunctioning equipment, including blown capacitor fuses, open-delta regulators, and open-delta transformers. Open-delta equipment can be more susceptible to voltage unbalance than closed-delta since they only utilize two phases to perform their transformations. Also, voltage unbalance can also be caused by uneven single-phase load distribution among the three phases - the likely culprit for a voltage unbalance of less than 2%. Furthermore, severe cases (greater than 5%) can be attributed to single-phasing in the utility's distribution lateral feeders because of a blown fuse due to fault or overloading on one phase.

1.10.4 Voltage Fluctuation

Voltage fluctuations can be described as repetitive or random variations of the voltage envelope due to sudden changes in the real and reactive power drawn by a load. The characteristics of voltage fluctuations depend on the load type and size and the power system capacity.

Figure 1.9 illustrates an example of a fluctuating voltage waveform. The voltage waveform exhibits variations in magnitude due to the fluctuating nature or intermittent operation of connected loads. The frequency of the voltage envelope is often referred to as the flicker frequency. Thus there are two important parameters to voltage fluctuations, the frequency of fluctuation and the magnitude of fluctuation. Both of these components are significant in the adverse effects of voltage fluctuations.

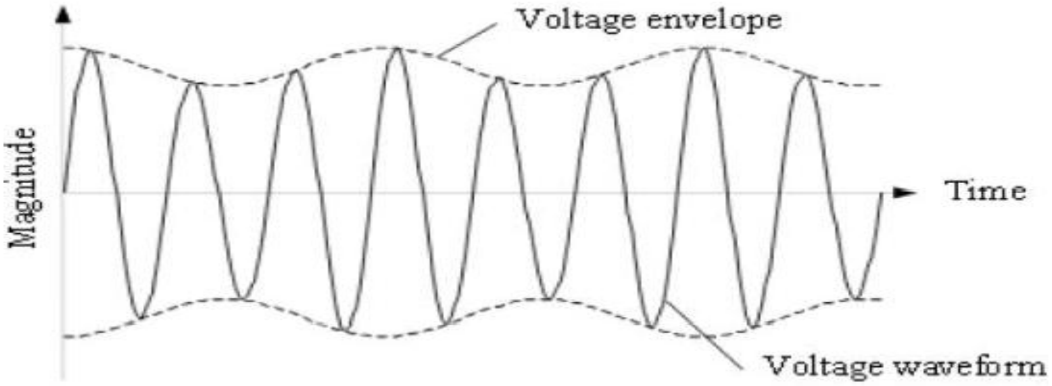


Fig. 1.9 Fluctuating Voltage Waveform

Voltage fluctuations are caused when loads draw currents having significant sudden or periodic variations. The fluctuating current that is drawn from the supply causes additional voltage drops in the power system leading to fluctuations in the supply voltage. Loads that exhibit continuous rapid variations are thus the most likely cause of voltage fluctuations.

- Arc furnaces
- Arc welders

- Installations with frequent motor starts (air conditioner units, fans)
- Motor drives with cyclic operation (mine hoists, rolling mills)
- Equipment with excessive motor speed changes (wood chippers, car shredders)

1.10.5 Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation. There are five primary types of waveform distortion:

- DC offset
- Harmonics
- Inter harmonics
- Notching
- Noise

a) ***DC Offset***: The presence of a dc voltage or current in an ac power system is termed dc offset. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters. Incandescent light bulb life extenders, for example, may consist of diodes that reduce the RMS voltage supplied to the light bulb by half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life. Direct current may also cause the electrolytic erosion of grounding electrodes and other connectors.

b) ***Harmonics:*** Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency usually 50 or 60 Hz). Periodically distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system.

c) ***Inter harmonics:*** Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz) are called inter harmonics. They can appear as discrete frequencies or as a wideband spectrum. The main sources of inter harmonic waveform distortion are static frequency converters, cycloconverters, induction furnaces and arcing devices. Power line carrier signals can also be considered as inter harmonics.

d) ***Noise:*** Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines.

Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Noise problems are often exacerbated by improper grounding that fails to conduct noise away from the power system. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and line conditioners.

1.11 Power Frequency Variations

Power frequency variations are a deviation from the nominal supply frequency. The supply frequency is a function of the rotational speed of the generators used to produce the electrical energy. At any instant, the frequency depends on the balance between the load and the capacity of the available generation as shown in figure 1.10.

A frequency variation occurs if a generator becomes un-synchronous with the power system, causing an inconsistency that is manifested in the form of a variation. The specified frequency variation should be within the limits $\pm 2.5\%$ Hz at all times for grid network.

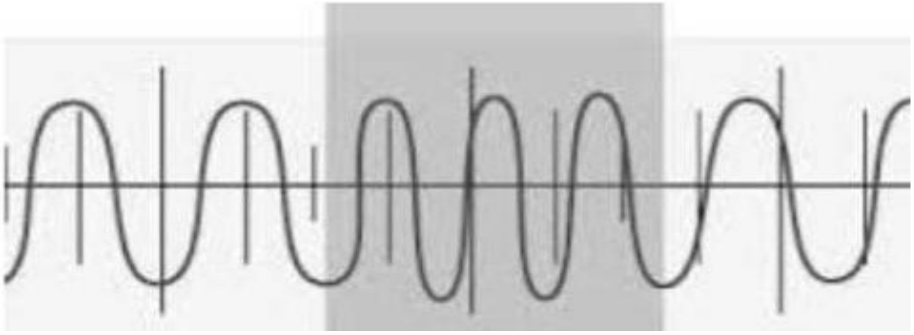


Fig. 1.10 Frequency Variation

1.12 International Standards of Power Quality

a) IEEE Standards

- IEEE power quality standards: Institute Of Electrical and Electronics Engineer.
- IEEE power quality standards: International Electro Technical Commission.

- IEEE power quality standards: Semiconductor Equipment and Material International.
- IEEE power quality standards: The International Union for Electricity Applications
- IEEE Std 519-1992: IEEE Recommended practices and requirements for Harmonic control in Electric power systems.
- IEEE Std 1159-1995: IEEE Recommended practices for monitoring electrical power
- IEEE std 141-1993, IEEE Recommended practice for electric power distribution for industrial plants.
- IEEE std 1159-1995, IEEE recommended practice for Monitoring electrical power quality.

b) IEC Standards

- Definitions and methodology 61000-1-X
- Environment 61000-2-X
- Limits 61000-3-X
- Tests and measurements 61000-4-X
- Installation and mitigation 61000-5-X
- Generic immunity and emissions 61000-6-X

1.13 CBEMA and ITI Curves

One of the most frequently employed displays of data to represent the power quality is the so-called CBEMA curve. A portion of the curve adapted from IEEE Standard 4469 that we typically use in our analysis of power quality monitoring results is shown in figure 1.11.

This curve was originally developed by CBEMA to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system. While many modern computers have greater tolerance than this, the curve has become a standard design target for sensitive equipment to be applied on the power system and a common format for reporting power quality variation data.

The axes represent magnitude and duration of the event. Points below the envelope are presumed to cause the load to drop out due to lack of energy. Points above the envelope are presumed to cause other malfunctions such as insulation failure, overvoltage trip, and over excitation. The upper curve is actually defined down to 0.001 cycle where it has a value of about 375 percent voltage.

We typically employ the curve only from 0.1 cycles and higher due to limitations in power quality monitoring instruments and differences in opinion over defining the magnitude values in the sub cycle time frame. The CBEMA organization has been replaced by ITI, and a modified curve has been developed that specifically applies to common 120-V computer equipment as shown in figure 1.12. The concept is similar to the CBEMA curve. Although developed for 120V computer equipment, the curve has been applied to general power quality evaluation like its predecessor curve.

Both curves are used as a reference in this book to define the withstand capability of various loads and devices for protection from power quality variations. For display of large quantities of power quality monitoring data, we frequently add a third axis to the plot to denote the number of events within a certain predefined cell of magnitude and duration.

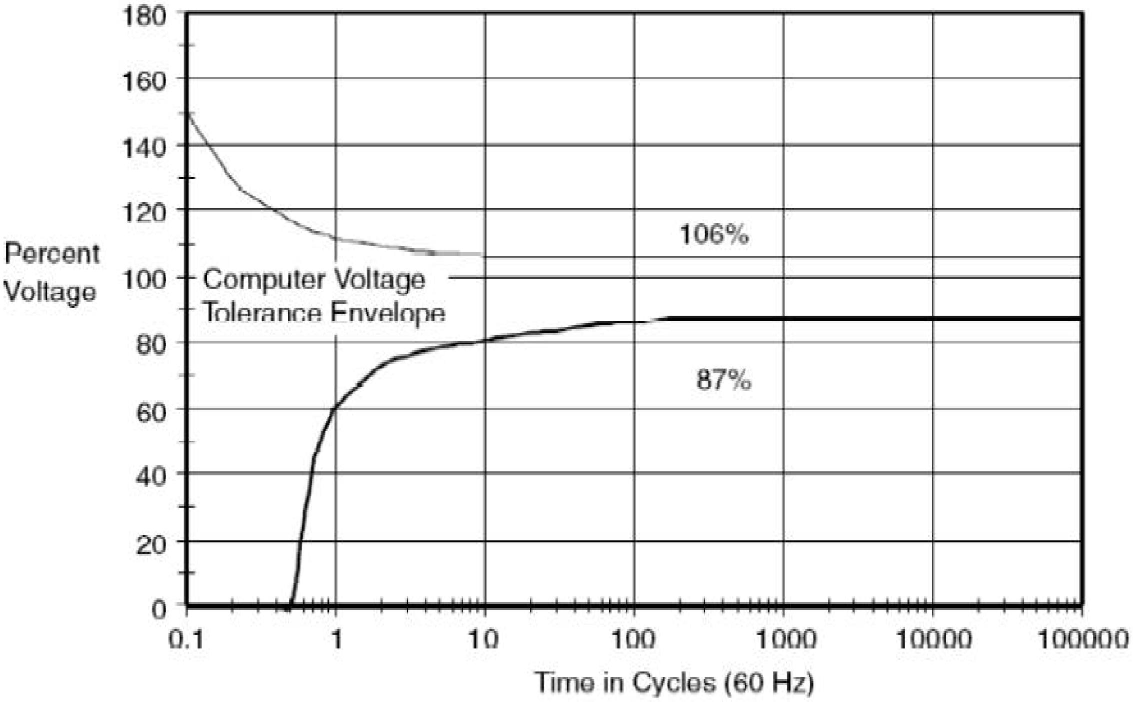


Fig. 1.11 A portion of the CBEMA curve commonly used as a design target for equipment And a format for reporting power quality variation data

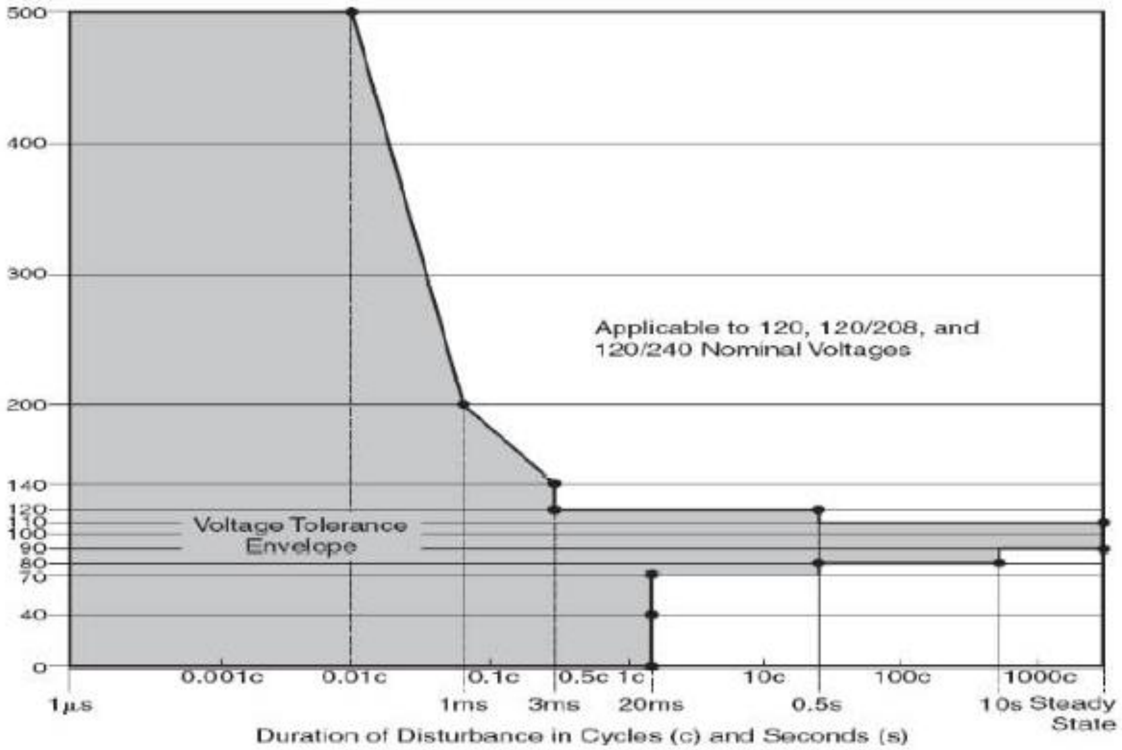


Fig. 1.12 ITI curve for susceptibility of 120-V computer equipment

1.14 Summary

Recently, power quality has become an important subject and area of research because of its increasing awareness and impacts on the consumers, manufacturers, and utilities. There are a number of economic and reliability issues for satisfactory operation of electrical equipment. As power quality problems are increasing manifold due to the use of solid-state controllers, which cannot be dispensed due to many financial benefits, energy conservation, and other production benefits, the research and development in mitigation techniques for power quality problems is also becoming relevant and important to limit the pollution of the supply system. In such a situation, it is quite important to study the causes, effects and mitigation techniques for power quality problems.

1.15 Review Questions

Short Answer Questions

1. What is power quality?
2. What are the power quality problems in AC systems?
3. Why is power quality important?

4. What are the causes of power quality problems?
5. What are the effects of power quality problems?
6. What is a nonlinear load?
7. What is voltage sag (dip)?
8. What is voltage swell?
9. What are the harmonics?
10. What are the inter harmonics?
11. What are the sub harmonics?
12. What is the role of a shunt passive power filter?
13. What is the role of a series passive power filter?
14. What is an active power filter?
15. What is the role of a shunt active power filter?
16. What is the role of a series active power filter?
17. What is the role of a DSTATCOM?
18. What is the role of a DVR?
19. What is the role of a UPQC?
20. What is a PFC?
21. What is an IPQC?
22. Why is the excessive neutral current present in a three-phase four-wire system?
23. How can the excessive neutral current be eliminated?
24. Which are the standards for harmonic current limits?
25. What are the permissible limits on harmonic current?

Essay Questions

1. Define Power quality. Explain the reasons for increased concern in power quality.
2. What are the major power quality issues? Explain in detail.
3. Explain briefly about international standards of power quality.
4. What are various terms used in power quality? Explain them in detail.
5. Distinguish between power quality, voltage stability and current quality.
6. Explain the different terminologies used in power quality.
7. Explain the need for power quality standardization and the causes for PQ deterioration. Hence explain the methods for improving it.

UNIT – II

VOLTAGE SAG AND INTERRUPTION

TOPICS COVERED: **Introduction – Sources of Sags and Interruptions – Estimating Voltage Sag Performance – Area of Vulnerability – Equipment Sensitivity to Voltage Sags – Voltage Sags due to Induction Motor Starting – Estimation of the Sag Severity – Mitigation of Voltage Sags – Motor Generator Set – Active Series Compensators – Static Transfer Switches – Fast Transfer Switches.**

2.1 Introduction

Voltage variations, such as voltage sags and momentary interruptions are two of the most important power quality concerns for customers. Voltage sags is the most common type of power quality disturbance in the distribution system. It can be caused by fault in the electrical network or by the starting of a large induction motor. Voltage sag is a reduction in voltage for a short time. A voltage sag or voltage dip is a short duration reduction in RMS voltage which can be caused by a short circuit, overload or starting of electric motors.

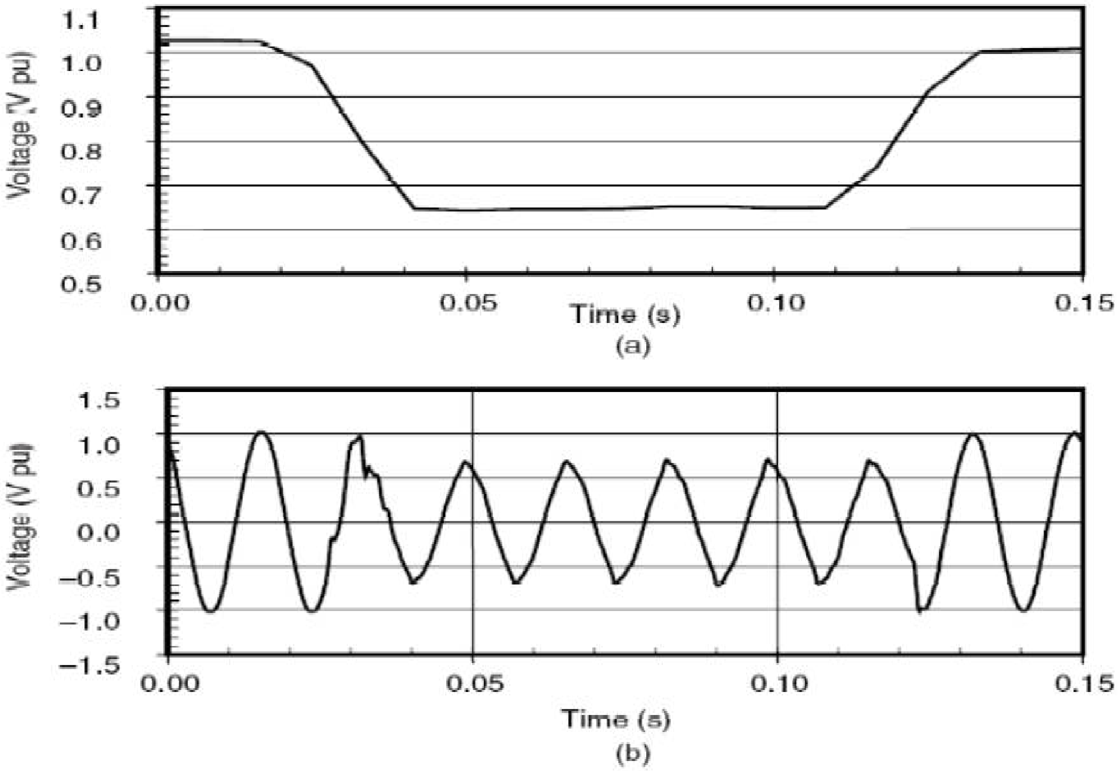


Fig. 2.1 Voltage sag caused by an SLG fault (a) RMS waveform for voltage Sag event. (b) Voltage sag waveform

2.2 Sources of Sags and Interruption

A sudden increase in load results in a corresponding sudden drop in voltage. Any sudden increase in load, if large enough, will cause a voltage sag in,

- Motors
- Faults cause the voltage sag.
- Switching operation

Since the electric motors draw more current when they are starting than when they are running at their rated speed, starting an electric motor can be a reason of voltage sag. When a line-to-ground fault occurs, there will be voltage sag until the protective switch gear operates. Some accidents in power lines such as lightning or falling an object can be a cause of line-to-ground fault and voltage sag as a result.

Sudden load changes or excessive loads can cause voltage sag. Depending on the transformer connections, transformers energizing could be another reason for happening voltage sags. Voltage sags can arrive from the utility but most are caused by in-building equipment. In residential homes, we usually see voltage sags when the refrigerator, air-conditioner or furnace fan starts up.

2.3 Estimating Voltage Sag Performance

It is important to understand the expected voltage sag performance of the supply system so that facilities can be designed and equipment specifications developed to assure the optimum operation of production facilities. The following is a general procedure for working with industrial customers to assure compatibility between the supply system characteristics and the facility operation,

- Determine the number and characteristics of voltage sags that result from transmission system faults.
- Determine the number and characteristics of voltage sags that result from distribution system faults (for facilities that are supplied from distribution systems).
- Determine the equipment sensitivity to voltage sags. This will determine the actual performance of the production process based on voltage sag performance calculated in steps 1 and 2.
- Evaluate the economics of different solutions that could improve the performance, either on the supply system or within the customer facility.

2.3.1 Area of Vulnerability

The concept of an area of vulnerability has been developed to help evaluate the likelihood of sensitive equipment being subjected to voltage lower than its minimum voltage sag ride-through capability. The latter term is defined as the minimum voltage magnitude a piece of equipment can withstand or tolerate without disoperation or failure. This is also known as the equipment voltage sag immunity or susceptibility limit. An area of vulnerability is determined by the total circuit miles of exposure to faults that can cause voltage magnitudes at an end-user facility to drop below the equipment minimum voltage sag ride-through capability. Figure 2.2 shows an example of an area of vulnerability diagram for motor contactor and adjustable-speed-drive loads at an end-user facility served from the distribution system. The loads will be subject to faults on both the transmission system and the distribution system.

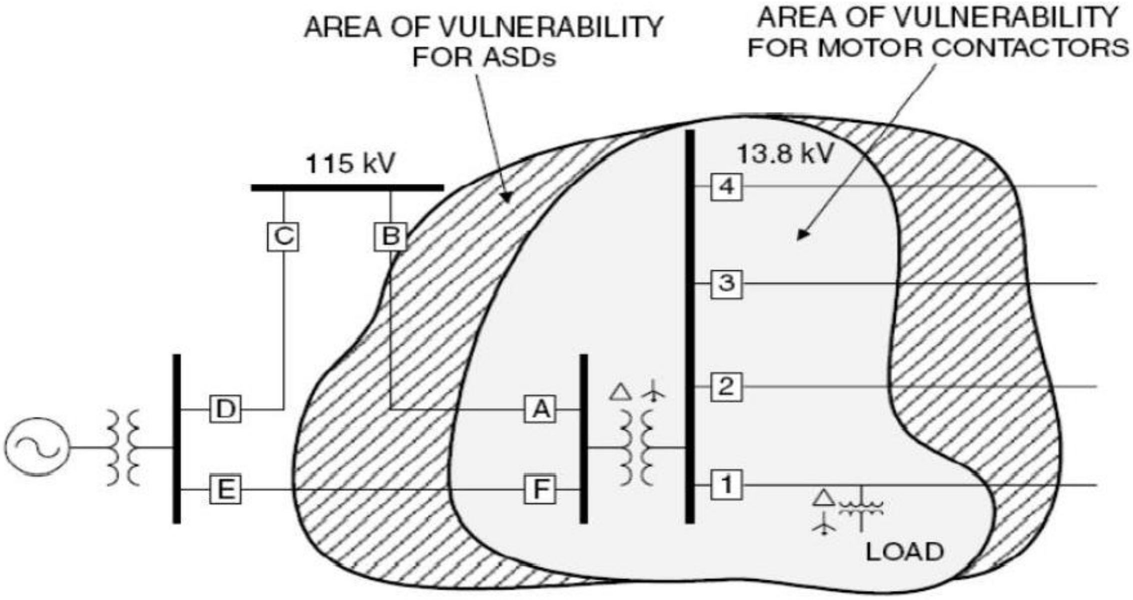


Fig. 2.2 Illustration of an area of vulnerability

2.3.2 Equipment Sensitivity to Voltage Sags

Equipment within an end-user facility may have different sensitivity to voltage sags. Equipment sensitivity to voltage sags is very dependent on the specific load type, control settings, and applications. Consequently, it is often difficult to identify which characteristics of a given voltage sag are most likely to cause equipment to misoperate. The most commonly used characteristics are the duration and magnitude of the sag. Other less commonly used characteristics include phase shift and unbalance, missing voltage, three-phase voltage unbalance during the sag event, and the point-in-the-wave at which the sag initiates and terminates. Generally, equipment sensitivity to voltage sags can be divided into three categories,

a) Equipment sensitive to only the magnitude of voltage sag.
b) Equipment sensitive to both the magnitude and duration of voltage sag.
c) Equipment sensitive to characteristics other than magnitude and duration.

2.3.2.1 Equipment Sensitive to only the Magnitude of Voltage Sag

This group includes devices such as under voltage relays, process controls, motor drive controls, and many types of automated machines (e.g., semiconductor manufacturing equipment). Devices in this group are sensitive to the minimum (or maximum) voltage magnitude experienced during a sag (or swell). The duration of the disturbance is usually of secondary importance for these devices.

2.3.2.2 Equipment Sensitive to both the Magnitude and Duration of Voltage Sag

This group includes virtually all equipment that uses electronic power supplies. Such equipment misoperates or fails when the power supply output voltage drops below specified values. Thus, the important characteristic for this type of equipment is the duration that the RMS voltage is below a specified threshold at which the equipment trips.

2.3.2.3 Equipment Sensitive to characteristics other than Magnitude and Duration

Some devices are affected by other sag characteristics such as the phase unbalance during the sag event, the point-in-the wave at which the sag is initiated, or any transient oscillations occurring during the disturbance. These characteristics are more subtle than magnitude and duration, and their impacts are much more difficult to generalize. As a result, the RMS variation performance indices defined here are focused on the more common magnitude and duration characteristics.

For end users with sensitive processes, the voltage sag ride-through capability is usually the most important characteristic to consider. These loads can generally be impacted by very short duration events, and virtually all voltage sag conditions last at least 4 or 5 cycles (unless the fault is cleared by a current-limiting fuse). Thus, one of the most common methods to quantify equipment susceptibility to voltage sags is using a magnitude-duration plot as shown in figure 2.3. It shows the voltage sag magnitude that will cause equipment to misoperate as a function of the sag duration.

The curve labeled CBEMA represents typical equipment sensitivity characteristics. The curve was developed by the CBEMA and was adopted in IEEE 446. Since the association reorganized in 1994 and was subsequently renamed the Information Technology Industry Council (ITI), the CBEMA curve was also updated and renamed the ITI curve. Typical loads will likely trip off when the voltage is below the CBEMA or ITI curves.

The curve labeled ASD represents an example ASD voltage sag ride through capability for a device that is very sensitive to voltage sags. It trips for sags below 0.9 pu that last for only 4 cycles. The contactor curve represents typical contactor sag ride-through characteristics. It trips for voltage sags below 0.5 pu that last for more than 1 cycle.

The area of vulnerability for motor contactors shown in Fig. 2.5 indicates that faults within this area will cause the end-user voltage to drop below 0.5 pu. Motor contactors having a minimum voltage sag ride-through capability of 0.5 pu would have tripped out when a fault causing a voltage sag with duration of more than 1 cycle occurs within the area of vulnerability. However, faults outside this area will not cause the voltage to drop below 0.5 pu.

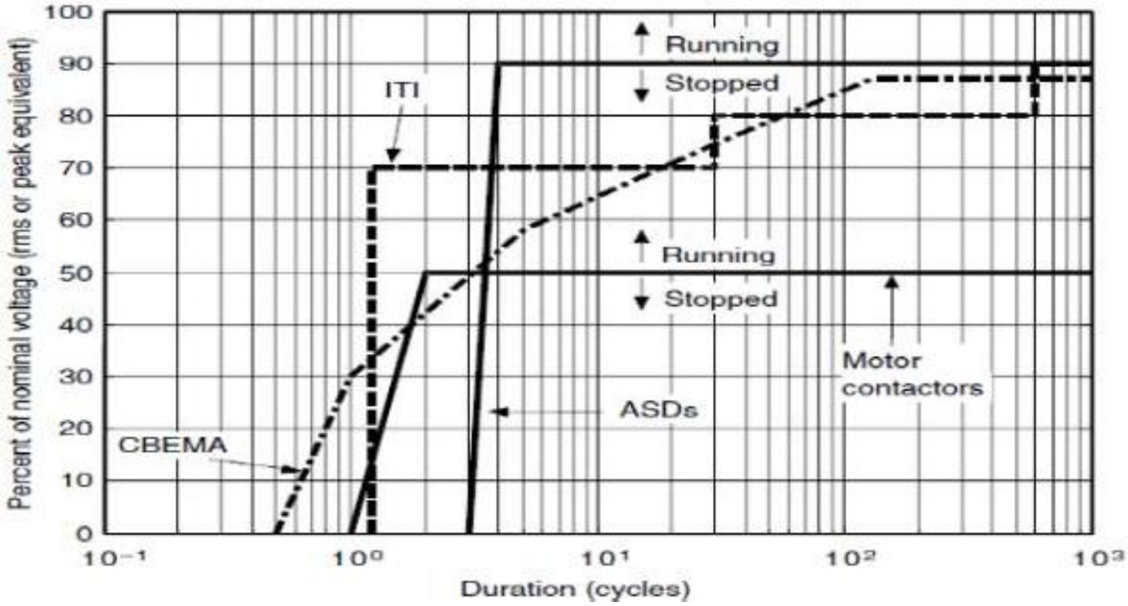


Fig 2.3 Typical equipment voltage sag ride through capability curves

2.3.3 Transmission system sag performance evaluation

The voltage sag performance for a given customer facility will depend on whether the customer is supplied from the transmission system or from the distribution system. For a customer supplied from the transmission system, the voltage sag performance will depend on only the transmission system fault performance. On the other hand, for a customer supplied from the distribution system, the voltage sag performance will depend on the fault performance on both the transmission and distribution systems.

Transmission line faults and the subsequent opening of the protective devices rarely cause an interruption for any customer because of the interconnected nature of most modern-day transmission networks. These faults do, however, causes voltage sags. Depending on the equipment sensitivity, the unit may trip off, resulting in substantial monetary losses.

ASPEN (Advanced System for Power Engineering) programs can calculate the voltage throughout the system resulting from fault around the system. It is also calculate the area of vulnerability in the specific location.

2.3.4 Utility distribution system sag performance evaluation

Customers that are supplied at distribution voltage levels are impacted by faults on both the transmission system and the distribution system. The analysis at the distribution level must also include momentary interruptions caused by the operation of protective devices to clear the faults.

A typical distribution system with multiple feeders and fused branches and protective devices. The utility protection scheme plays an important role in the voltage sag and momentary interruption performance. The critical information needed to compute voltage sag performance can be summarized as follows,

- Number of feeders supplied from the substation.
- Average feeder length.
- Average feeder reactance.
- Short-circuit equivalent reactance at the substation.

They are two possible locations for faults on the distributed system (i.e) On the same feeder and on parallel feeder.

2.4 Voltage Sags due to Induction Motor Starting

Voltage sags can causes:

- Motor load to start/ stop
- Digital devices to reset causing loss of data
- Equipment damage and /or failure
- Materials spoilage

- Lost production due to downtime
- Additional costs
- Product reworks
- Product quality impacts
- Cost of investigations into problem
- Impacts on customer relations such as late delivery.
- Cost of sales

Voltage sags due to Motor Starting:

Voltage sag produced by induction motor starting current is one of the main causes of sensitive equipment dropout. The use of motor starter reduces the voltage sag depth but increases its duration. The subsequent connection to full voltage originates new sag separated from the first one by a few seconds.

An induction motor will draw six to ten times its full load current while starting. This lagging current then causes a voltage drop across the impedance of the system. Generally induction motors are balanced 3 phase loads, voltage sags due to their starting are symmetrical. Each phase draws approximately the same in rush current. The magnitude of voltage sag depends on Characteristics of the induction motor, Strength of the system at the point where motor is connected.

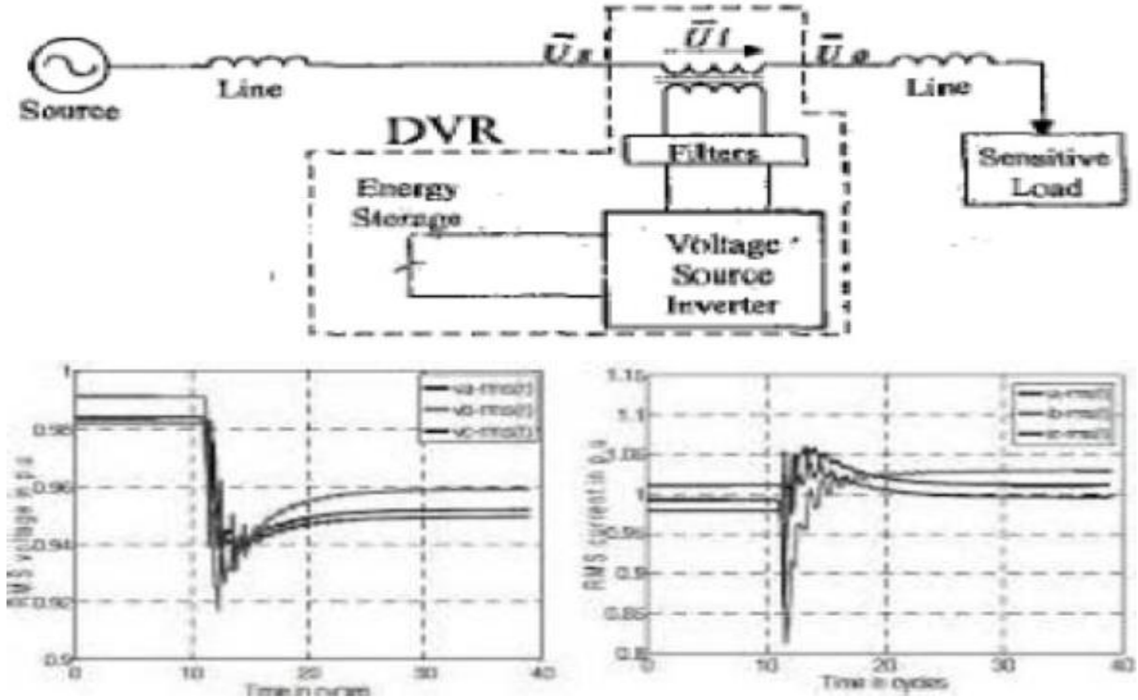


Fig 2.4 Voltage Sag registered at RMS Voltage and RMS Current

2.5 Estimation of the Sag Severity

If full-voltage starting is used, the sag voltage, in per unit of nominal system voltage is,

$$V_{\text{Min (Pu)}} = \frac{V_{(\text{Pu})} . \, kVA_{SC}}{kVA_{LR} + kVA_{SC}}$$

Where $V_{(pu)}$ = actual system voltage in per unit of nominal

kVA_{LR} = motor locked rotor KVA

kVA_{SC} = system short-circuit KVA at motor

If the result is above the minimum allowable steady-state voltage for the affected equipment, then the full-voltage starting is acceptable. If not, then the sag magnitude versus duration characteristic must be compared to the voltage tolerance envelope of the affected equipment. The required calculations are fairly complicated and best left to a motor-starting or general transient analysis computer program. The following data will be required for the simulation as illustrated in figure 2.5.

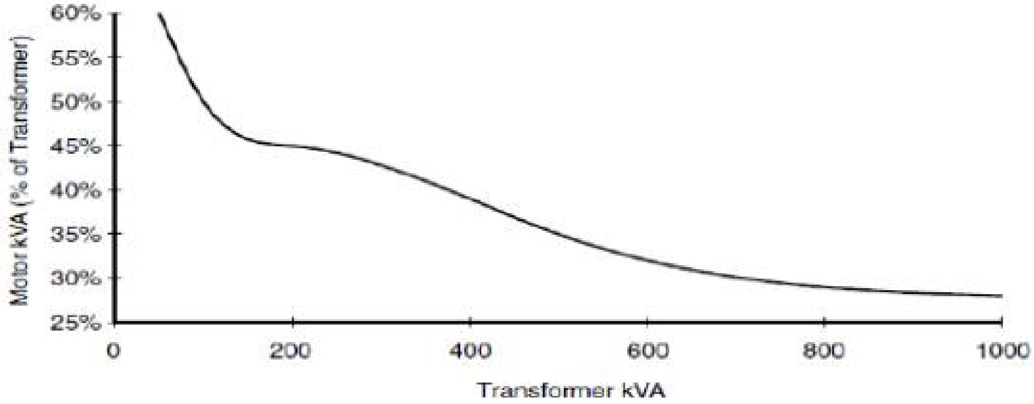


Fig. 2.5 Typical motor versus transformer size for full-voltage starting sags of 90 percent

- Parameter values for the standard induction motor equivalent circuit R_1, X_1, R_2, X_2 and X_M.
- Number of motor poles and rated rpm (or slip).
- WK_2 (inertia constant) values for the motor and the motor load.
- Torque versus speed characteristic for the motor load.

2.6 Mitigation of Voltage Sags

Different power quality problems would require different solution. It would be very costly to decide on mitigate measure that do not or partially solve the problem. These costs include lost productivity, labor costs for clean up and restart, damaged product, reduced product quality, delays in delivery and reduced customer satisfaction.

When a customer or installation suffers from voltage sag, there is a number of mitigation methods are available to solve the problem. These responsibilities are divided into three parts that involves utility, customer and equipment manufacturer.

Different mitigation methods are,

- Dynamic voltage restorer
- Active series Compensators
- Distribution static compensator (DSTATCOM)
- Solid state transfer switch (SSTS)
- Static UPS with energy storage
- Backup storage energy supply (BSES)
- Ferro resonant transformer
- Flywheel and Motor Generator set
- Static VAR Compensator (SVC)

2.7 Motor Generator Set

Motor-generator (M-G) sets come in a wide variety of sizes and configurations. This is a mature technology that is still useful for isolating critical loads from sags and interruptions on the power system. A motor powered by the line drives a generator that powers the load. Flywheels on the same shaft provide greater inertia to increase ride through time.

When the line suffers a disturbance, the inertia of the machines and the flywheels maintains the power supply for several seconds. This arrangement may also be used to separate sensitive loads from other classes of disturbances such as harmonic distortion and switching transients as shown in figure 2.6.

While simple in concept, M-G sets have disadvantages for some types of loads,

1. There are losses associated with the machines, although they are not necessarily larger than those in other technologies described here.
2. Noise and maintenance may be issues with some installations.
3. The frequency and voltage drop during interruptions as the machine slows. This may not work well with some loads.

Another type of M-G set uses a special synchronous generator called a written-pole motor that can produce a constant 60Hz frequency as the machine slows. It is able to supply a constant output by continually changing the polarity of the rotor's field poles.

Thus, each revolution can have a different number of poles than the last one. Constant output is maintained as long as the rotor is spinning at speeds between3150 and 3600 revolutions per minute (RPM). Flywheel inertia allows the generator rotor to keep rotating at speeds above 3150 RPM once power shuts off.

The rotor weight typically generates enough inertia to keep it spinning fast enough to produce 60 HZ for 15 sec under full load. Another means of compensating for the frequency and voltage drop while energy is being extracted is to rectify the output of the generator and feed it back into an inverter. This allows more energy to be extracted, but also introduces losses and cost.

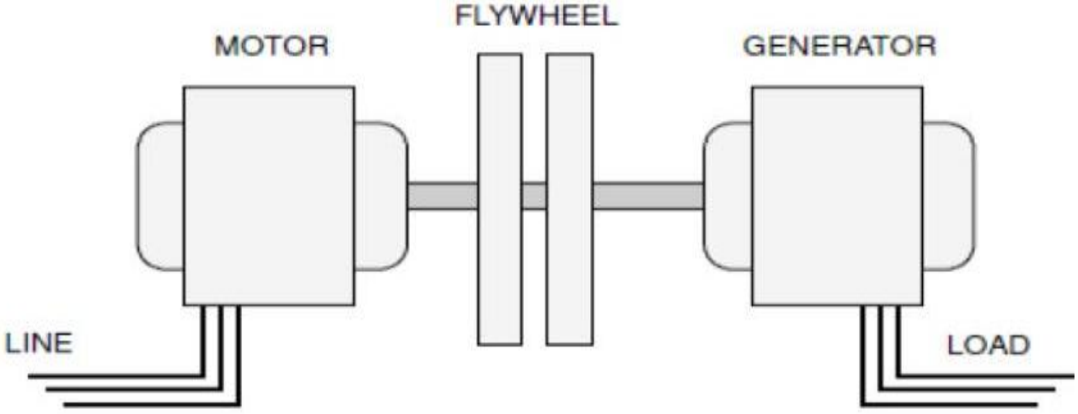


Fig. 2.6 Motor Generator Set

2.8 Active Series Compensators

Advances in power electronic technologies and new topologies for these devices have resulted in new options for providing voltage sag ride through support to critical loads. One of the important new options is a device that can boost the voltage by injecting a voltage in series with the remaining voltage during a voltage sag condition. These are referred to as active series compensation devices. They are available in size ranges from small single-phase devices (1 to 5 KVA) to very large devices that can be applied on the medium-voltage systems (2 MVA and larger).

Figure 2.7 shows an example of a small single-phase compensator that can be used to provide ride-through support for single-phase loads. A one-line diagram illustrating the power electronics that are used to achieve the compensation is shown in Fig. When a disturbance to the input voltage is detected, a fast switch opens and the power is supplied through the series-connected electronics.

This circuit adds or subtracts a voltage signal to the input voltage so that the output voltage remains within a specified tolerance during the disturbance. The switch is very fast so that the disturbance seen by the load is less than a quarter cycle in duration. This is fast enough to avoid problems with almost all sensitive loads. The circuit can provide voltage boosting of about 50 percent, which is sufficient for almost all voltage sag conditions.

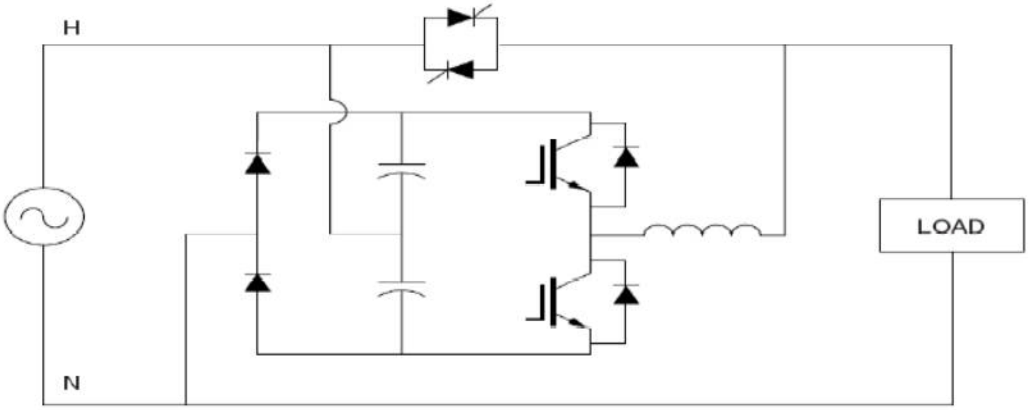


Fig. 2.7 Illustrating the operation of the Active Series Compensator

2.9 Static Transfer Switches

The static transfer switch (STS) is an electrical device that allows instantaneous transfer of power source to the load. If one power source fails the STS to backup power source. A static transfer switch used to switch between a primary supply and a backup supply in the event of a disturbance. The controls would switch back to the primary supply after normal power is restored.

Classification of STS

- Low voltage STS (Vt Up to 600Vt, Ct rating from 200 amps to 4000 amps)
- Medium voltage STS (Vt from 4.61 KV to 34.5 KV)
- Fast acting STS's that can transfer between two power source in four to zero milliseconds are increasingly being applied to protect large loads and entire load facilities from short duration power disturbance.
- These products use solid state power electronics or static switches as compared to electromechanical switches, which are slow for the application.

The basic STS unit consists of three major parts

- Control and Metering

- Silicon controlled rectifier
- Breakers/ Bus assembly

2.10 Fast Transfer Switches

FTS is used to obtain the minimum time of switch between two sources of power. This can be achieved by analyzing the phase shift between sine waves of two power sources. FTS permits to control zero phase shifts between input signals of power sources. These signals are passed through A/D converter and then to PLB form the control signal for solid state relay to secure the moment of zero phase shifts between input signals. It increases the speed of connecting the load to the power sources with optimal parameters.

Performance of Fast Transfer Switches:

- Under normal condition the voltage and frequency of power sources 1 and power sources 2 are inside suitable range of tolerance and load get power from Power Sources 1 through closed Solid State Relay 1.
- Zero Detector 1 and Zero Detector 2 form menders from input sine wave signal. Generate the control signal from PLB the unit of ADC converter input voltage from Power Sources 1, Power Sources 2.
- In PLB, the measured the value with reference minimum and maximum value of input output voltage are compared.
- If any measured value of signal from Power Sources 1 is out of tolerance then should be formed the signal to the switch the load to Power Sources 2.
- The same procedure is used to control the frequency of input signal and phase shift between Power Sources 1 and Power Sources 2.
- If any parameter of signal power source is changed then ADC would form the value of code and this value goes to PLB.
- After comparing the measurement value of input voltage with minimum and maximum accepted values.
- If the signal will be formed to switch off the Solid State Relay 1 means signal to switch on the Solid State Relay 2 will form is according with synchronism and phase shift between signals from Power Sources 1 and Power Sources 2.
- In general any case failure of one commercial source of power, the switch transfers the load to another source in very short time.

- It is also achieve by synchronized phase control of signal from both power sources. It makes possible to choose the power source during the time interval less than 1ms.

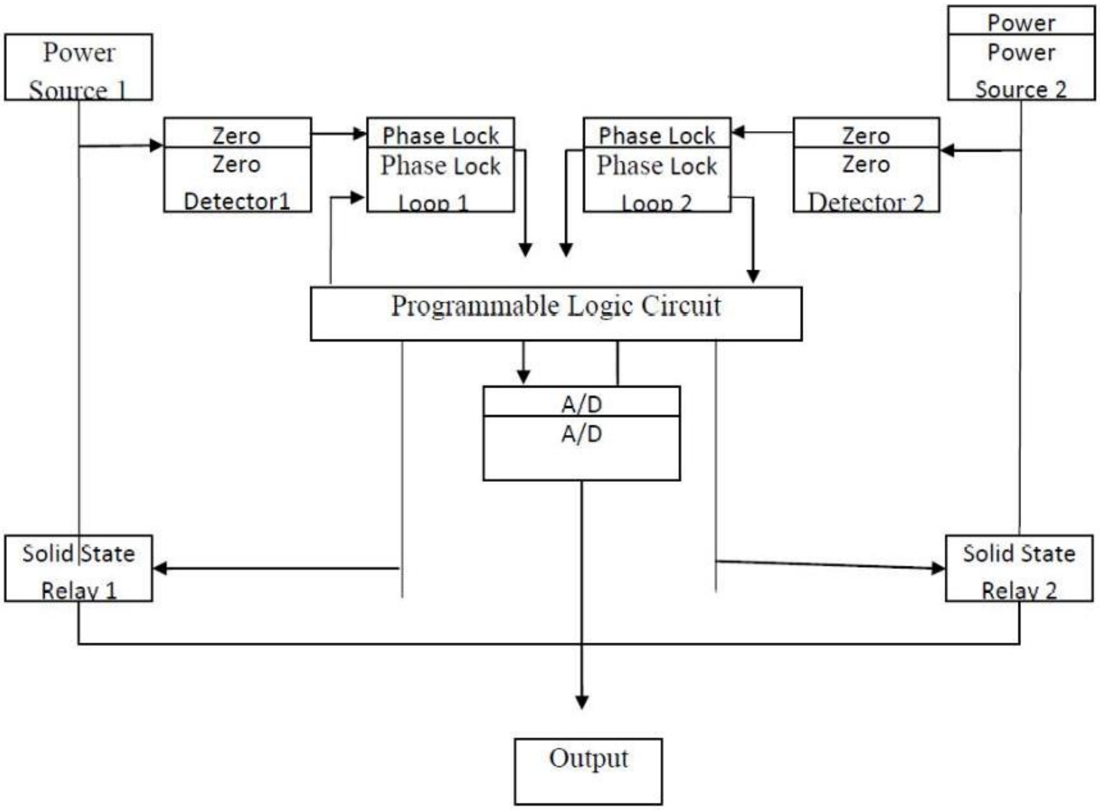


Fig. 2.8 Structure of FTS

2.11 Summary

2.12 Review Questions

Short Answer Questions

1. List the sources of sag and interruptions.
2. Mention the methods to improve voltage sags in utility system.
3. Define the depth of the voltage dip.
4. Define the duration of the voltage dip.
5. Explain the area of vulnerability.
6. What are the factors affecting equipment sensitivity to the voltage sag?
7. What are the three categories of equipment sensitivity?
8. What is the use of estimation of voltage sag?
9. List the devices used to reduce the voltage sag.
10. Mention the types of compensations.

11. What is STS (Static Transfer Switch)?
12. What are the classifications of STS?
13. Define about Fast Transfer Switch (FTS).

Essay Questions

1. Discuss about the sources of sags and interruption.
2. Explain how the voltage sag performance is estimated?
3. Describe the mitigation of voltage sag.
4. Discuss the role of Active Series Compensators in power quality improvement.
5. Write notes on Static transfer switches and Fast transfer switches.
6. Write notes on ferroresonant transformer.
7. Write notes on Magnetic synthesizer.
8. Explain about power quality improvement using motor generators sets.
9. Discuss about motor starting sags.

UNIT – III

OVER VOLTAGES

TOPICS COVERED: Introduction – Classification of Transient Over Voltage – Sources of over voltages – Over Voltage due to Lightning – Over Voltage due to Network Switching – Utility Capacitor Switching – Ferro Resonance – Mitigation of Voltage Swells – Surge arresters – Low Pass Filters – Power Conditioners – Lightning Protection – Shielding and Surge Arrester – Line Arresters – Protection of Transformers – Protection of Cables – Computer Analysis tools for Transient – PSCAD and EMTP.

3.1 Introduction

Transient over voltages in electrical transmission and distribution networks result from the unavoidable effects of lightning strikes and network switching operations. These over voltages have the potential to result in large financial losses each year due to damaged equipment and lost production. They are also known as surges or spikes. Transient over voltages can be classified as,

- Impulsive transient
- Oscillatory transient

A transient is a natural part of the process by which the power system moves from one steady state to another. Its duration is in the range of microseconds to milliseconds. Low frequency transients are caused by network switching. High frequency transients are caused by lightning and by inductive loads turning off. Surge suppressors are devices that conduct across the power line when some voltage threshold is exceeded.

Typically they are used to absorb the energy in high frequency transients. The devices are used for over voltage protection is,

- Surge arrester (crowbar & clamping device)
- Transient over voltage Surge suppresser
- Isolation transformer
- Low pass filter
- Low impedance power conditioners
- Pre-insertion resistors (transmission and distribution)
- Pre-insertion inductors (transmission)

- Synchronous closing (transmission and distribution)

3.2 Classification of Transient over Voltages

Transient over voltages can be classified into two broad categories,

1. Impulsive transient
2. Oscillatory transient

Impulse Transient:

An impulsive transient is a sudden non power frequency change in the steady state condition of the voltage or current waveforms that is essentially in one direction either positive or negative with respect to those waveforms as shown in figure 3.1.

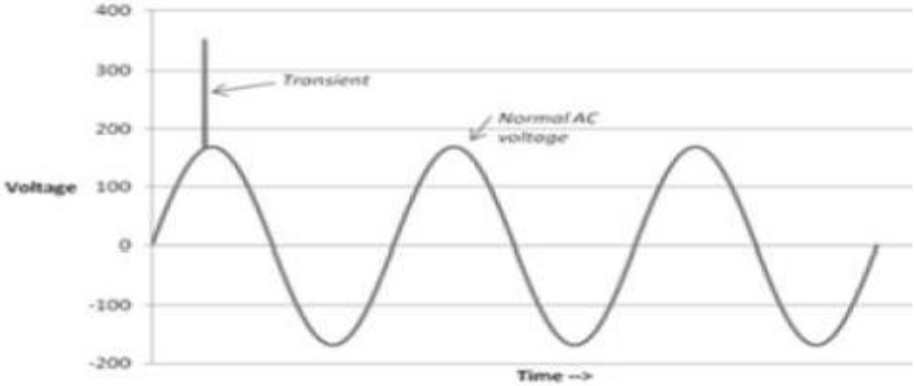


Fig. 3.1 Impulse Transient

Oscillatory Transient:

A sudden, non power frequency change in the steady state condition of voltage or current that is bidirectional in polarity. An oscillatory transient is a sudden non power frequency change in the steady state condition of the voltage or current waveforms that is essentially in both directions positive and negative with respect to those waveforms as shown in figure 3.2.

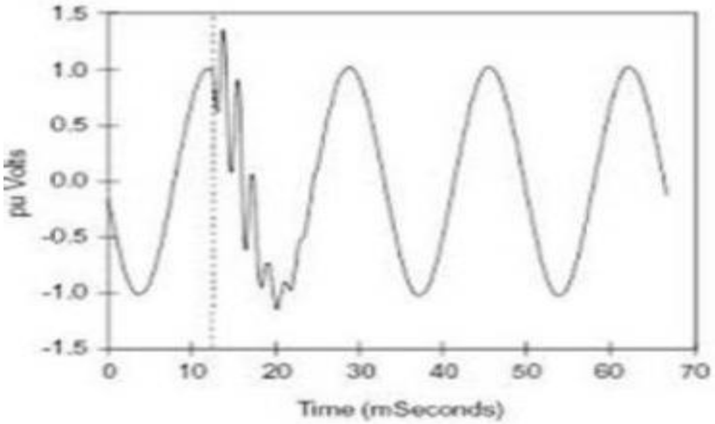


Fig. 3.2 Oscillatory Transient

3.3 Sources of Over Voltages

Some of the causes of transient over voltages on power systems are,

- Lightning – either direct strokes or by induction from nearby strokes.
- Switching surges
- Switching of utility capacitor banks
- Phase to ground arcing
- Resonance and Ferro resonance conditions on long or lightly loaded circuits.

3.3.1 Over Voltage Due to Lightning

Lighting is an electrical discharge in the air between clouds between clouds, between different charge centre within the same cloud, or between cloud and earth. Even through more discharges occur between or within clouds, there are enough strokes that terminate on the earth to cause problems to power systems and sensitive electronic equipment.

3.3.2 Over Voltage Due to Network Switching

Switching operations within the distribution network are a major cause of oscillatory transient over voltages. Such operations include switching of utility capacitor banks, Switching of circuit breakers to clear network faults and Switching of distribution feeders.

3.3.3 Utility Capacitor Switching

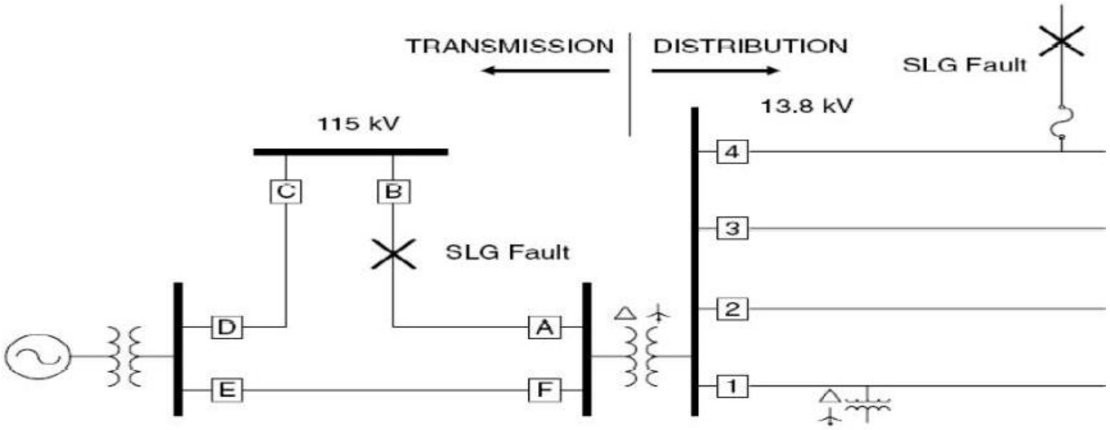


Fig. 3.3 Utility Capacitor Switching

This is one of the most common switching events on utility systems; it is one of the main causes of oscillatory transients. This transient can propagate into the utility’s local power system, pass through its distribution transformer, and enter into the end user’s load facilities. A common symptom that directly relates to utility capacitor switching over voltages is that the resulting oscillatory transients appear at nearly identical times each day. This is because electric utilities, in anticipation of an increase in load, frequently switch their capacitors by time clock as illustrated in figure 3.3.

3.3.4 Ferro Resonance

Ferro resonance is a special case of series LC resonance where the inductance involved is nonlinear and it is usually related to equipment with iron cores. It occurs when line capacitance resonates with the magnetizing reactance of a core while it goes in and out of saturation.

Ferro resonance is a general term applied to a wide variety of interactions between capacitors and iron core inductors that result in unusual voltages and or currents. In linear circuits, resonance occurs when the capacitive reactance equals the inductive reactance at the frequency at which the circuit is driven.

Iron core inductors have non linear characteristics and have a range of inductance values. Therefore, there may not be a case where the inductive reactance is equal to the capacitive reactance, but yet very high and damaging overvoltage occurs. In power system the ferro resonance occurs when a non linear inductor is fed from a series capacitor. The non linear inductor in power system can be due to,

- The magnetic core of a wound type voltage transformer
- Bank type transformer
- The complex structure of a 3 limb three phase transformer.
- The complex structure of a 5 limb three phase power transformer.

The circuit capacitance in power system can be due to a number of elements such as,

- The circuit to circuit capacitance
- Parallel lines capacitance
- Conductor to earth capacitance
- Circuit breaker grading capacitance

3.4 Mitigation of Voltage Swells

Over voltages are extremely transient phenomena occurring for only fractions of a second, but which can never less have a negative effect on electronic equipment and can even result in their total failure. The total losses are due not only to the hardware damage and resultant repair costs, but above all to the major consequential costs due to stoppages in health facilities offices and production plants.

Although damage due to over voltage primarily occurs in industry and large community and office complexes, the losses suffered in the private sector due to damaged video, TV equipment and personal computers have also reached considerable levels. Over voltage protection units such as surge arresters and other protective systems can be installed at low cost in relation to the potential losses, so it makes economic sense to install such equipment.

The basic principles of over voltage protection of load equipments are,

- Limit the voltage across sensitive insulation
- Divert the surge current away from the load
- Block the surge current entering into the load
- Bonding of equipment with ground
- Prevent surge current flowing between grounds
- Design a low pass filter using limiting and blocking principle

3.5 Surge Arresters

A surge arrester is a protective device for limiting surge voltages on equipment by discharging or bypassing surge current. Surge arrester allows only minimal flow of the 50 Hz/60Hz power current to ground. After the high frequency lightning surge current has been discharged. A surge arrester correctly applied will be capable of repeating its protective function until another surge voltage must be discharged.

There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle, providing low resistance path for the surges to the round.

- Rod arrester
- Horn gap arrester
- Multi gap arrester
- Expulsion type lightning arrester
- Valve type lightning arrester

3.5.1 Rod gap arrester:

It is a very simple type of diverter and consists of two 1.5 cm rods, which are bent at right angles with a gap in between as shown in Fig. One rod is connected to the line circuit and the other rod is connected to earth. The distance between gap and insulator (i.e. distance

P) must not be less than one third of the gap length so that the arc may not reach the insulator and damage it.

Generally, the gap length is so adjusted that breakdown should occur at 80% of spark-voltage in order to avoid cascading of very steep wave fronts across the insulators.

The string of insulators for an overhead line on the bushing of transformer has frequently a rod gap across it. Fig 8 shows the rod gap across the bushing of a transformer. Under normal operating conditions, the gap remains non-conducting. On the occurrence of a high voltage surge on the line, the gap sparks over and the surge current is conducted to earth. In this way excess charge on the line due to the surge is harmlessly conducted to earth as shown in figure 3.4.

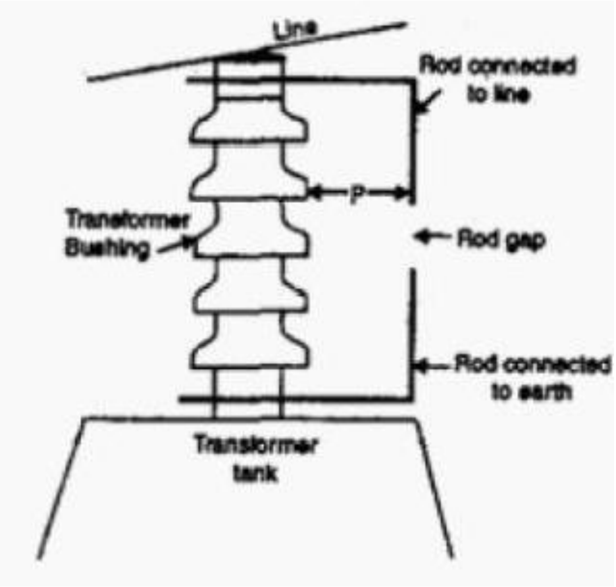


Fig. 3.4 Typical Rod Gap Arrester

3.5.2 Horn gap arrester:

Figure 3.5 shows the horn gap arrester. It consists of a horn shaped metal rods A and B separated by a small air gap. The horns are so constructed that distance between them gradually increases towards the top as shown. The horns are mounted on porcelain insulators. One end of horn is connected to the line through a resistance and choke coil L while the other end is effectively grounded.

The resistance R helps in limiting the follow current to a small value. The choke coil is so designed that it offers small reactance at normal power frequency but a very high reactance at transient frequency. Thus the choke does not allow the transients to enter the apparatus to be protected.

The gap between the horns is so adjusted that normal supply voltage is not enough to cause an arc across the gap.

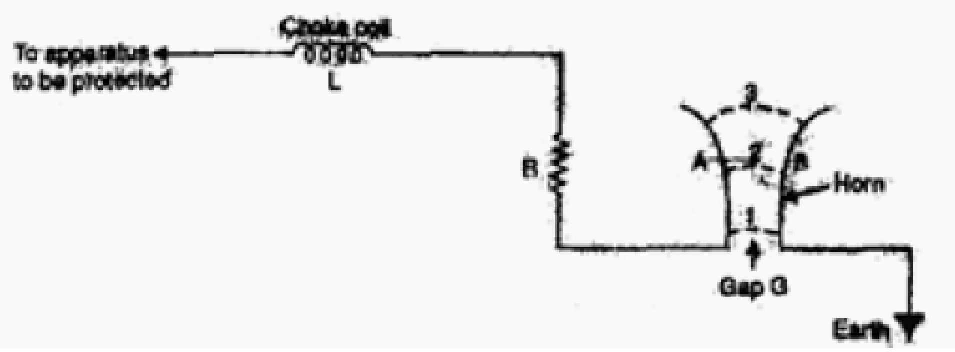


Fig. 3.5 Typical Horn Gap Arrester

Under normal conditions, the gap is non-conducting i.e. normal supply voltage is insufficient to initiate the arc between the gap. On the occurrence of an over voltage, spark-over takes place across the small gap G. The heated air around the arc and the magnetic effect of the arc cause the arc to travel up the gap. The arc moves progressively into positions 1, 2 and 3.

At some position of the arc (position 3), the distance may be too great for the voltage to maintain the arc; consequently, the arc is extinguished. The excess charge on the line is thus conducted through the arrester to the ground.

3.5.3 Multi gap arrester:

Figure 3.6 shows the multi gap arrester. It consists of a series of metallic (generally alloy of zinc) cylinders insulated from one another and separated by small intervals of air gaps. The first cylinder (i.e. A) in the series is connected to the line and the others to the ground through a series resistance. The series resistance limits the power arc. By the inclusion of series resistance, the degree of protection against traveling waves is reduced.

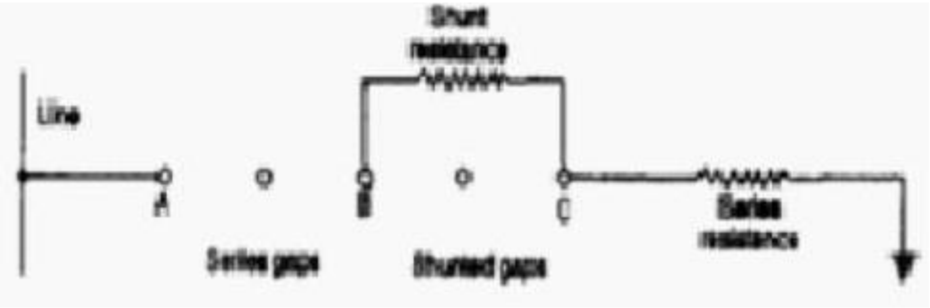


Fig. 3.6 Typical Multi gap Arrester

In order to overcome this difficulty, some of the gaps (B to C in Fig. 3.6) are shunted by resistance. Under normal conditions, the point B is at earth potential and the normal supply voltage is unable to break down the series gaps. On the occurrence an over voltage, the breakdown of series gaps A to B occurs.

The heavy current after breakdown will choose the straight – through path to earth via the shunted gaps B and C, instead of the alternative path through the shunt resistance.

3.5.4 Expulsion type arrester:

This type of arrester is also called ‘protector tube’ and is commonly used on system operating at voltages up to 33kV. Fig shows the essential parts of an expulsion type lightning arrester.

It essentially consists of a rod gap AA’ in series with a second gap enclosed within the fiber tube. The gap in the fiber tube is formed by two electrodes. The upper electrode is connected to rod gap and the lower electrode to the earth. One expulsion arrester is placed under each line conductor. Figure 3.7 shows the installation of expulsion arrester on an overhead line.

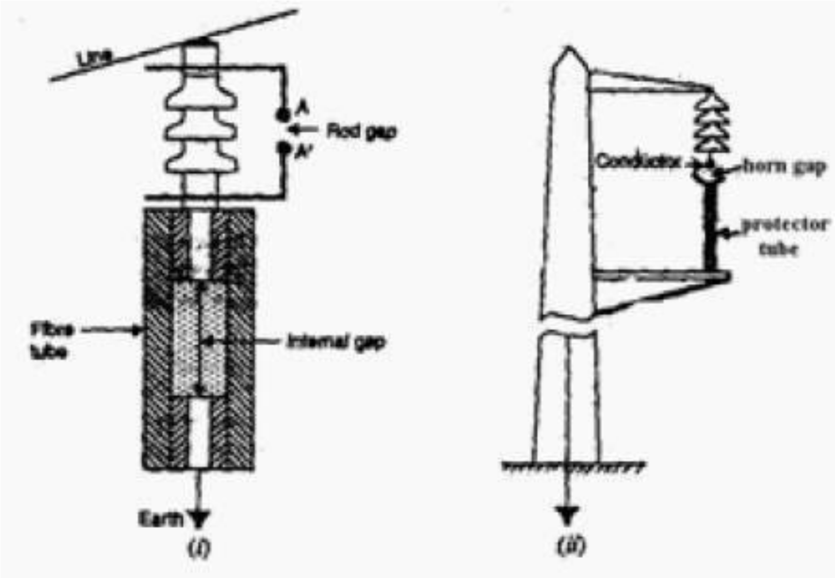


Fig. 3.7 Typical expulsion arrester

On the occurrence of an over voltage on the line, the series gap AA’ spanned and an arc is stuck between the electrodes in the tube. The heat of the arc vaporizes some of the fiber of tube walls resulting in the production of neutral gas. In an extremely short time, the gas builds up high pressure and is expelled through the lower electrode, which is hollow. As the gas leaves the tube violently it carries away ionized air around the arc.

3.5.5 Valve type arrester:

Valve type arresters incorporate non linear resistors and are extensively used on systems, operating at high voltages. Fig shows the various parts of a valve type arrester. It consists of two assemblies (i) series spark gaps and (ii) non-linear resistor discs in series. The non-linear elements are connected in series with the spark gaps. Both the assemblies are accommodated in tight porcelain container.

The spark gap is a multiple assembly consisting of a number of identical spark gaps in series. Each gap consists of two electrodes with fixed gap spacing. The voltage distribution across the gap is line raised by means of additional resistance elements called grading resistors across the gap. The spacing of the series gaps is such that it will withstand the normal circuit voltage. However an over voltage will cause the gap to break down causing the surge current to ground via the non-linear resistors as shown in figure 3.8.

The non-linear resistor discs are made of inorganic compound such as thyrite or metrosil. These discs are connected in series. The non-linear resistors have the property of offering a high resistance to current flow when normal system voltage is applied, but a low resistance to the flow of high surge currents. In other words, the resistance of these non-linear elements decreases with the increase in current through them and vice-versa.

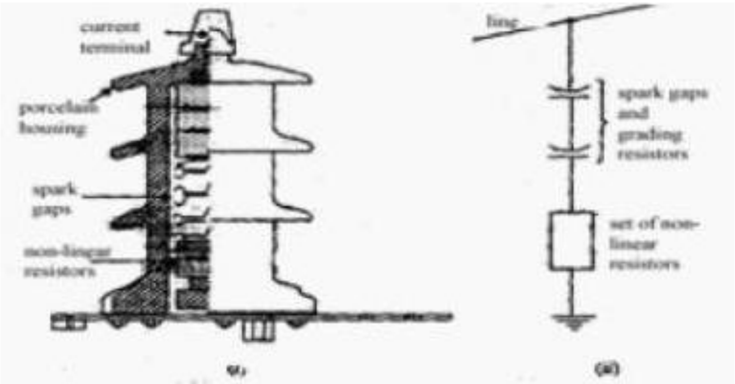


Fig. 3.8 Non-Linear Resistor Discs

Under normal conditions, the normal system voltage is insufficient to cause the breakdown of air gap assembly. On the occurrence of an over voltage, the breakdown of the series spark gap takes place and the surge current is conducted to earth via the non-linear resistors. Since the magnitude of surge current is very large, the non-linear elements will offer a very low resistance to the passage of surge. The result is that the surge will rapidly go to earth instead of being sent back over the line. When the surge is over, the non-linear resistors assume high resistance to stop the flow of current.

3.6 Low Pass Filters

Low pass filters are composed of series inductors and parallel capacitors in general electric circuits. This LC combination provides a low impedance path to ground for selected resonant frequencies. Low pass filters employ CLC to achieve better protection even for high frequency transients. In surge protection usage, voltage clamping devices are added in parallel to the capacitors as illustrated in figure 3.9.

A low-pass filter is a filter that passes signals with a frequency lower than a certain cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. The filter is sometimes called a high-cut filter, or treble cut filter in audio applications. A low-pass filter is the opposite of a high-pass filter. A band-pass filter is a combination of a low-pass and a high-pass filter.

Low-pass filters exist in many different forms, including electronic circuits used in audio, anti-aliasing filters for conditioning signals prior to analog-to-digital conversion, digital filters for smoothing sets of data, acoustic barriers, blurring of images, and so on. The moving average operation used in fields such as finance is a particular kind of low-pass filter, and can be analyzed with the same signal processing techniques as are used for other low-pass filters.

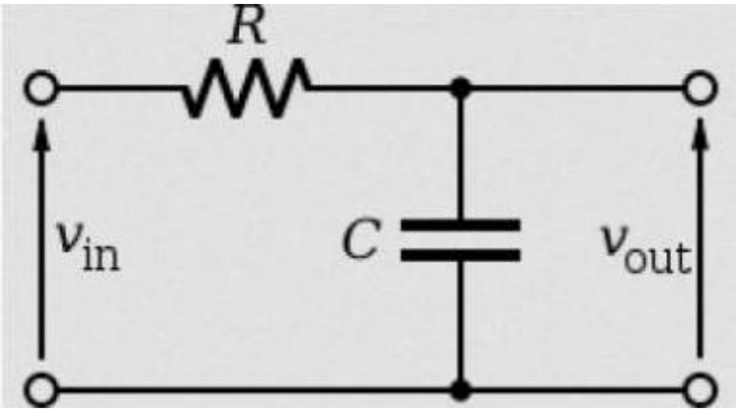


Fig. 3.9 Low Pass Filter

3.7 Power Conditioners

Low impedance power conditioners are used primarily to interface with the switch mode power supplies found in electronic equipment. Low impedance power conditioners differ from isolation transformer in that this conditioner have much lower impedance and have a filter. The filter is on the output side and protects against high frequency noise and impulses. Normally the neutral to ground connection can be made on load side because of the existence of an isolation transformer. However, low to medium frequency transients can cause problems for power conditioners.

3.8 Lightning Protection

Lighting is an electrical discharge in the air between clouds, between different charge centre within the same cloud, or between cloud and earth. Even through more discharges occur between or within clouds, there are enough strokes that terminate on the earth to cause problems to power systems and sensitive electronic equipment as shown in figure 3.10.

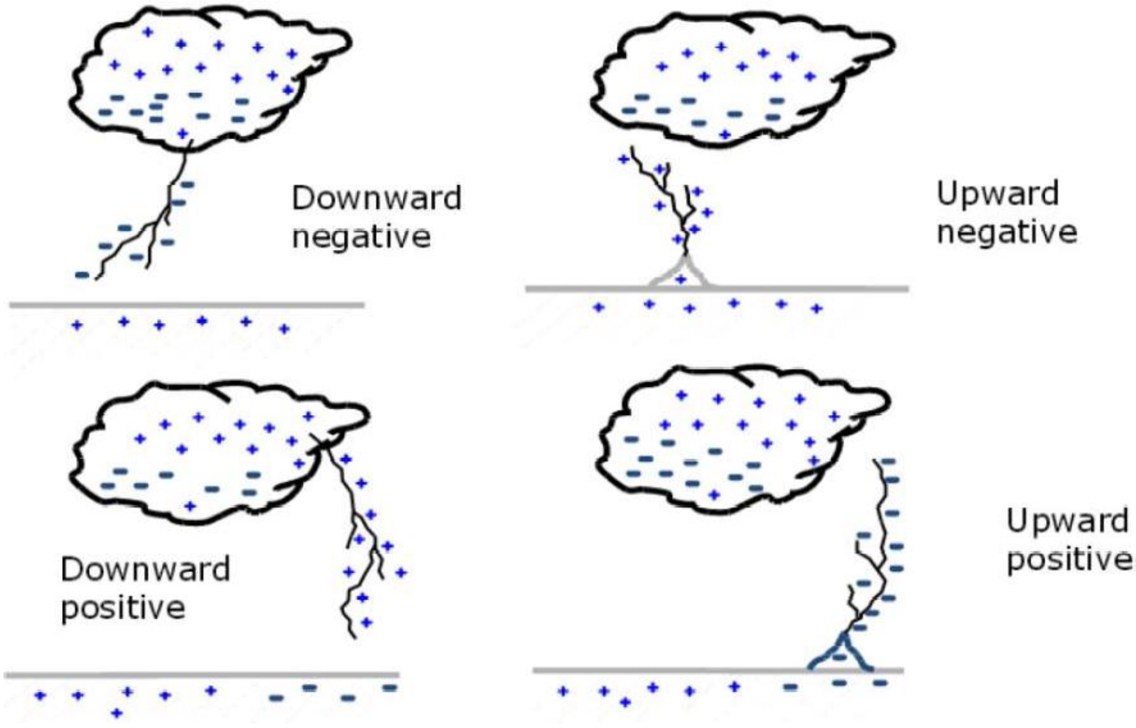


Fig. 3.10 Electrical Discharge

Lightning protection methods are

- Shielding and surge arresters
- Transmission line arresters

3.8.1 Shielding and Surge Arrester

Shield wire and surge arresters play a significant role for protecting overhead distribution lines. The line with shield wire can reduce the number of flashovers in open ground and number of flashovers than shield wire. The application of surge arresters provides better performance than shield wire as shown in figure 3.11.

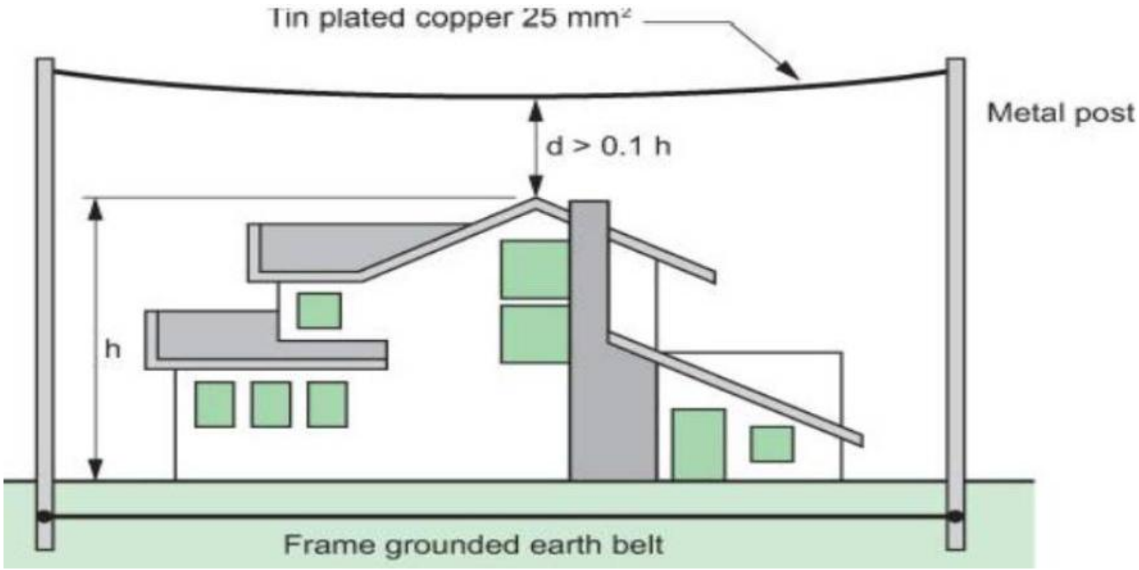


Fig. 3.11 Surge Arrester

Provides both shielding and Surge arresters:

- Minimize the possibility of direct lightning strike to bus and major equipments in the substation and hence the outage and possible failure of major electrical equipment.
- Shielding may allow some smaller strokes to strike the bus work and equipment. Even though these strokes may not cause flash over they may damage internal insulation systems of transformer, etc… unless they have proper surge arresters mounted at their terminals.
- Surge arresters will provide coordinated protection from lightning and switching surges.

3.8.2 Line Arresters

3.9 Protection of Transformers

There are different kinds of transformers such as two winding or three winding electrical power transformers, auto transformer, regulating transformers, earthing transformers, rectifier transformers etc. Different transformers demand different schemes of transformer protection depending upon their importance, winding connections, earthing methods and mode of operation etc.

It is common practice to provide Buchholz relay protection to all 0.5 MVA and above transformers. While for all small size distribution transformers, only high voltage fuses are used as main protective device. For all larger rated and important distribution transformers, over current protection along with restricted earth fault protection is applied. Differential protection should be provided in the transformers rated above 5 MVA.

Nature of Transformer Faults:

A transformer generally suffers from following types of transformer fault,

- Over current due to overloads and external short circuits
- Terminal faults
- Winding faults
- Incipient faults

Generally Differential protection is provided in the electrical power transformer ratedmorethan5MVA. The Differential Protection of Transformer has many advantages over other schemes of protection.

1. The faults occur in the transformer inside the insulating oil can be detected by Buchholz relay. But if any fault occurs in the transformer but not in oil then it cannot be detected by Buchholz relay. Any flash over at the bushings are not adequately covered by Buchholz relay. Differential relays can detect such type of faults. Moreover Buchholz relay is provided in transformer for detecting any internal fault in the transformer but Differential Protection scheme detects the same in faster way.
2. The differential relays normally response to those faults which occur inside the differential protection zone of transformer.

3.9.1 Differential Protection Scheme:

Principle of Differential Protection scheme is one simple conceptual technique. The differential relay actually compares between primary current and secondary current ofpower transformer, if any unbalance found in between primary and secondary currents the relay will actuate and inter trip both the primary and secondary circuit breaker of the transformer.

Suppose you have one transformer which has primary rated current I_p and secondary current I_s. If you install CT of ratio I_p/1A at primary side and similarly, CT of ratio I_s/1A at secondary side of the transformer. The secondary's of these both CTs are connected together in such a manner that secondary currents of both CTs will oppose each other. In other words, the secondary's of both CTs should be connected to same current coil of differential relay in such a opposite manner that there will be no resultant current in that coil in normal working condition of the transformer. But if any major fault occurs inside the transformer due to which the normal ratio of the transformer disturbed then the secondary current of both transformer will not remain the same and one resultant current will flow through the current coil of the differential relay, which will actuate the relay and inter trip both the primary and secondary circuit breakers. To correct phase shift of current because of star - delta connection of transformer winding in case of three phase transformer, the current transformer secondary's should be connected in delta.

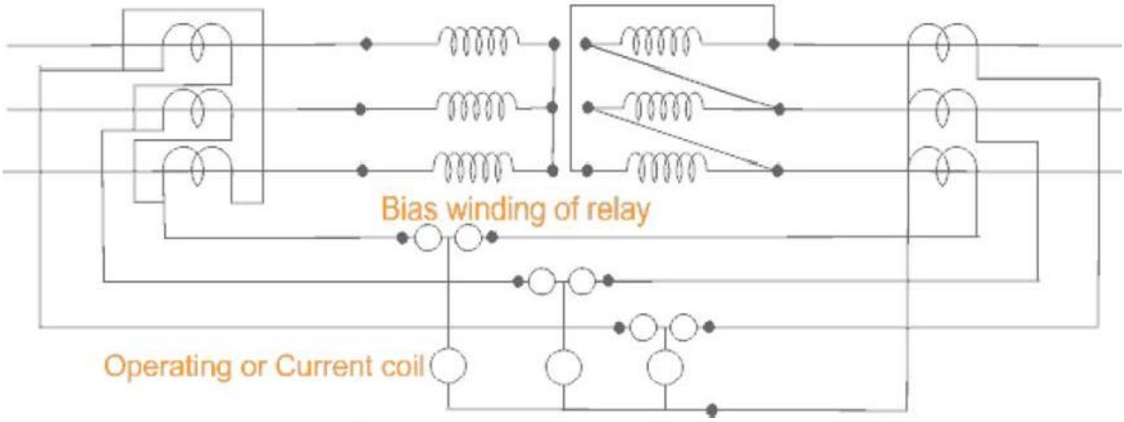


Fig. 3.12 Schematic Diagram of Differential Protection Scheme

3.10 Protection of Cables

A cable is two or more wires running side by side and bonded, twisted, or braided together to form a single assembly. The term originally referred to a nautical line of specific length where multiple ropes, each laid clockwise, are then laid together anti-clockwise and shackled to produce a strong thick line, resistant to water absorption, that was used to anchor large ships.

In mechanics, cables, otherwise known as wire ropes, are used for lifting, hauling, and towing or conveying force through tension. In electrical engineering cables are used to carry electric currents. An optical cable contains one or more optical fibers in a protective jacket that supports the fibers.

In building construction, electrical cable jacket material is a potential source of fuel for fires. To limit the spread of fire along cable jacketing, one may use cable coating materials or one may use cables with jacketing that is inherently fire retardant. The plastic covering on some metal clad cables may be stripped off at installation to reduce the fuel source for fires.

Inorganic coatings and boxes around cables safeguard the adjacent areas from the fire threat associated with unprotected cable jacketing. However, this fire protection also traps heat generated from conductor losses, so the protection must be thin. To provide fire protection to a cable, the insulation is treated with fire retardant materials, or non-combustible mineral insulation is used (MICC cables).

3.11 Computer Analysis tools for Transient – PSCAD and EMTP

The following computational tools are used in general to solve different electrical network problems,

- Digital Computers
- Analog Computers
- Transient electrical network analyzers
- Special purpose simulators such as HVDC simulator

The types of studies usually conducted are as follows,

- Power flow studies
- Dynamic Simulation
- Control System parameter optimization studies
- Harmonic studies
- Switching transient studies

Digital Computers:

Digital computers are the most versatile and can be used to solve all the earlier mentioned problems, although in particular cases and depending on the facilities available, other methods can be more advantages and economical. As very large and fast digital computers are available today, invariably all large problems are solved using digital computers with commercial software packages or locally developed special purpose computer programs.

Analog Computers:

An analog computer is a form of computer that uses the continuously changeable aspects of physical phenomena such as electrical, mechanical, or hydraulic quantities to model the problem being solved. In contrast, digital computers represent varying quantities symbolically, as their numerical values change. As an analog computer does not use discrete values, but rather continuous values, processes cannot be reliably repeated with exact equivalence, as they can with Turing machines. Analog computers do not suffer from the quantization noise inherent in digital computers, but are limited instead by analog noise.

Analog computers were widely used in scientific and industrial applications where digital computers of the time lacked sufficient performance. Analog computers can have a very wide range of complexity. Slide rules and monographs are the simplest, while naval gunfire control computers and large hybrid digital/analog computers were among the most complicated. Systems for process control and protective relays used analog computation to perform control and protective functions.

3.11.1 Power System Computer Aided Design – PSCAD / EMTDC

PSCAD/EMTDC is a general-purpose time domain simulation program for multi-phase power systems and control networks. It is mainly dedicated to the study of transients in power systems. A full library of advanced components allows a user to precisely model interactions between electrical networks and loads in various configurations. A graphical user interface and numerous control tools make PSCAD a convenient and interactive tool for both analysis and design of any power system.

PSCAD seamlessly integrated visual environment features all aspects of conducting a simulation, including circuit assembly, run-time control, analysis and reporting. Users can easily interact with the components during the simulation because of the variety of control tools. The solution meters and the plotting traces are also visible and available during the simulation. Signals can be analyzed in real time.

PSCAD features a broad range of models for power system and power electronic studies such as,

- Frequency dependent transmission lines and cables
- Transformers (classical model with saturation/Umec model)
- Various machines, (synchronous, asynchronous, DC)
- Various turbines (hydro, steam, wind)
- Converters & FACTS
- Drive & control blocks
- Relays

Fast and Accurate:

The time steps interpolation technique combines accuracy and quickness: it allows the simulation to precisely represent the commutations of breakers and switches in the electrical model, for any model's size, up to extremely large models. PSCAD results are solved as instantaneous values, and can be converted to phasor magnitudes and angles via built-in transducers and measurement functions such as true RMS meters or FFT spectrum analyzers. The PSCAD simulation tool can duplicate the response of a power system at any frequency, because the computation step chosen by the user can go from several nanoseconds to several seconds.

Optimization:

PSCAD features multi-run capabilities, enabling a user to run a case multiple times with a set of parameters changed each time in a predetermined manner. This facility makes optimization an easy game as the optimum results (according the criterion the users defines before) are highlighted by the software.

Customization:

Create custom components? PSCAD features the built-in Component Workshop, the tool used to create all the Master Library components. The look of the components and the data forms are all designed graphically. It allows each user to easily create their own component library.

Applications:

- Power lines & cables
- Large non-linear industrial loads
- Transformers with saturation
- Power electronic systems & drives
- FACTS/HVDC systems
- Protection relay coordination
- Arc furnace flicker
- Distributed power generation
- Rotating machines
- Embedded systems

3.11.2 EMTP

EMTP is an acronym for Electro Magnetic Transients Program. It is usually part of a battery of software tools targeting a slice of the spectrum of design and operation problems presented by Electric Power Systems to the Electrical Engineer, that of the so-called "electromagnetic transients" and associated insulation issues.

3.12 Summary

3.13 Review Questions

Short Answer Questions

1. Define transient over voltages.
2. Define voltage magnification phenomena?
3. Give the various aspects of equipment specific design and protection issues for the capacitor switching transients.
4. What are the various Causes of over voltages?
5. What is the need of surge arrestors?
6. What is metal-oxide surge-arrester?
7. What is the role of surge arrestor on shielded and unshielded transmission line?
8. Define lightning phenomena.
9. What is Ferro resonance?
10. Give the cable life equation as a function of impulses.
11. What is the need of Computer analysis tools for transient studies?
12. Give any two analysis examples available in PSCAD/EMTDC?

UNIT – IV

HARMONICS

TOPICS COVERED: Introduction – Harmonics sources from commercial Load – Harmonics sources from Industrial Loads – Locating Harmonic Sources – Power System Response Characteristics – Effects of Harmonics – Harmonic Distortion – Harmonic Distortion Evaluation – Devices for controlling Harmonic Distortion – Devices for controlling Harmonic Distortion – Passive Filters – Active Filters – Passive Power Filters – Shunt Active Power Filters – Series Active Power Filters – Hybrid Power Filters – IEEE and IEC standards.

4.1 Introduction

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

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

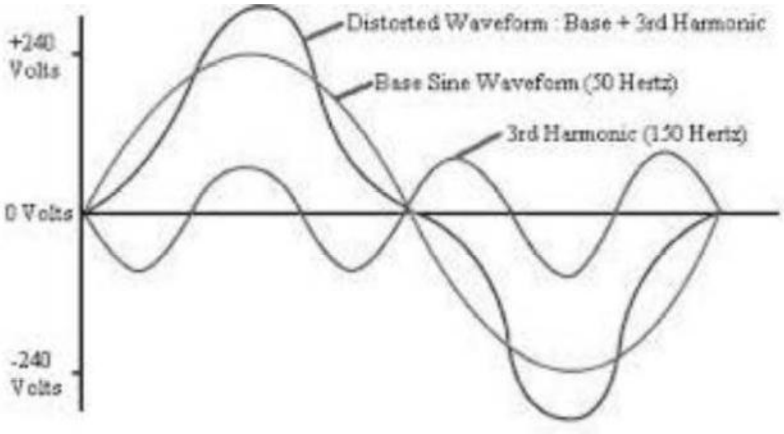


Fig. 4.1 Fundamental Harmonic Frequency

4.2 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.

4.2.1 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.

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 shown in figure 4.2 use dc-to-dc conversion techniques to achieve a smooth dc output with small, lightweight components. The input diode bridge is directly connected to the ac line, eliminating the transformer. This results in a coarsely regulated dc voltage on the capacitor. This direct current is then converted back to alternating current at a very high frequency by the switcher and subsequently rectified again. Personal computers, printers, copiers, and most other single-phase electronic equipment now almost universally employ switch-mode power supplies. The key advantages are the light weight, compact size, efficient operation, and lack of need for a transformer. Switch-mode power supplies can usually tolerate large variations in input voltage.

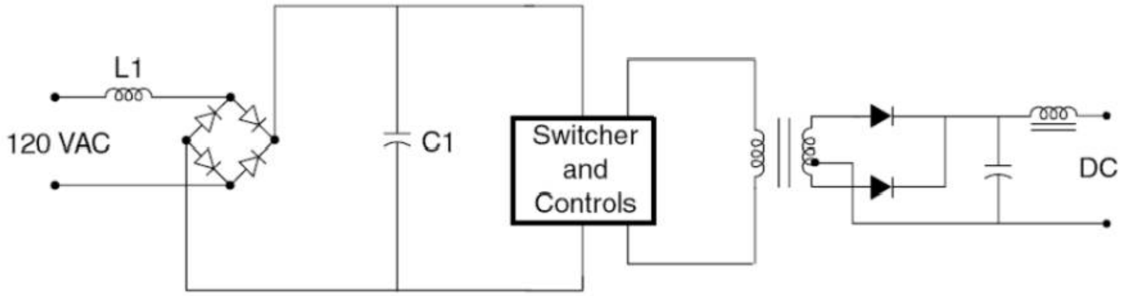


Fig. 4.2 Switch-mode power supply

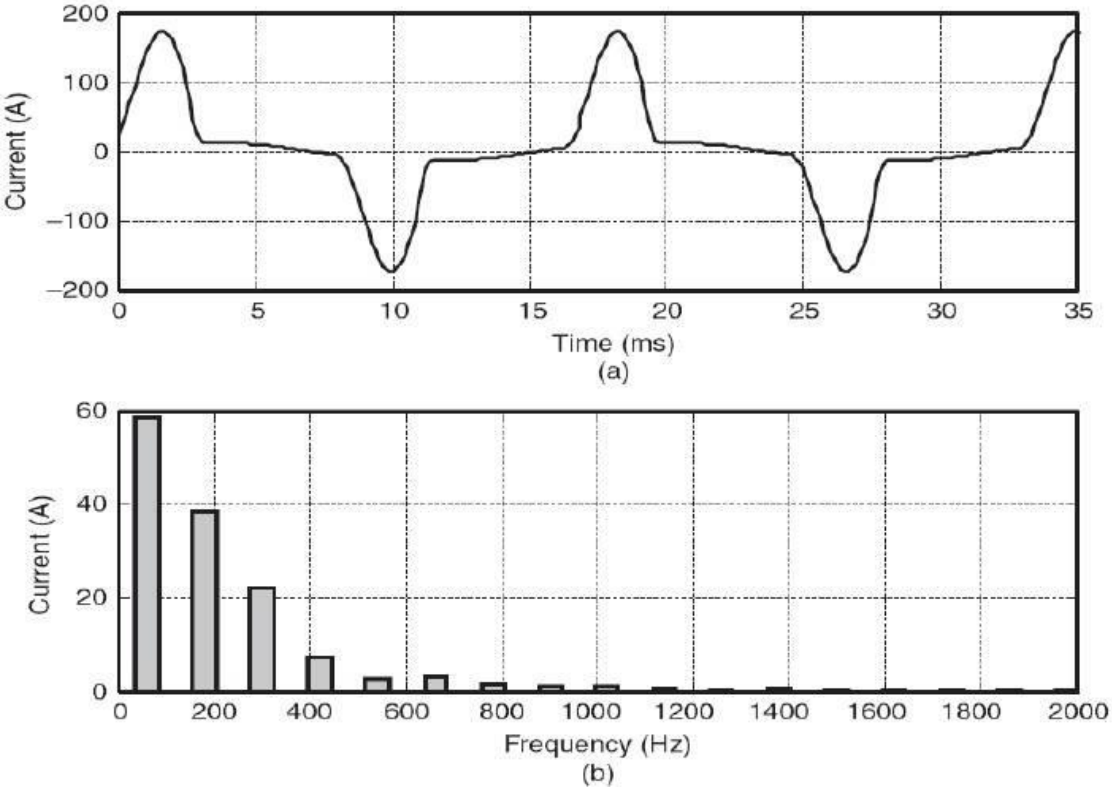


Fig. 4.3 SMPS current and harmonic spectrum

Because there is no large ac-side inductance, the input current to the power supply comes in very short pulses as the capacitor C_1 regains its charge on each half cycle. Figure

4.3 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.

4.2.2 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. 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.

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

Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves since the main harmonic distortion comes from the behavior of the arc. Figure 4.4

shows a measured fluorescent lamp current and harmonic spectrum. The current THD is a moderate 15 percent. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. Figure 4.8 shows a fluorescent lamp with an electronic ballast that has a current THD of 144.

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

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

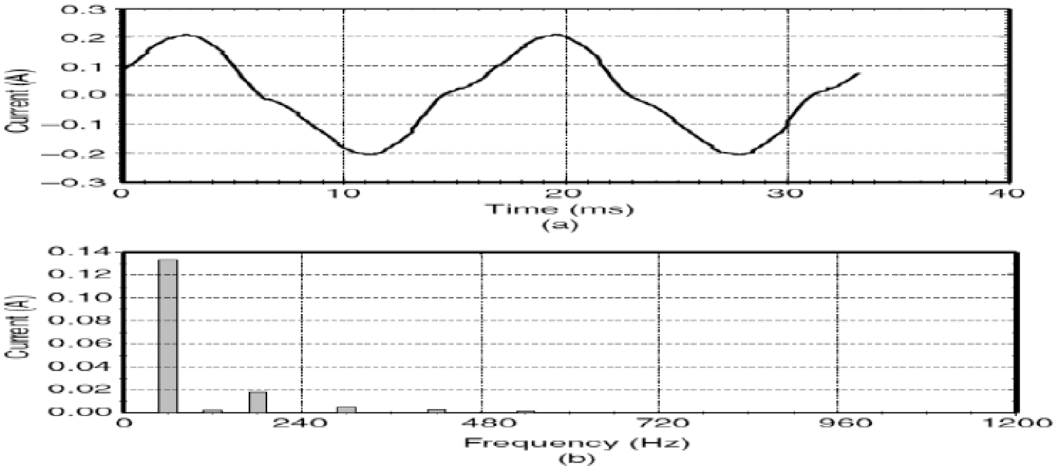


Fig. 4.4 Fluorescent lamp with (a) magnetic ballast current waveform and (b) its harmonic spectrum

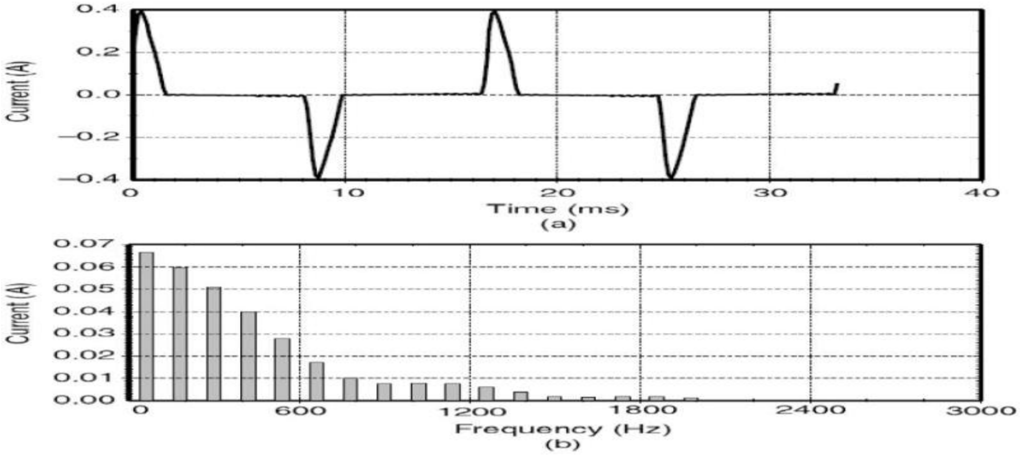


Fig. 4.5 Fluorescent lamp with (a) electronic ballast current waveform and (b) its harmonic spectrum

Since fluorescent lamps are a significant source of harmonics in commercial buildings, they are usually distributed among the phases in a nearly balanced manner. With a delta- connected supply transformer, this reduces the amount of triplen harmonic currents flowing onto the power supply system as shown in figure 4.5.

4.2.3 Adjusting speed drives for HVAC and Elevators

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

4.3 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 misoperation of sensitive electronic equipment. Nonlinear industrial loads can generally be grouped into three categories,

1. Three-phase power converters
2. Arcing devices
3. Saturable devices

4.3.1 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 4.6. This is a typical current source type of adjustable-speed drive. The harmonic spectrum given in figure 4.6 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 4.7.

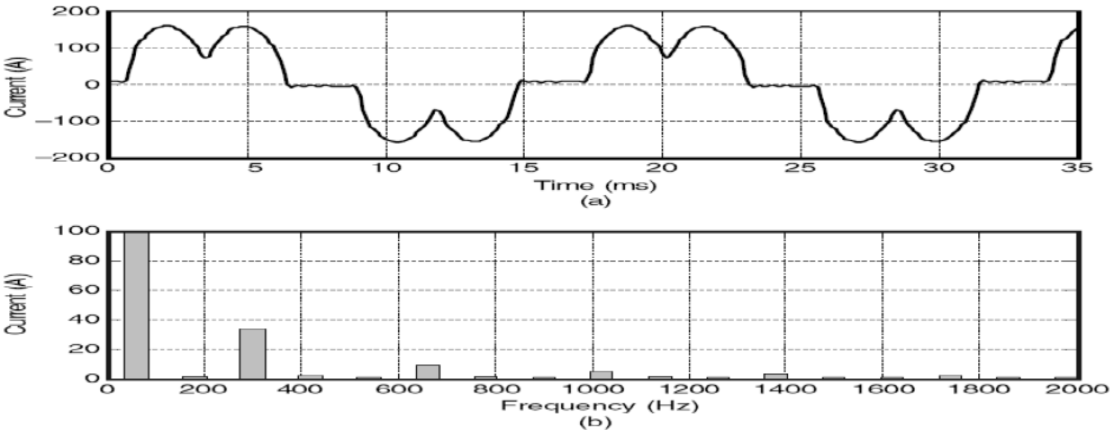


Fig. 4.6 Current and harmonic spectrum for CSI-type ASD

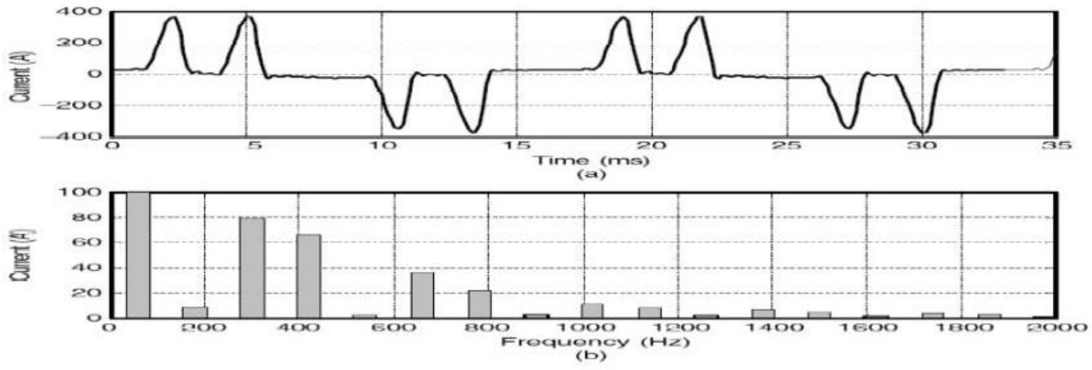


Fig. 4.7 Current and harmonic spectrum for PWM-type ASD

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

4.3.2 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 4.8. 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.

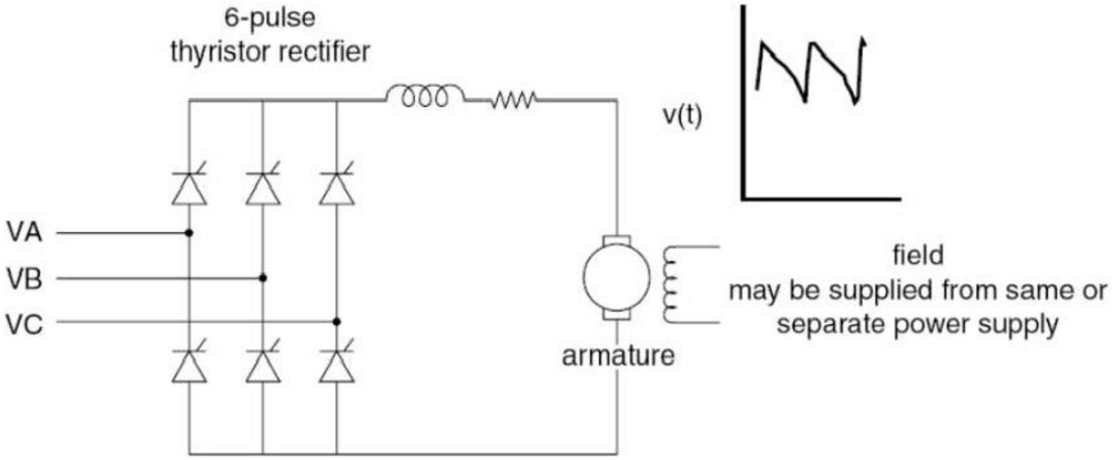


Fig. 4.8 Six-pulse dc ASD

4.3.3 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 as shown in figure 4.9. 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.

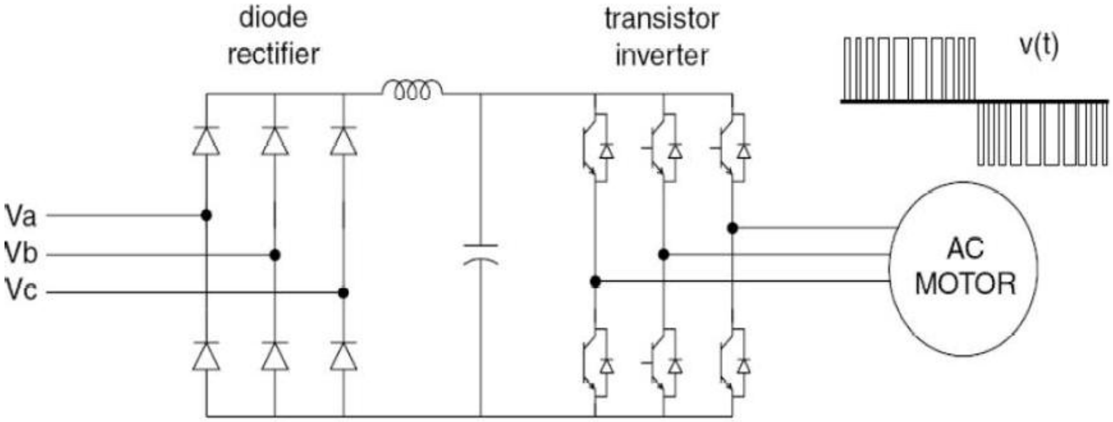


Fig. 4.9 PWM ASD

Very high power drives employ SCRs and inverters. These may be 6- pulse, as shown in figure 4.10, or like large dc drives, 12-pulse. VSI drives as shown in figure 4.10(a) are limited to applications that do not require rapid changes in speed. CSI drives as shown in figure 4.10(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.

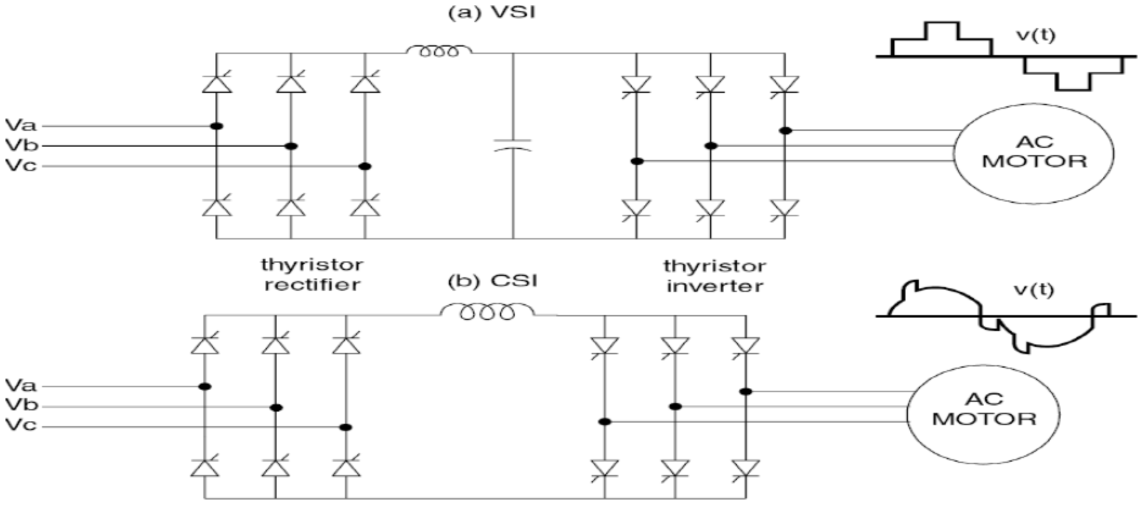


Fig. 4.10 Large ac ASDs

4.3.4 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 4.11 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

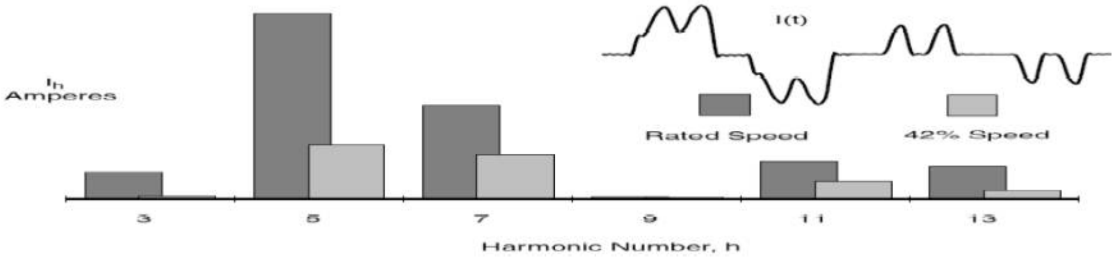


Fig. 4.11 Effect of PWM ASD speed on ac current harmonics

4.3.5 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 4.12, the arc is basically a voltage clamp in series with a reactance that limits current to a reasonable value.

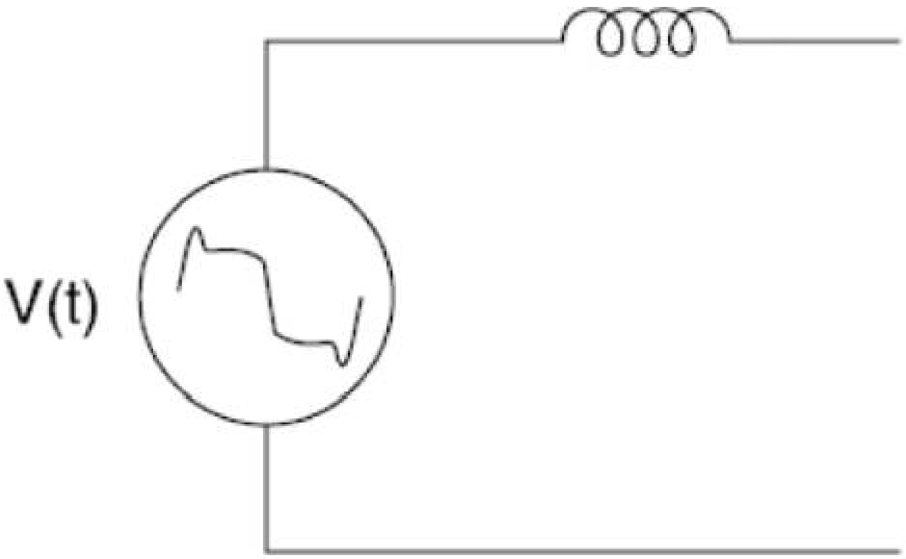


Fig. 4.12 Equivalent circuit for an arcing device

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

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

4.3.6 Saturation 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 as shown in figure 4.13.

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.

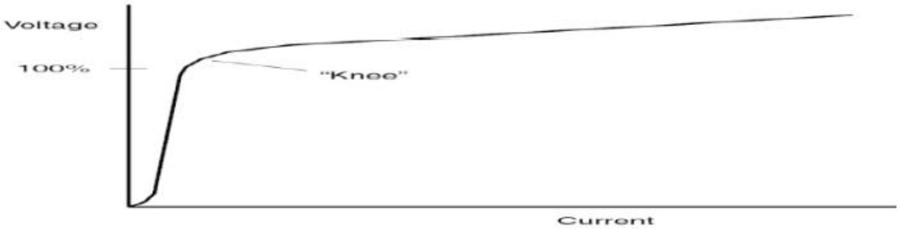


Fig. 4.13 Transformer magnetizing characteristic

Although transformer exciting current is rich in harmonics at normal operating voltage as shown in figure 4.14, it is typically less than 1 percent of rated full load current. Transformers are not as much of a concern as electronic power converters and arcing devices which can produce harmonic currents of 20 percent of their rating, or higher. However, their effect will be noticeable, particularly on utility distribution systems, which have hundreds of transformers. It is common to notice a significant increase in triplen harmonic currents during the early morning hours when the load is low and the voltage rises. Transformer exciting current is more visible then because there is insufficient load to obscure it and the increased voltage causes more current to be produced. Harmonic voltage distortion from transformer over excitation is generally only apparent under these light load conditions.

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

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

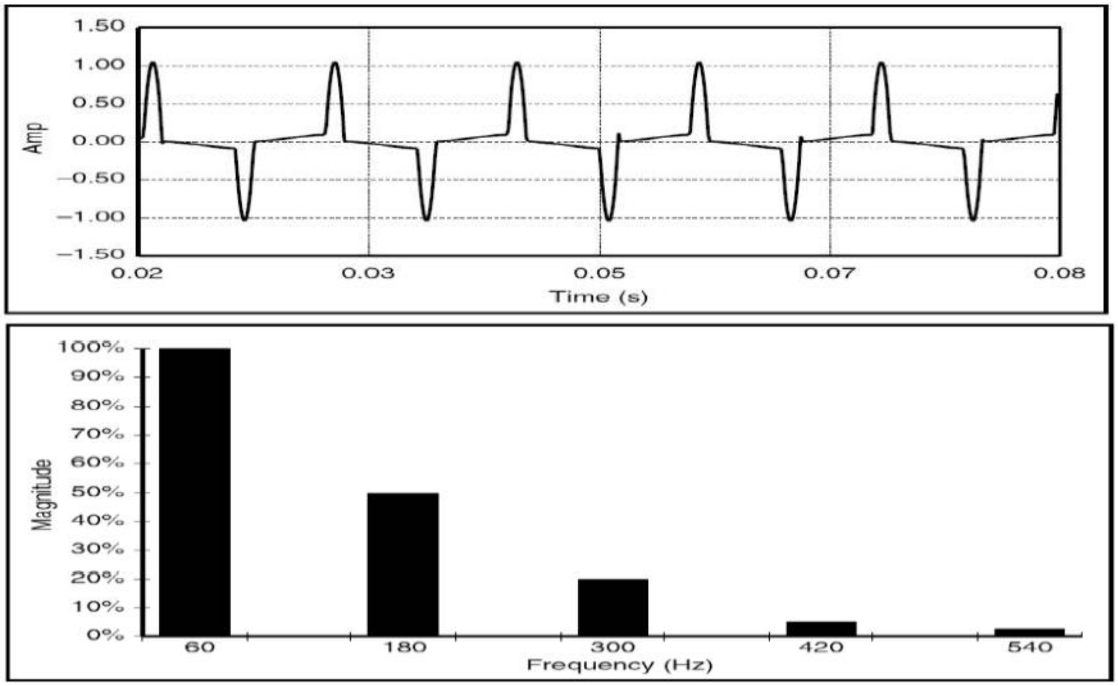


Fig. 4.14 Transformer magnetizing current and harmonic spectrum

4.4 Locating Harmonic Sources

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

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

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

4.5 Power System Response Characteristics

The power system response characteristics are,

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

4.5.1 System Impedance

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

$$Z_{SC} = R_{SC} + jX_{SC} = \frac{kV^2}{MVA_{SC}} = \frac{kVX1000}{\sqrt{3}I_{SC}}$$

Where,

Z_{SC} = Short Circuit Impedance

R_{SC} = Short Circuit Resistance

X_{SC} = Short Circuit Reactance

kV = Phase – to – Phase Voltage, kV

MVA_{SC} = Three – Phase Short Circuit, MVA

I_{SC} = Short Circuit Current, A

ZSC is a phasor quantity, consisting of both resistance and reactance. However, if the short-circuit data contain no phase information, one is usually constrained to assuming that the impedance is purely reactive. This is a reasonably good assumption for industrial power systems for buses close to the mains and for most utility systems. When this is not the case, an effort should be made to determine a more realistic resistance value because that will affect the results once capacitors are considered. The inductive reactance portion of the impedance changes linearly with frequency. One common error made by novices in harmonic analysis is to forget to adjust the reactance for frequency. The reactance at the h^{th} harmonic is determined from the fundamental impedance reactance X_1 by,

$$X_h = hX_1$$

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

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

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

$$X_{SC} \approx X_{ts}$$

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

$$X_{tX} = \left(\frac{kV^2}{MVA_{3\emptyset}}\right) XZ_{tX}(\%)$$

Where MVA_3 is the kVA rating of the transformer. This assumes that the impedance is predominantly reactive. For example for a 1500kVA, 6 percent transformer, the equivalent impedance on the 480V side is,

$$X_{tX} = (\frac{kV^2}{MVA_{3\emptyset}}) X Z_{tX}(\%) = (\frac{0.480^2}{1.5}) X 0.06 = 0.0092\Omega$$

A plot of impedance versus frequency for an inductive system (no capacitors installed) would look like figure 4.15. Real power systems are not quite as well behaved. This simple model neglects capacitance, which cannot be done for harmonic analysis.

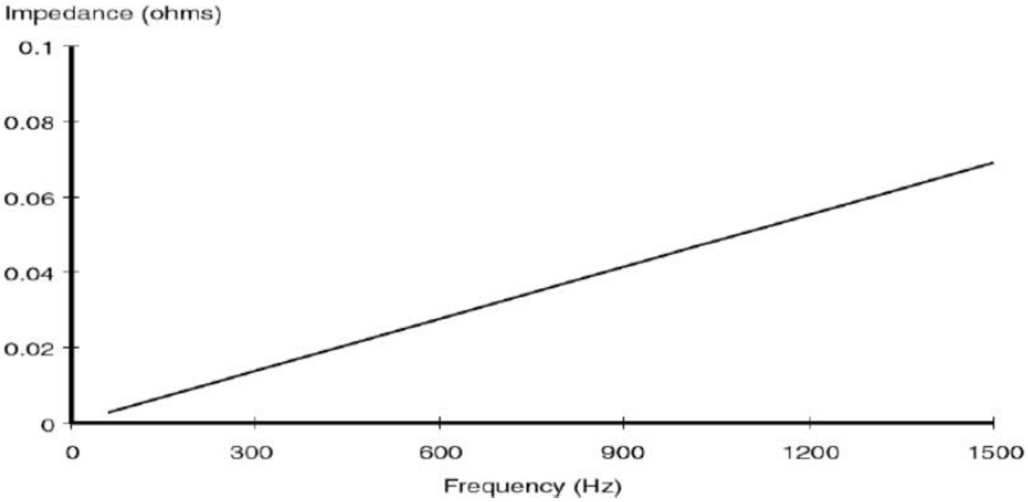


Fig. 4.15 Impedance versus frequency for inductive system

4.5.2 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 X_C decreases proportionately.

$$X_C = \frac{1}{2nfC}$$

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,

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

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, 1200kvar, 13.8kV capacitor bank, the positive-sequence reactance in ohms would be,

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

4.5.3 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 4.16 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 4.17(b). Furthermore, since the power system is assumed to have an equivalent voltage source of fundamental frequency only, the power system voltage source appears short circuited in the figure. Parallel resonance occurs when the reactance of XC and the distribution system cancel each other out. The frequency at which this phenomenon occurs is called the parallel resonant frequency. It can be expressed as follows,

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

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

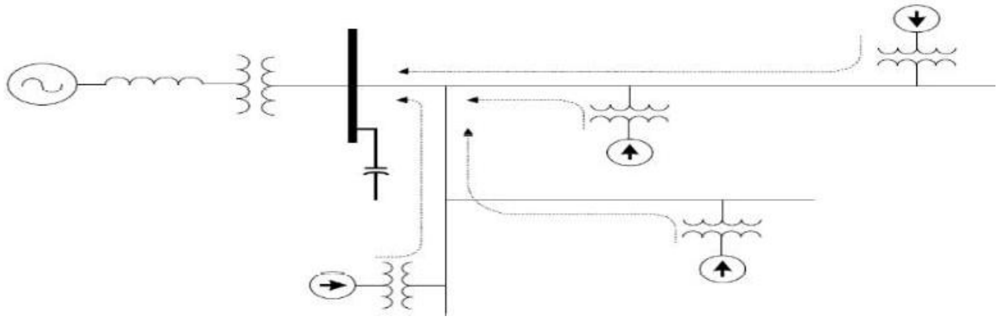


Fig. 4.16 System with potential parallel resonance problems

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

Q often is known as the quality factor of a resonant circuit that determines the sharpness of the frequency response. Q varies considerably by location on the power system. It might be less than 5 on a distribution feeder and more than 30 on the secondary bus of a large step-down transformer. From Equations it is clear that during parallel resonance, a small harmonic current can cause a large voltage drop across the apparent impedance, i.e., $V_p = Q\,XL_{eq}\,I_h$. 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,

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

(Or)

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

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

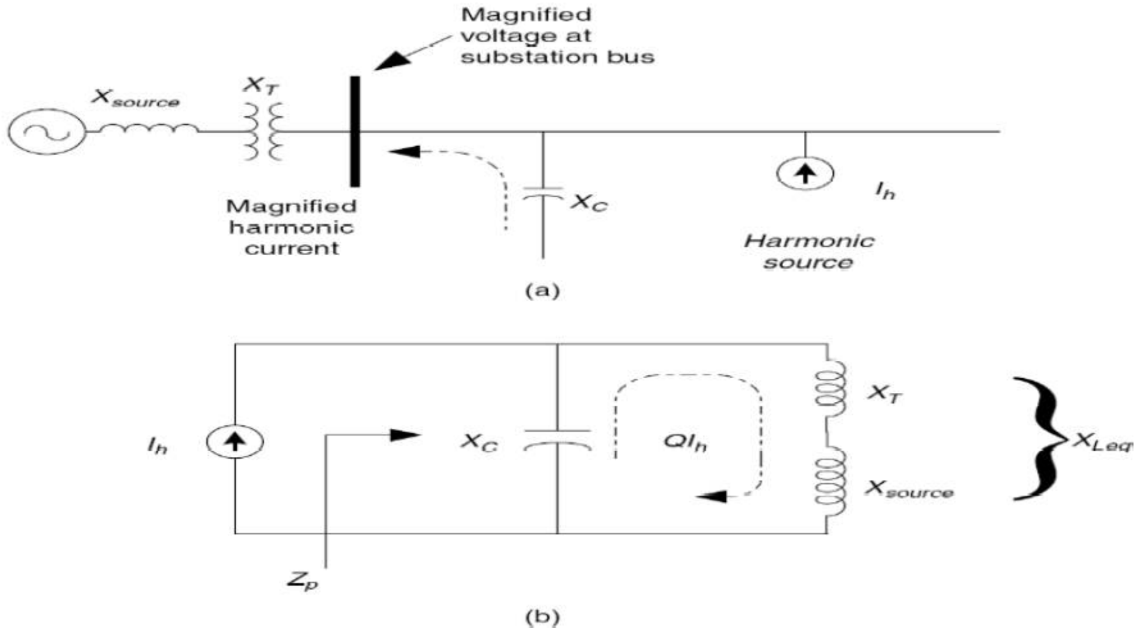


Fig. 4.17 at harmonic frequencies, the shunt capacitor bank appears in parallel with the system inductance. (a) Simplified distribution circuit; (b) parallel resonant circuit as seen from the harmonic source

The extent of voltage and current magnification is determined by the size of the shunt capacitor bank. Figure 4.18 shows the effect of varying capacitor size in relation to the transformer on the impedance seen from the harmonic source and compared with the case in which there is no capacitor. The following illustrates how the parallel resonant frequency is computed. Power systems analysts typically do not have L and C readily available and prefer to use other forms of this relationship. They commonly compute the resonant harmonic hr based on fundamental frequency impedances and ratings using one of the following,

$$h_r = \sqrt{\frac{X_C}{X_{SC}}} = \sqrt{\frac{MVA_{SC}}{MVar_{cap}}} \approx \sqrt{\frac{KVA_{ts} X 100}{Kvar_{cap} X Z_{ts}\,(\%)}}$$

Where,

h_r = Resonant harmonic

X_C = Capacitor reactance

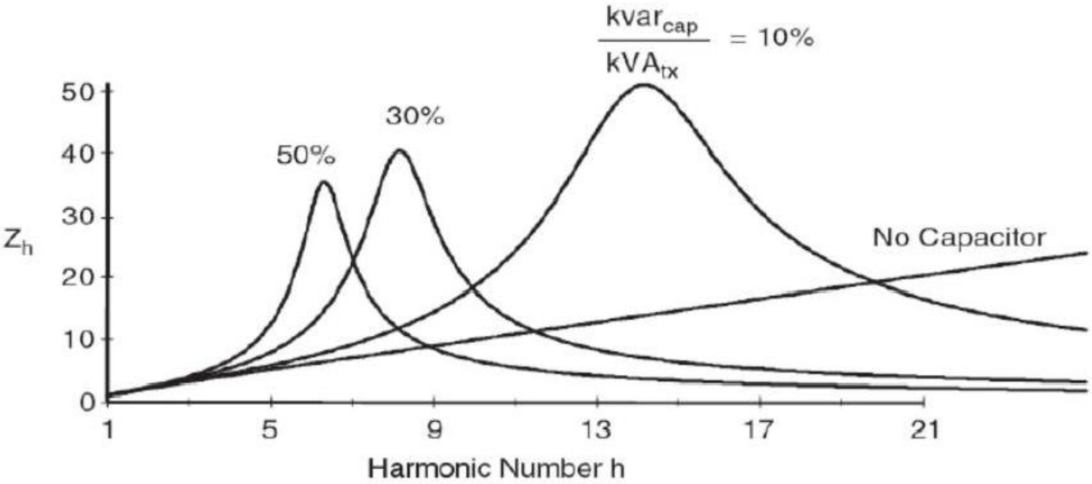


Fig. 4.18 System frequency response as capacitor size is varied in relation to transformer

X_{SC} = System Short Circuit Reactance

MVA_{SC} = System Short Circuit MVA

MVA_{cap} = Mvar rating of capacitor bank

kVA_{ts} = KVA rating of step down transformer

Z_{ts} = 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.

$$h_r \approx \sqrt{\frac{\mathrm{KVA_{ts}X100}}{\mathrm{Kvar_{cap}XZ_{ts}}(\%)}} = \sqrt{\frac{1500\mathrm{X}100}{500\mathrm{X}6}} = 7.07$$

4.5.4 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 4.19.

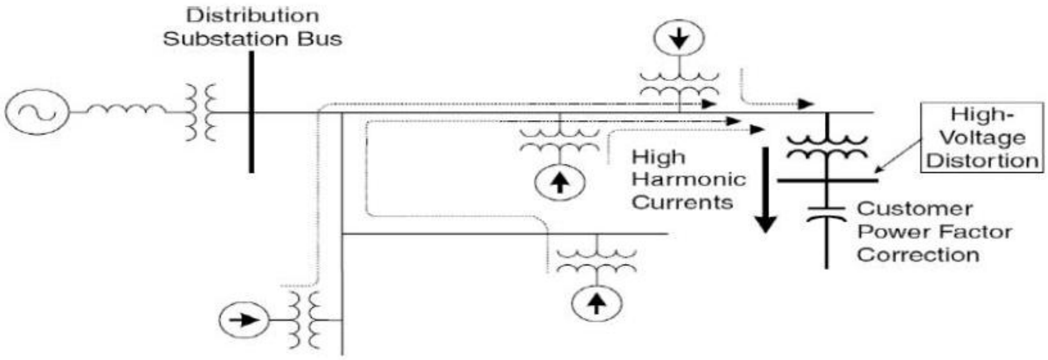


Fig. 4.19 System with potential series resonance problems

During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources. The simplified circuit is shown in figure 4.20. 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,

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

Where V_h and V_s are the harmonic voltage corresponding to the harmonic current Ih and the voltage at the power factor capacitor bank respectively. The resistance R of the series resonant circuit is not shown in figure 4.20 and it is small compared to the reactance.

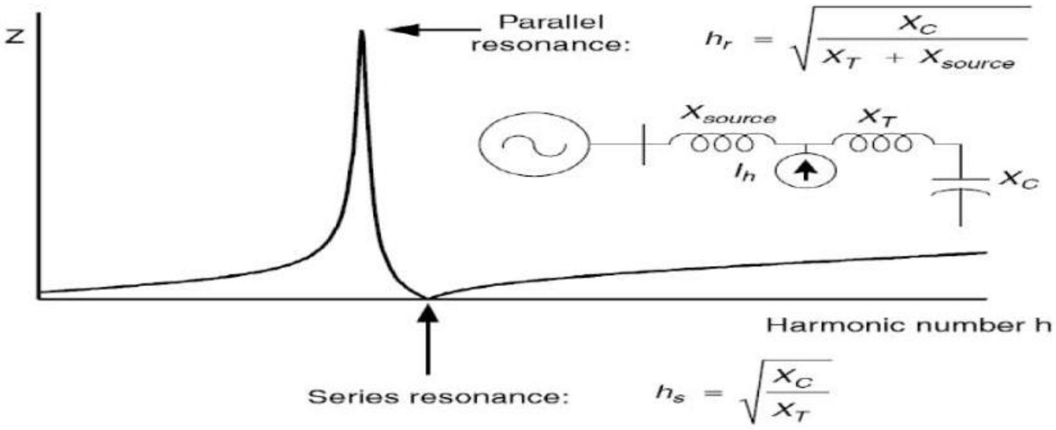


Fig. 4.20 Frequency response of a circuit with series resonance

The negligible impedance of the series resonant circuit can be exploited to absorb desired harmonic currents. This is indeed the principle in designing a notch filter. In many systems with potential series resonance problems, parallel resonance also arises due to the circuit topology. One of these is shown in figure 4.20 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 frequency due to the source inductance contribution. The parallel resonant frequency can be represented by the following equation,

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

4.6 Effects of Harmonics

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

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

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

4.7 Harmonic Distortion

Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage. Figure 4.21 illustrates this concept by the case of a sinusoidal voltage applied to a simple nonlinear resistor in which the voltage and current vary according to the curve shown. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape. This is the source of most harmonic distortion in a power system.

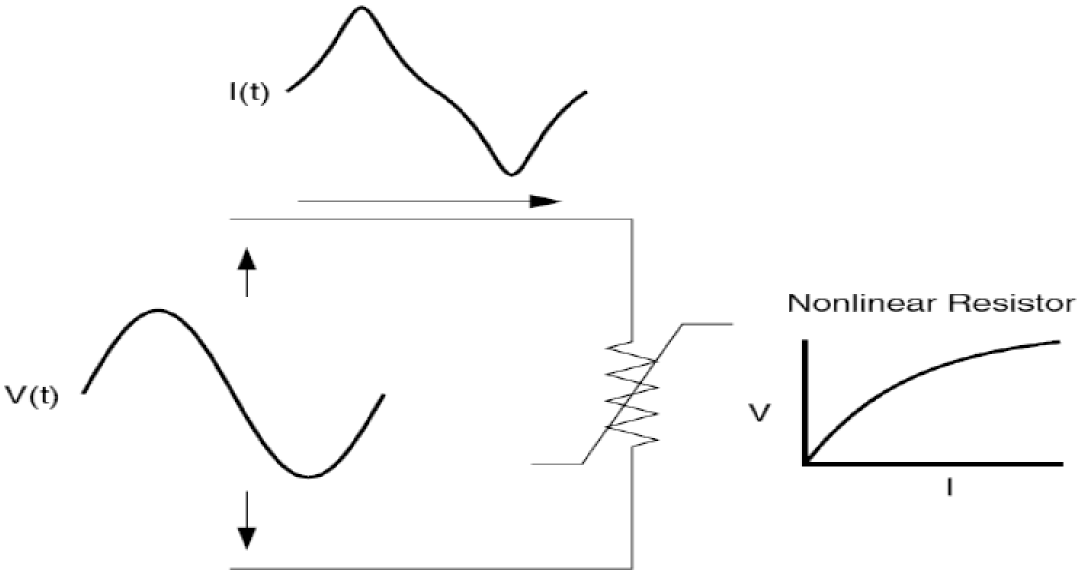


Fig. 4.21 Current distortion caused by nonlinear resistance

Figure 4.22 illustrates that any periodic, distorted waveform can be expressed as a sum of sinusoids. When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a harmonic of the fundamental, hence the name of this subject matter. The sum of sinusoids is referred to as a Fourier series, named after the great mathematician who discovered the concept.

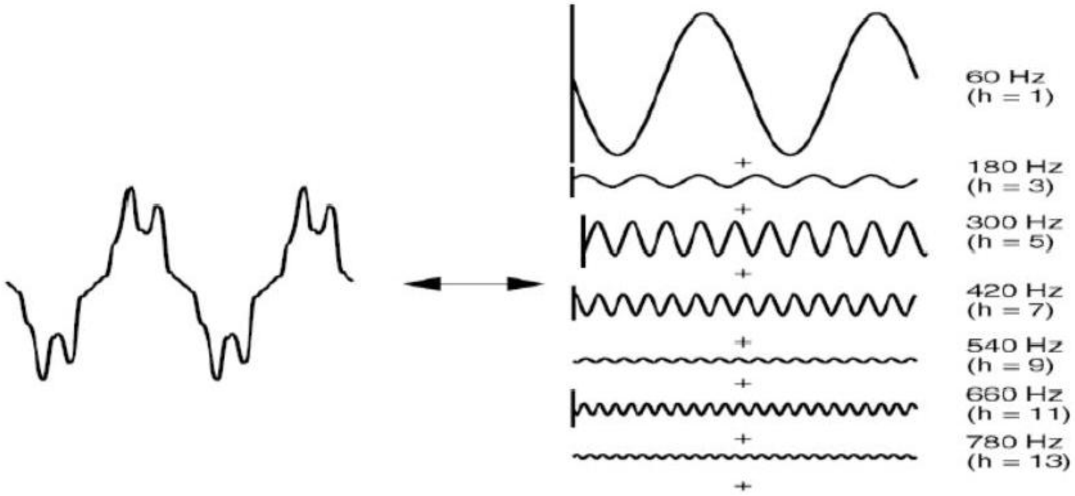


Fig. 4.22 Fourier series representation of a distorted waveform

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

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

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

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

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

4.7.1 Voltage and Current Distortion

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

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

As suggested by this list, there are separate causes and effects for voltages and currents as well as some relationship between them. Thus, the term harmonics by itself is inadequate to definitively describe a problem. Nonlinear loads appear to be sources of harmonic current in shunt with and injecting harmonic currents into the power system.

As figure 4.23 shows voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system, although, assuming that the source bus is ultimately a pure sinusoid, there is a nonlinear load that draws a distorted current. The harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. The amount of voltage distortion depends on the impedance and the current. Assuming the load bus distortion stays within reasonable limits (e.g., less than 5 percent), the amount of harmonic current produced by the load is generally constant.

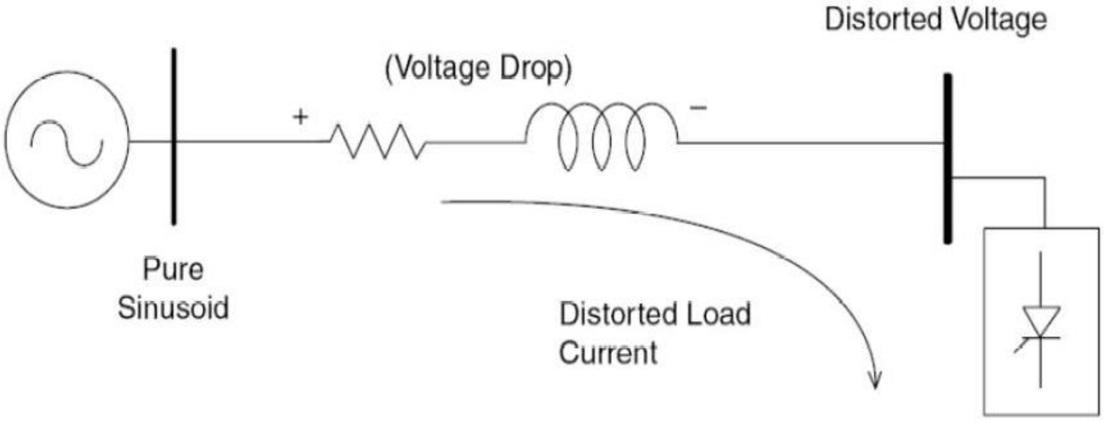


Fig. 4.23 Harmonic currents flowing through the system impedance result in harmonic voltages at the load

While the load current harmonics ultimately cause the voltage distortion, it should be noted that load has no control over the voltage distortion. The same load put in two different locations on the power system will result in two different voltage distortion values. Recognition of this fact is the basis for the division of responsibilities for harmonic control that are found in standards such as,

1. The control over the amount of harmonic current injected into the system takes place at the end-use application.
2. Assuming the harmonic current injection is within reasonable limits, the control over the voltage distortion is exercised by the entity having control over the system impedance, which is often the utility.

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

4.7.2 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.

4.7.3 Total Harmonic Distortion

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

$$\mathrm{THD} = \frac{\sqrt{\sum_{h=1}^{h_{max}} M_h^2}}{M_1}$$

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 Equations. The THD is related to the RMS value of the waveform as follows,

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

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.

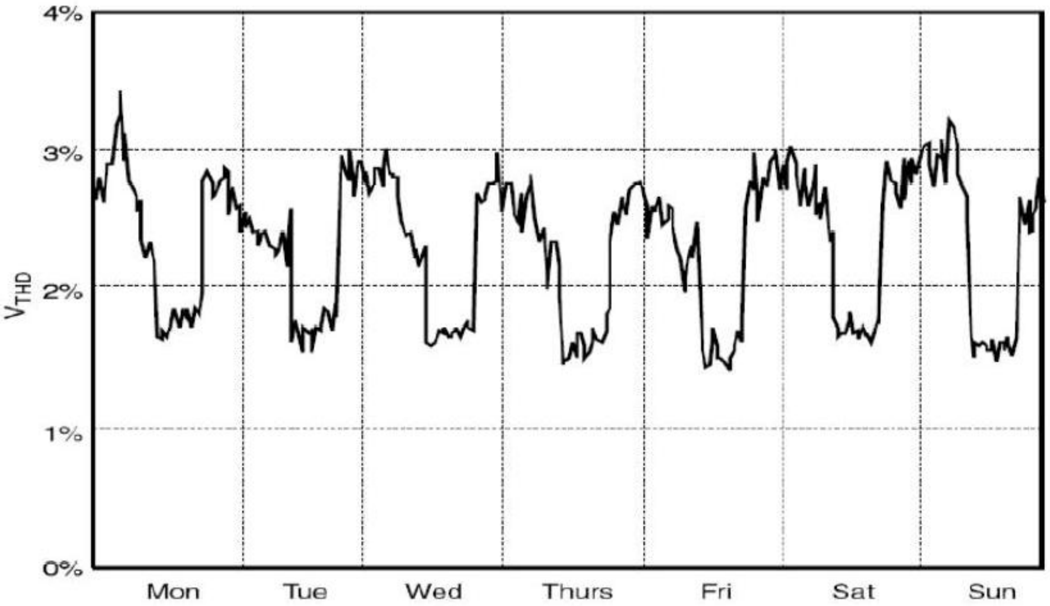


Fig. 4.24 Variation of the voltage THD over a 1-week period

The THD index is most often used to describe voltage harmonic distortion. Harmonic voltages are almost always referenced to the fundamental value of the waveform at the time of the sample. Because fundamental voltage varies by only a few percent, the voltage THD is nearly always a meaningful number. Variations in the THD over a period of time often follow a distinct pattern representing nonlinear load activities in the system. Figure 4.24 shows the voltage THD variation over a 1-week period where a daily cyclical pattern is obvious. The voltage THD shown in figure 4.24 was taken at a 13.2kV distribution substation supplying a residential load. High-voltage THD occurs at night and during the early morning hours since the nonlinear loads are relatively high compared to the amount of linear load during these hours. A 1-week observation period is often required to come up with a meaningful THD pattern since it is usually the shortest period to obtain representative and reproducible measurement results.

4.7.4 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.

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

4.8 Harmonic Distortion Evaluation

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

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

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

4.8.1 Concept of point of common coupling

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

The PCC can be located at either the primary side or the secondary side of the service transformer depending on whether or not multiple customers are supplied from the transformer. In other words, if multiple customers are served from the primary of the transformer, the PCC is then located at the primary. On the other hand, if multiple customers are served from the secondary of the transformer, the PCC is located at the secondary. Figure 4.25 illustrates these two possibilities.

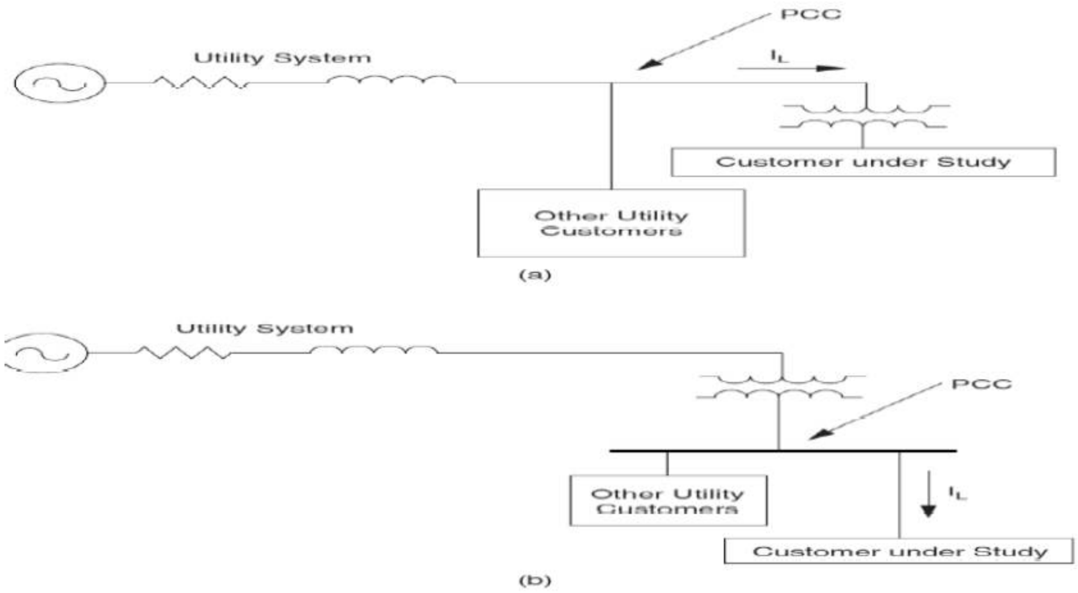


Fig. 4.25 PCC selection depends on where multiple customers are served. (a) PCC at the transformer primary where multiple customers are served. (b) PCC at the transformer secondary where multiple customers are served

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

4.8.2 Harmonic Evaluation on the utility system

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

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

Table 4.1 Harmonic Voltage Distortion Limits in Percent of Nominal Fundamental Frequency Voltage

Bus voltage at PCC, $V_n(KV)$	**Individual harmonic voltage distortion (%)**	**Total voltage distortion,** $THDV_n(\%)$
$V_n \leq 69$	3.0	5.0
$69 < V_n \leq 161$	1.5	2.5
$V_n > 161$	1.0	1.5

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

1. Harmonic currents injected from individual end users on the system must be limited. These currents propagate toward the supply source through the system impedance, creating voltage distortion. Thus by limiting the amount of injected harmonic currents, the voltage distortion can be limited as well. This is indeed the basic method of controlling the overall distortion levels proposed by IEEE Standard 519- 1992.
2. The overall voltage distortion levels can be excessively high even if the harmonic current injections are within limits. This condition occurs primarily when one of the harmonic current frequencies is close to a system resonance frequency. This can result in unacceptable voltage distortion levels at some system locations. The highest voltage distortion will generally occur at a capacitor bank that participates in the resonance. This location can be remote from the point of injection.

4.8.3 Voltage Limits Evaluation Procedure

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

Characterization of harmonic sources: Characteristics of harmonic sources on the system are best determined with measurements for existing installations. These measurements should be performed at facilities suspected of having offending nonlinear loads. The duration of measurements is usually at least 1 week so that all the cyclical load variations can be captured. For new or planned installations, harmonic characteristics provided by manufacturers may sufficient as shown in figure 4.26.

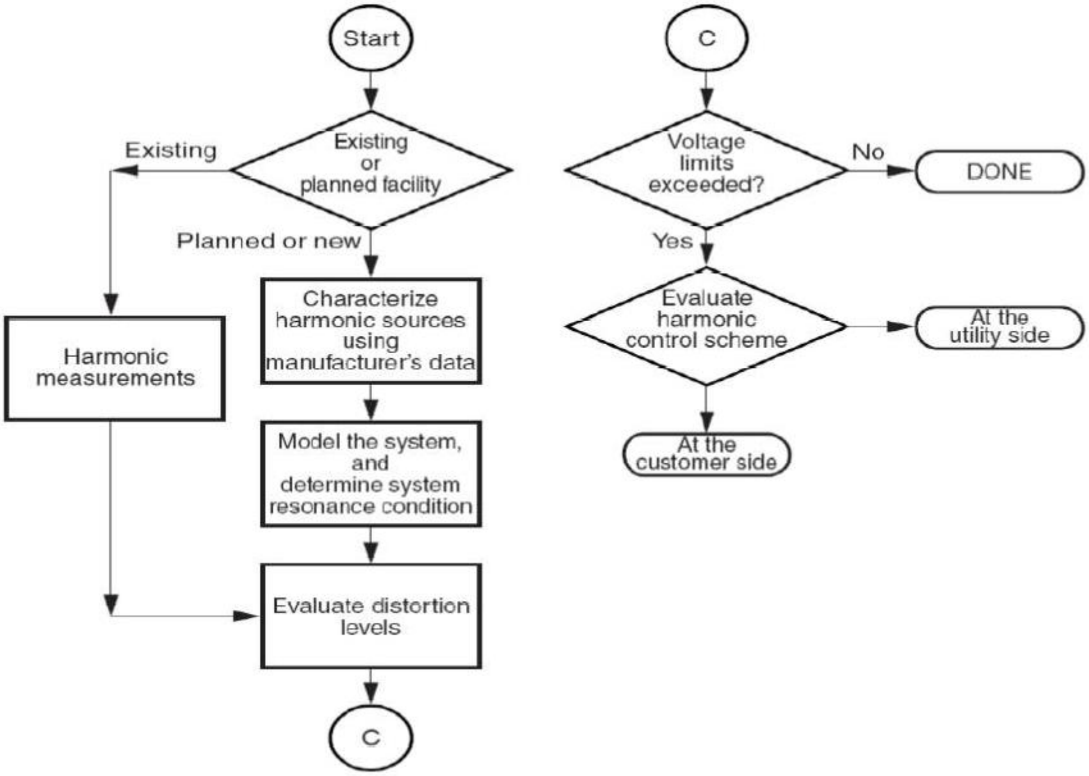


Fig. 4.26 Voltage limit evaluation procedure

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

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

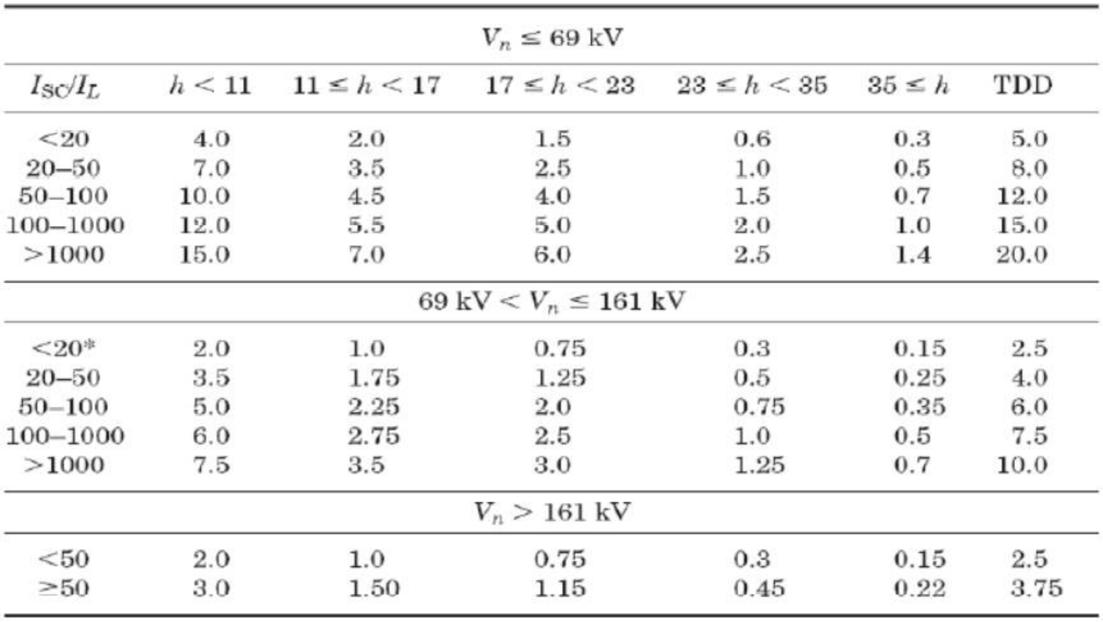
Evaluate expected distortion levels: Even with system resonance close to characteristic harmonics, the voltage distortion levels around the system may be acceptable. On distribution systems, most resonances are significantly damped by the resistances on the system, which reduces magnification of the harmonic currents. The estimated harmonic sources are used with the system configuration yielding the worst-case frequency-response characteristics to compute the highest expected harmonic distortion. This will indicate whether or not harmonic mitigation measures are necessary.

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

4.8.4 Harmonic Evaluation for end-user facilities

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

Table 4.2 Variables and Additional Restrictions



			$V_n \leq 69$ kV			
I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
			69 kV $< V_n \leq$ 161 kV			
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
			$V_n >$ 161 kV			
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

I_h is the magnitude of individual harmonic components (RMS amps). I_{SC} is the short-circuit current at the PCC. I_L is the fundamental component of the maximum demand load current at the PCC. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated. The individual harmonic component limits apply to the odd-harmonic components. Even harmonic components are limited to 25 percent of the limits. Current distortion which results in a dc offset at the PCC is not allowed. The total demand distortion (TDD) is expressed in terms of the maximum demand load current.

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L} X100\%$$

If the harmonic-producing loads consist of power converters with pulse number q higher than 6, the limits indicated in Table 6.2 are increased by a factor equal to $\sqrt{q/6}$. In computing the short-circuit current at the PCC, the normal system conditions that result in minimum short-circuit capacity at the PCC should be used since this condition results in the most severe system impacts.

Procedure to determine the short-circuit ratio is as follows:

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

$$I_{SC} = \frac{1000 \text{ X MVA}}{\sqrt{3}\mathrm{KV}} \mathrm{A}$$

- Find the load average kilowatt demand PD over the most recent 12months. This can be found from billing information.
- Convert the average kilowatt demand to the average demand current in amperes using the following expression,

$$I_L = \frac{\mathrm{KW}}{\mathrm{PF}\sqrt{3}\mathrm{KV}} \mathrm{A}$$

Where, PF is the average billed power factor.

- The short-circuit ratio is now determined by,

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

4.9 Devices for controlling Harmonic Distortion

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

4.9.1 Passive Filters

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

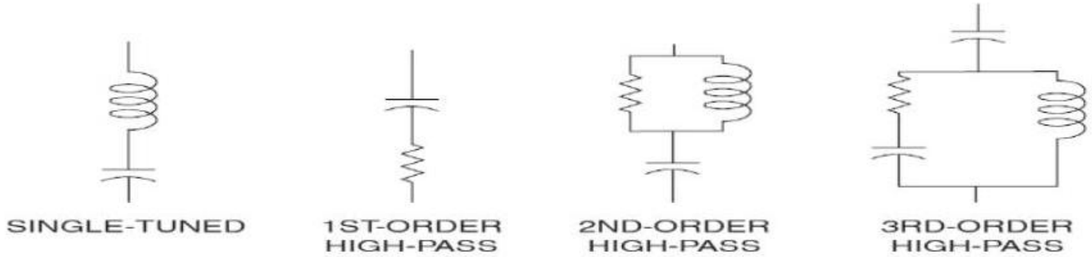


Fig. 4.27 Common passive filter configurations

4.9.1.1 Shunt Passive Filters

The most common type of passive filter is the single tuned “notch” filter. This is the most economical type and is frequently sufficient for the application. The notch filter is series-tuned to present low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter. Notch filters can provide power factor correction in addition to harmonic suppression. In fact, power factor correction capacitors may be used to make notch filters. The dry-type iron- core reactor is positioned atop the capacitors, which are connected in a star configuration with the other phases. Each capacitor can is fused with a current- limiting fuse to minimize damage in case of a can failure. In outdoor installations it is often more economical to use air-core reactors.

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

$$h_{\text{notch}} = \sqrt{\frac{X_C}{3X_F}}$$

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

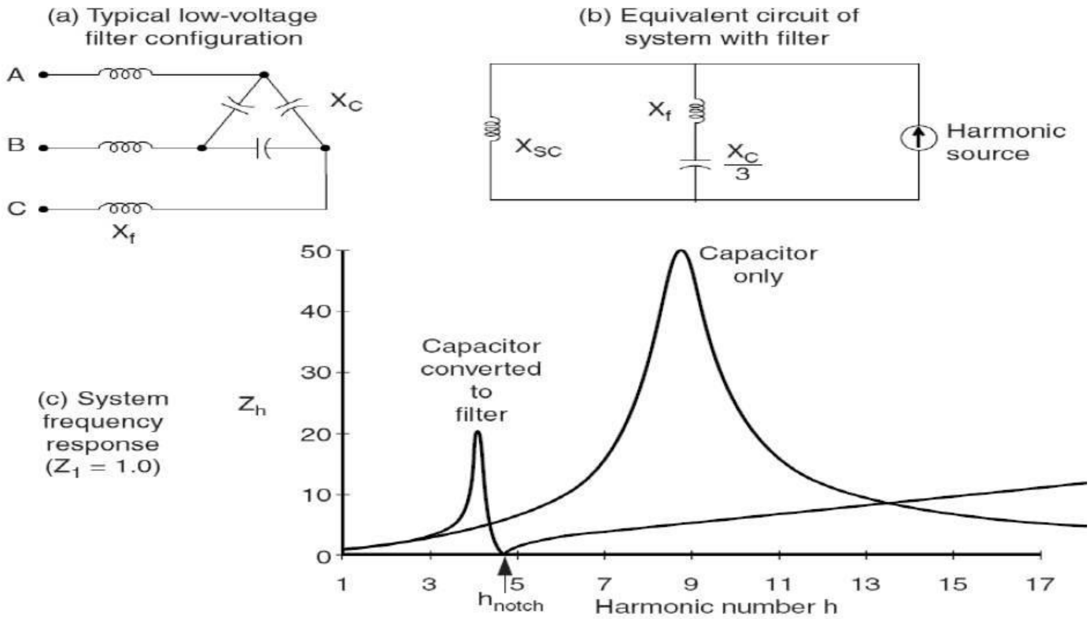


Fig. 4.28 creating a fifth-harmonic notch filter and its effect on system response

4.9.1.2 Series Passive Filters

Unlike a notch filter which is connected in shunt with the power system, a series passive filter is connected in series with the load. The inductance and capacitance are connected in parallel and are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic currents at the tuned frequency only.

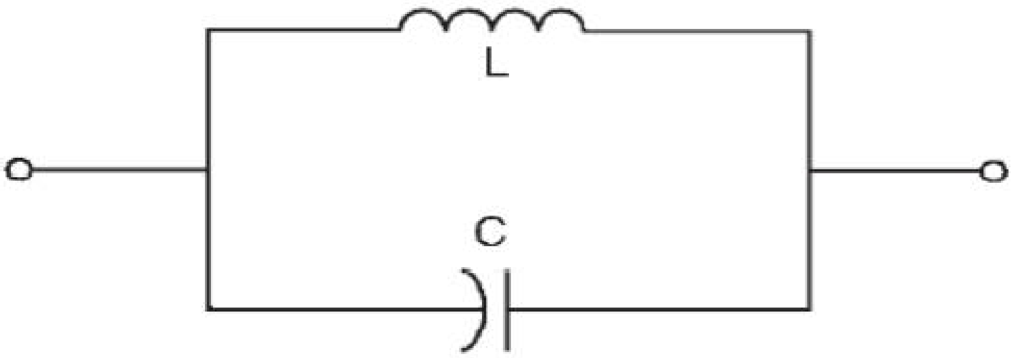


Fig. 4.29 Series passive filter

At fundamental frequency, the filter would be designed to yield low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses. Figure 4.29 shows a typical series filter arrangement. Series filters are used to block a single harmonic current (such as the third harmonic) and are especially useful in a single-phase circuit where it is not possible to take advantage of zero-sequence characteristics. The use of the series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequency.

4.9.1.3 Low Pass Broad Band Filters

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

Designing a shunt or series filter to eliminate or reduce these widespread and time-varying harmonics would be very difficult using shunt filters. Therefore, an alternative harmonic filter must be devised. A low-pass broadband filter is an ideal application to block multiple or widespread harmonic frequencies. Current with frequency components below the filter cutoff frequency can pass; however, current with frequency components above the cutoff frequency is filtered out. Since this type of low-pass filter is typically designed to achieve a low cutoff frequency, it is then called a low-pass broadband filter. A typical configuration of a low-pass broadband filter is shown in figure 4.30.

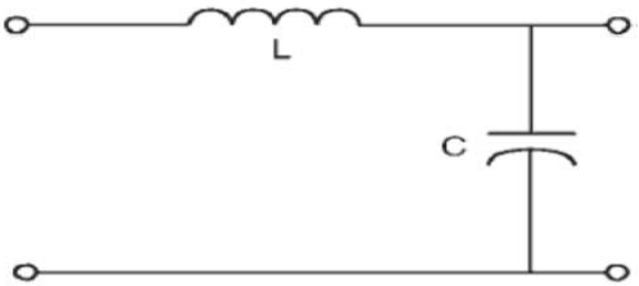


Fig. 4.30 Low pass broadband filter configuration

4.9.1.4 C Filters

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

4.9.2 Active Filters

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

The basic idea is to replace the portion of the sine wave that is missing in the current in a nonlinear load. Figure 4.31 illustrates the concept. An electronic control monitors the line voltage and/or current, switching the power electronics very precisely to track the load current or voltage and force it to be sinusoidal. As shown, there are two fundamental approaches: one that uses an inductor to store current to be injected into the system at the appropriate instant and one that uses a capacitor. Therefore, while the load current is distorted to the extent demanded by the nonlinear load, the current seen by the system is much more sinusoidal.

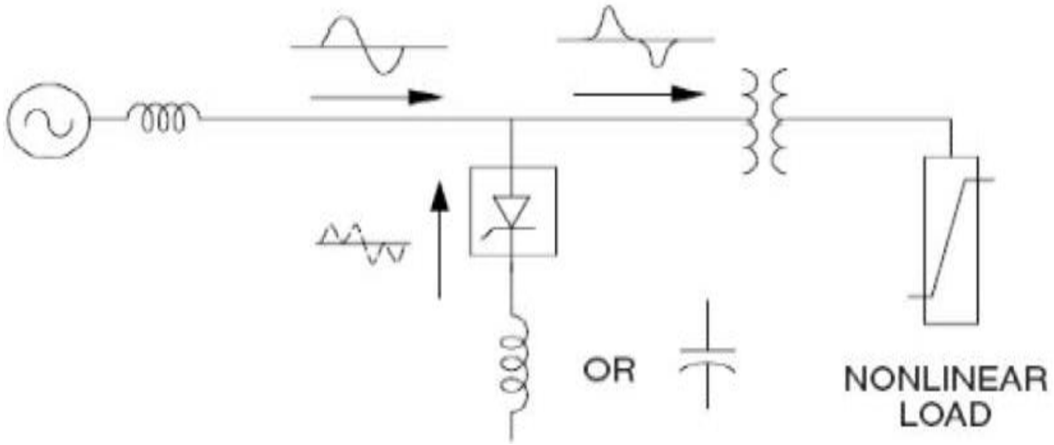


Fig. 4.31 Application of an active filter at a load

4.10 Passive Power Filters

Power converters using thyristors and other semiconductor switches are widely used to feed controlled electric power to electrical loads such as adjustable speed drives (ASDs), furnaces, and large power supplies. Such solid-state converters are also used in HVDC transmission systems, AC distribution systems, and renewable electrical power generation. As nonlinear loads, the solid-state converters draw harmonics and reactive power components of current from the AC mains. The injected harmonic currents, and reactive power burden, cause low system efficiency and poor power factor. They also result in disturbance to other consumers and protective devices and interference to nearby communication networks. Traditionally, passive power filters (PPFs) are used to reduce harmonics and capacitors are generally employed to improve the power factor of the AC loads. The passive filters are classified into many categories such as shunt, series, hybrid, single tuned, double tuned, damped, band-pass, and high- pass. In high power rating such as HVDC systems, they are very much in use even nowadays due to simplicity, low cost, robust structure, and benefits of meeting reactive power requirements in most of the applications at fundamental frequency. Moreover, they are also extensively used in hybrid configurations of power filters, where the major portion of filtering is taken care by passive filters.

In medium and low power ratings, especially in distribution systems, the passive filters are used again because of their low cost and simplicity. However, the requirements of passive filters in the distribution systems are much different from those in high power rating applications of transmission and other applications. In many situations, the requirement of reactive power at fundamental frequency is quite low and the design of passive filters becomes very challenging to reduce RMS current of the supply where dominance is of the harmonic currents. Typical examples are ASDs and power supplies, among others, consisting of diode rectifiers at the front end of equipment with a capacitive filter at the DC bus of these converters. These applications do not need any amount of reactive power due to the presence of a diode rectifier, but harmonic currents are produced by them in excess. Because of the low value of power capacitors in passive filters, these filters become very sensitive to the parallel resonance between filter capacitors and source impedance (mainly inductive in nature). If the parallel resonance frequency occurs at or near a harmonic produced by the load, a severe voltage distortion and a harmonic current amplification may be produced. It may result in nuisance fuse blowing and/or breaker operation. Therefore, utmost care must be taken in the design of passive filters to avoid such parallel resonance and associated problems. However, if the passive filters are used along with a small active filter that blocks or avoids such parallel resonance, then the objective is confined to reducing RMS current of the supply to fully utilize the capabilities of passive filters irrespective of such problems that are taken care by other means. In view of these increasing applications of passive filters, the design and selection of these filters are becoming interesting and challenging. Because of these reasons, in recent years, many texts, standards, and publications have also appeared on the passive power filters. Therefore, it is considered very relevant to present the basic concepts of the design and applications of the passive power filters.

4.10.1 State of the Art on Passive Power Filters

The PPF technology is a mature technology for providing compensation for harmonic currents and reactive power in AC networks. It has evolved in the past half century with development in terms of varying configurations. Passive filters are also used to eliminate voltage harmonics, to regulate the terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems. These objectives are achieved either individually or in combination depending upon the requirements and configuration that needs to be selected appropriately. This section describes the history of development and the current status of the PPF technology.

Because of the widespread use of solid-state control of AC power, the power quality issues have become significant. Therefore, the applications of the passive filters have also increased manifold. In view of these requirements, the passive filters are classified based on

i. Topology (e.g., tuned and damped)
ii. Connection (e.g., series and parallel/shunt)
iii. Supply system (e.g., single-phase two-wire, three-phase three-wire, and three-phase four-wire) to meet the requirements of various types of nonlinear loads on supply systems.

Single- phase loads such as domestic lights, ovens, television sets, computer power supplies, air conditioners, laser printers, and Xerox machines behave as nonlinear loads and cause power quality problems. Single-phase two- wire passive filters are investigated in varying configurations to meet the requirements of single-phase nonlinear loads. Many configurations of PPFs such as passive series filters, passive shunt filters, and a combination of both have been developed and commercialized to meet varying requirements of nonlinear loads.

Major amount of AC power is consumed by three-phase loads such as ASDs with solid-state controllers both with current-fed (line commutated inverter-fed synchronous motor drives, DC motor drives, current source inverter-fed AC motor drives) and with voltage-fed (diode bridge rectifier with capacitive filter in voltage source inverter-fed AC motor drives, power supplies) configurations of converters. Therefore, three-phase three-wire passive filters are used to reduce harmonics and to meet the reactive power requirements of such loads.

In distribution systems, the four-wire configuration of the supply system is very important for balancing the AC network, for taking advantages of three-phase supply systems, and for meeting the requirements of distributed single-phase loads. In such conditions, additional problems not of load balancing but of neutral current are also observed, which have to be taken care by proper design of passive filters.

In majority of the cases, shunt passive filters have been considered more appropriate to mitigate the harmonic currents and partially to meet reactive power requirement of these loads and to relieve the AC network from this problem, especially current-fed types of nonlinear loads (thyristor converters with constant current DC load). However, in voltage-fed types of loads (diode rectifiers with a DC capacitive filter), passive series filters are considered better for blocking of harmonic currents.

4.10.2 Classification of Passive Filters

Passive filters can be classified based on the topology, connection, and the number of phases. Figures 4.32 and 4.33 show the classification of the passive power filters based on the topology and the number of phases, respectively. The topology can be shunt, series and hybrid and further sub classified as tuned and damped to act as low-pass and high-pass for shunt filters or to act as low-block and high-block for series filters. The PPFs may be connected in shunt, series, or a combination of both for compensating different types of nonlinear loads as shown in Figure 4.32. Other major classification is based on the number of phases such as single-phase (two-wire) and three-phase (three-wire or four-wire) PPFs with these supply systems as shown in Figure 4.33. Various configurations of the passive filters are shown in Figures 4.34 – 4.49.

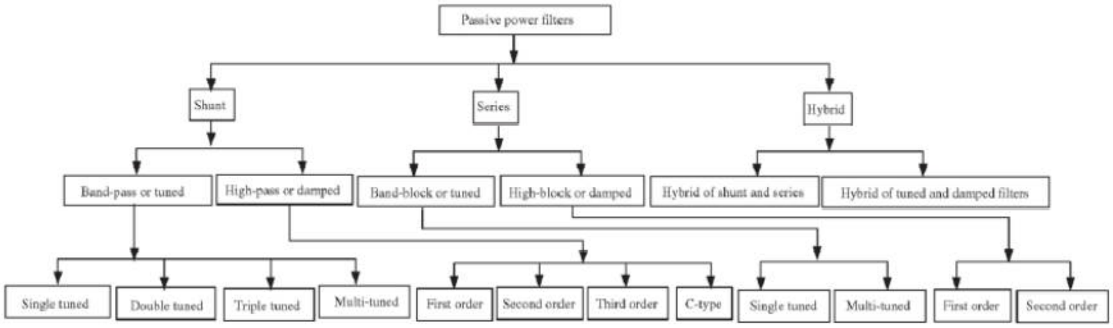


Fig. 4.32 Topology based classification of Passive Power Filters

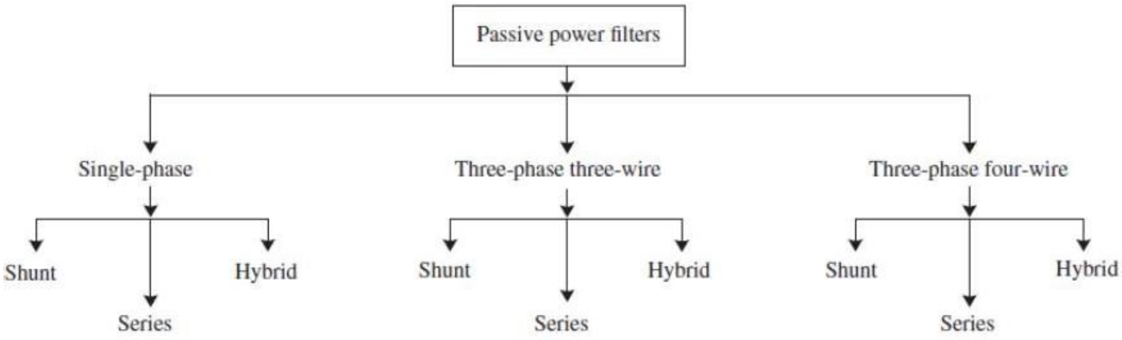


Fig. 4.33 Supply-based classification of passive power filters

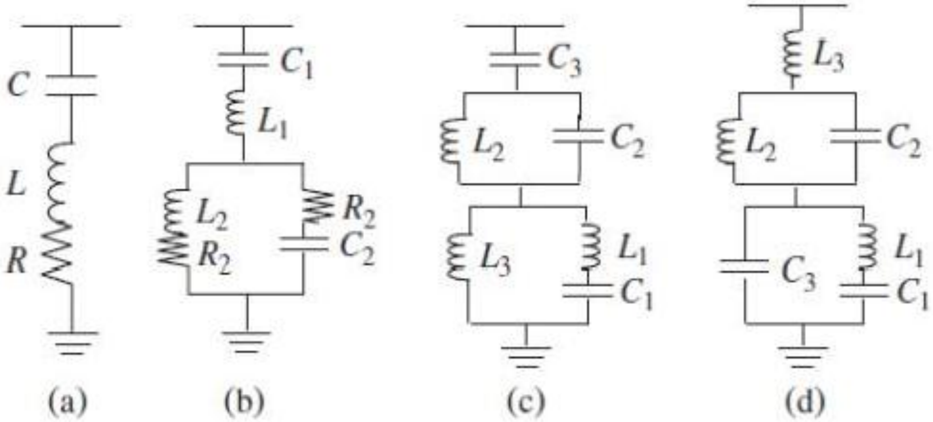


Fig. 4.34 Shunt passive tuned or band-pass filters (a) single tuned (b) double tuned (c) Triple tuned with a series capacitor (d) triple tuned with a series inductor

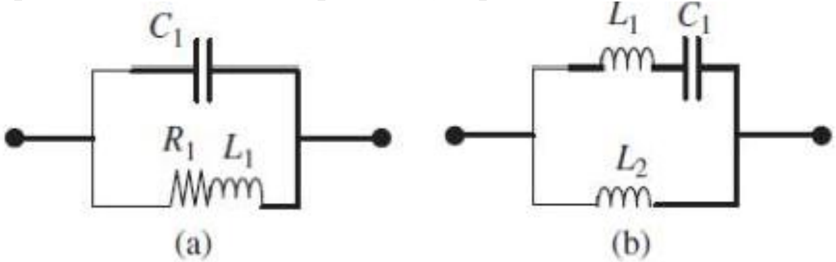


Fig. 4.35 Series passive tuned or band-block filters (a) single tuned (b) double tuned

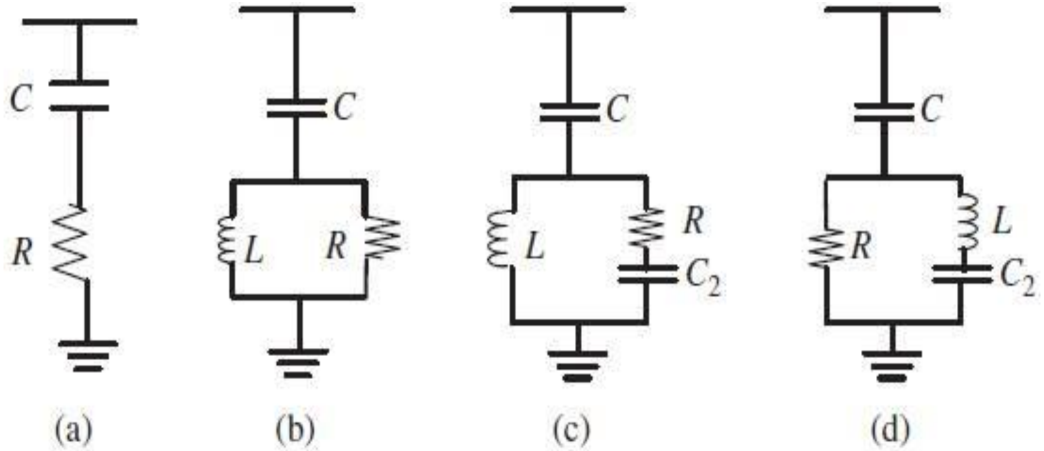


Fig. 4.36 Shunt passive damped or high-pass filters (a) first order (b) second order (c) Third order (d) C-type

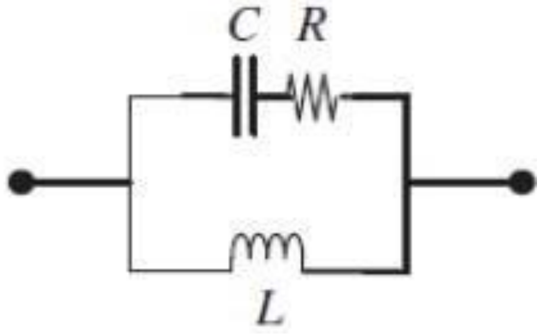


Fig. 4.37 A series passive damped or high-block filter

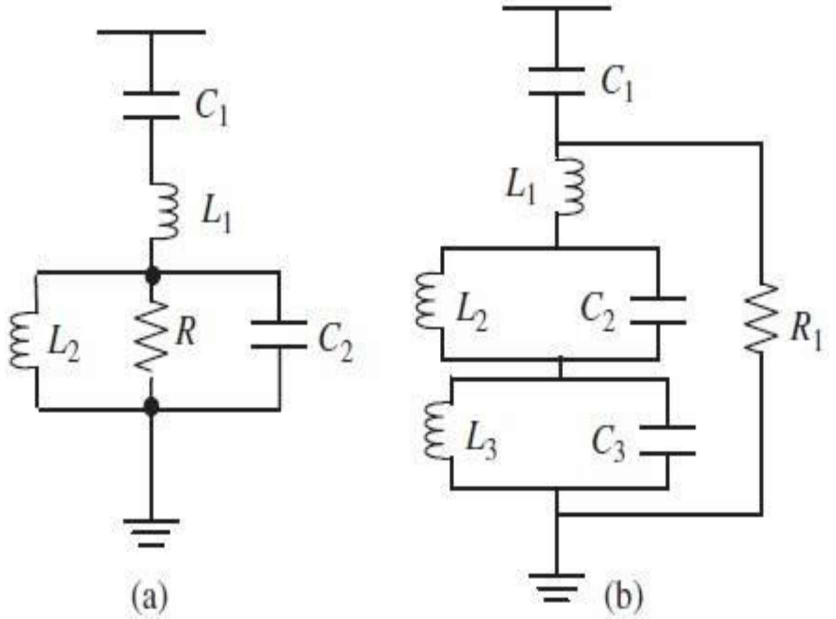


Fig. 4.38 Hybrid passive filters (a) damped double tuned (b) damped triple tuned

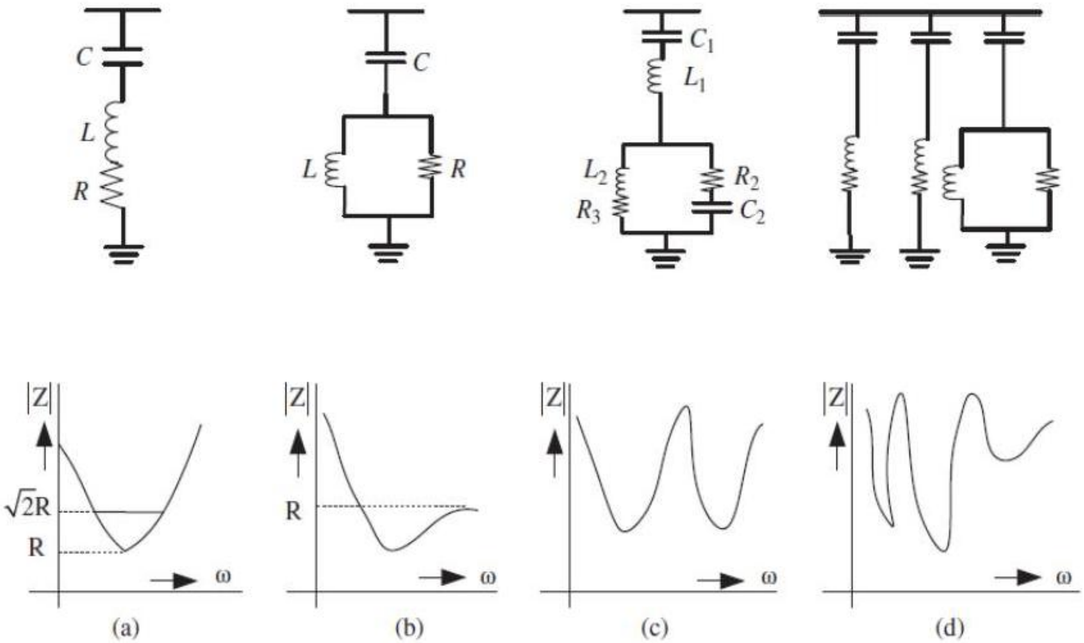


Fig. 4.39 Common types of passive shunt filters with impedance–frequency plots (a) band-pass (b) high-pass (c) double band-pass (d) composite

4.10.2.1 Topology Based Classification

PPFs can be classified based on the topology used, for example, tuned filters, damped filters, or a combination of both. Figures 4.34 and 4.35 show the passive tuned filters for shunt and series configurations that are most widely used for the elimination of current harmonics and for reactive power compensation. These are mainly used at the load end because current harmonics are injected by nonlinear loads. These inject equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection. These can also provide the reactive power in the power system network for improving the voltage profile.

Figures 4.36 and 4.37 show the passive damped filters for shunt and series configurations for eliminating all higher order harmonics. These are connected before the load either in shunt or in series with the AC mains depending upon the requirements of the nonlinear load for the elimination of current harmonics and for regulating the terminal voltage of the load.

Figure 4.38 shows the hybrid passive filters as a combination of tuned and damped filters. Another classification of hybrid passive filters includes a combination of shunt and series filters. These are used in single-phase as well as three-phase configurations. These are considered ideal PPFs that eliminate voltage and current harmonics and are capable of providing clean power to critical and harmonic-prone loads such as computers and medical equipment. These can balance and regulate terminal voltages.

4.10.2.2 Connected Based Classification

PPFs can also be classified based on the connection used, for example, shunt filters, series filters, or a combination of both. The combinations of passive series and passive shunt filters are known as hybrid filters. These are mainly used at the load end because current harmonics are injected by nonlinear loads.

Shunt Filters:

Passive shunt filters are connected in parallel to harmonic-producing loads to provide low-impedance paths for harmonic currents so that these harmonic currents do not enter supply systems and are confined to flow in the local passive circuits preferably consisting of lossless passive elements such as inductors (*L*) and capacitors (*C*) to reduce losses in the filter system. Practically, capacitors may have very low internal power losses; however, inductors have reasonable resistance and other losses (core loss if the core is made of a ferromagnetic material). Therefore, losses in the inductors cannot be neglected and are considered as an equivalent resistance connected in series with the inductors. It is also represented in terms of quality factor of the inductor. There are various types of passive shunt filters as shown in Figure 4.39. It can be a notch filter sharply tuned at one particular frequency, which is also known as a single tuned filter. It is a simple series *RLC* circuit, in which *R* is the resistance of the inductor as shown in Figure 4.39 a. The value of the capacitor, also known as the size of the filter, is decided by the reactive power requirements of the loads and its inductor value is decided by the tuned frequency. Therefore, these types of tuned or notch filters provide harmonic current and voltage reduction and power factor correction because of capacitive reactive power at fundamental frequency as this filter circuit behaves as capacitive impedance at fundamental frequency. The resistance of the reactor (inductor) decides the sharpness of tuning and is responsible for limiting the harmonic current to flow in the passive filter. Normally, the notch filters are used at more than one tuned frequency and may have more than one series *RLC* circuit for multiple harmonics. Sometimes two tuned filters are combined in one circuit. It is known as a double tuned or double band-pass filter, as shown in Figure 8.8c, having minimum impedance at both the tuned frequencies. The main use of the double tuned filter is in high-voltage applications because of reduction in the number of inductors to be subjected to full line impulse voltages. More than two tuned filters (triple and quadruple) can also be combined in one circuit, but no specific advantage is achieved and there is difficulty in adjustment. Moreover, more than two tuned filters are rarely used in practice and only in a few applications.

Other types of passive filters, shown in Figure 4.39 b and d, are known as high-pass filters that absorb all higher order harmonics. They are also known as damped filters as they provide damping due to the presence of a resistor in the circuit. These filters have higher losses, but fortunately at high frequencies not much higher currents and power losses are present in the loads. These can be first-order simple series *RC* circuits. These help to improve the voltage profile at the point of common coupling (PCC) even for very high frequencies. Normally, a second-order high-pass filter is used as it also reduces the harmonic components in the system. It consists of an external resistor in parallel to the inductor and a capacitor connected in series with the *RL* circuit as shown in Figure 4.39 b. Third-order high-pass filters are also used sometimes, as shown in Figure 4.39 d, for reducing the losses and for better filtering characteristics.

Series Filters:

Passive series filters are connected in series with harmonic-producing loads to provide high impedance for blocking harmonic currents so that these harmonic currents do not enter supply systems and are confined to flow in the local passive circuits preferably consisting of parallel connected lossless passive elements such as inductors (*L*) and capacitors (*C*) to reduce losses in the filter system. The passive series filter is a simple parallel *LC* circuit, as shown in Figures 4.35 and 4.37. At fundamental frequency, the filter is designed to offer very low impedance, thereby allowing the fundamental current with negligible voltage drop and losses. Series filters are used to block single harmonic current such as third harmonic current. These are used in small power ratings in single-phase systems to block dominant third harmonic current. For blocking multiple harmonic currents, multiple harmonic filters need to be connected in series, as shown in Figures 4.35 and 4.37. These may also have a high-block filter with a parallel *LC* circuit and a resistance in series with the capacitor. Such a configuration of multiple series connected filters has significant series voltage drop and losses at fundamental frequency. In addition, these filters must be designed to carry full rated load current with over current protection. Moreover, at fundamental frequency, these consume lagging reactive power resulting in further voltage drop. Hence, a shunt filter is much cheaper than a series filter for equal effectiveness. Therefore, series filters are much less in use compared with passive shunt filters. However, single-phase series filters at single tuned frequency to block third harmonic current are quite popular in small power rating voltage-fed nonlinear loads.

Hybrid Filters:

Hybrid filters, consisting of series and shunt passive filters as shown in figures 4.46–4.49, can be used in many industrial applications. As mentioned earlier, both passive shunt and passive series filters have some drawbacks if they are used individually. However, a passive hybrid filter consisting of a single tuned passive series filter with a single tuned passive shunt filter and a high-pass passive shunt filter offers very good filtering characteristics. A single tuned passive series filter is able to block resonance between the supply and the passive shunt filter and absorbs excess reactive power of the passive shunt filter at light load conditions. This type of hybrid passive filter offers very good filtering characteristics under varying loads. Similarly, other types of passive hybrid filters such as low-pass broadband filters are considered a good option, which consist of leakage reactance of a series transformer for stepping down the voltage for the load and then a capacitor at the load offering good filtering characteristics with a low cutoff frequency and preventing harmonics from penetrating into the high-voltage side above this cutoff frequency.

4.10.2.3 Supply System Based Classification

This classification of the PPFs is based on the supply and/or the load system, for example, single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads such as domestic appliances connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral, such as ASDs fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on three-phase four-wire supply systems, such as computers and commercial lighting. Hence, PPFs may also be classified accordingly as two-wire, three-wire and four-wire PPFs.

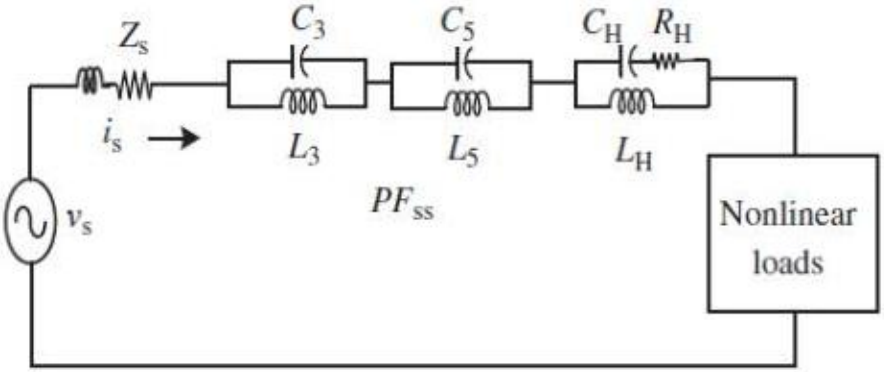


Fig. 4.40 A single-phase passive series filter

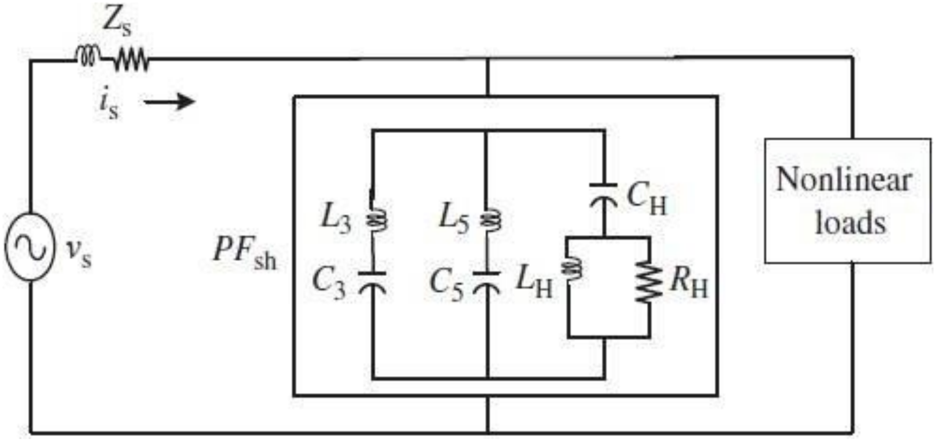


Fig. 4.41 A single-phase passive shunt filter

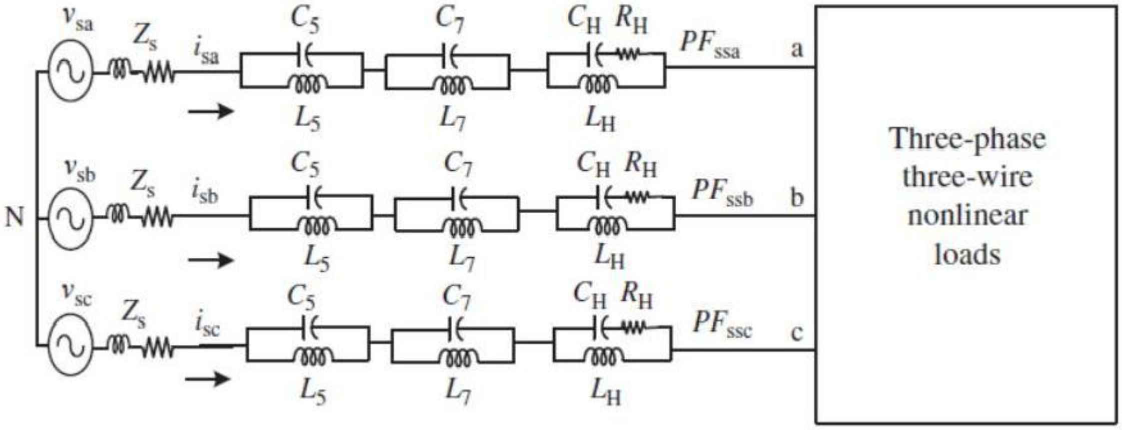


Fig. 4.42 A three-phase three-wire passive series filter

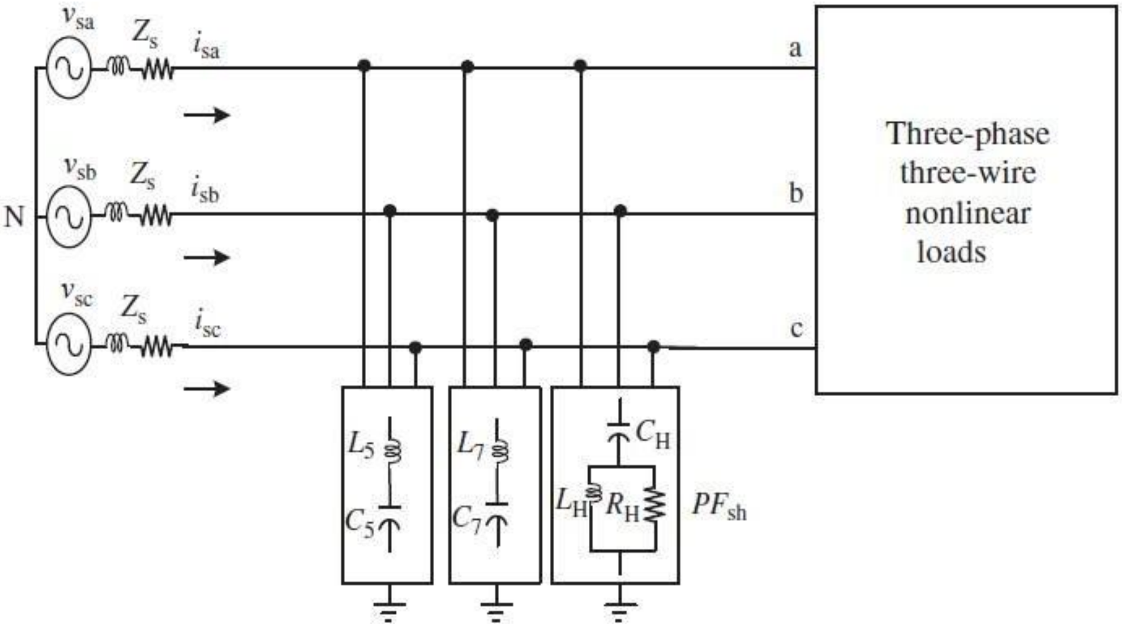


Fig. 4.43 A three-phase three-wire passive shunt filter

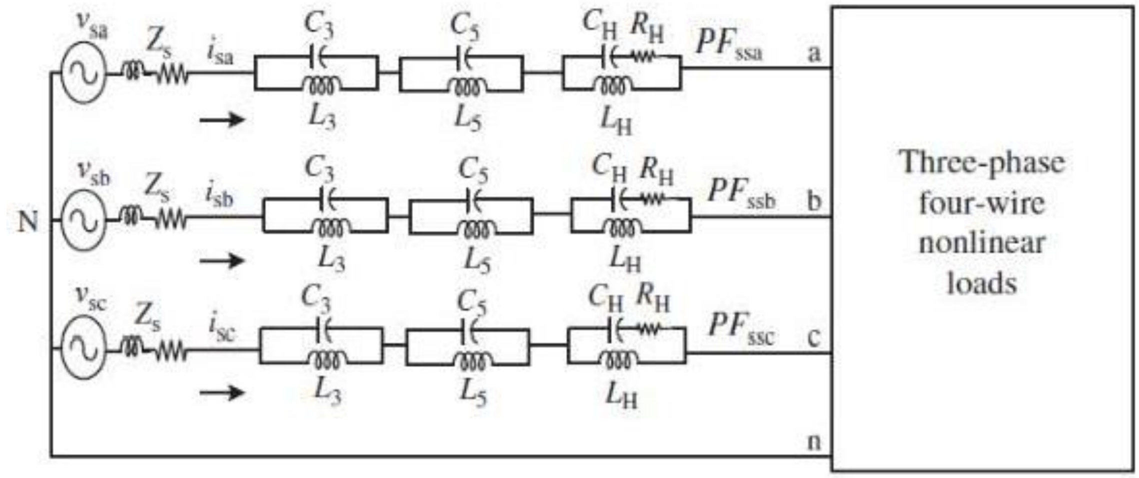


Fig. 4.44 A three-phase four-wire passive series filter

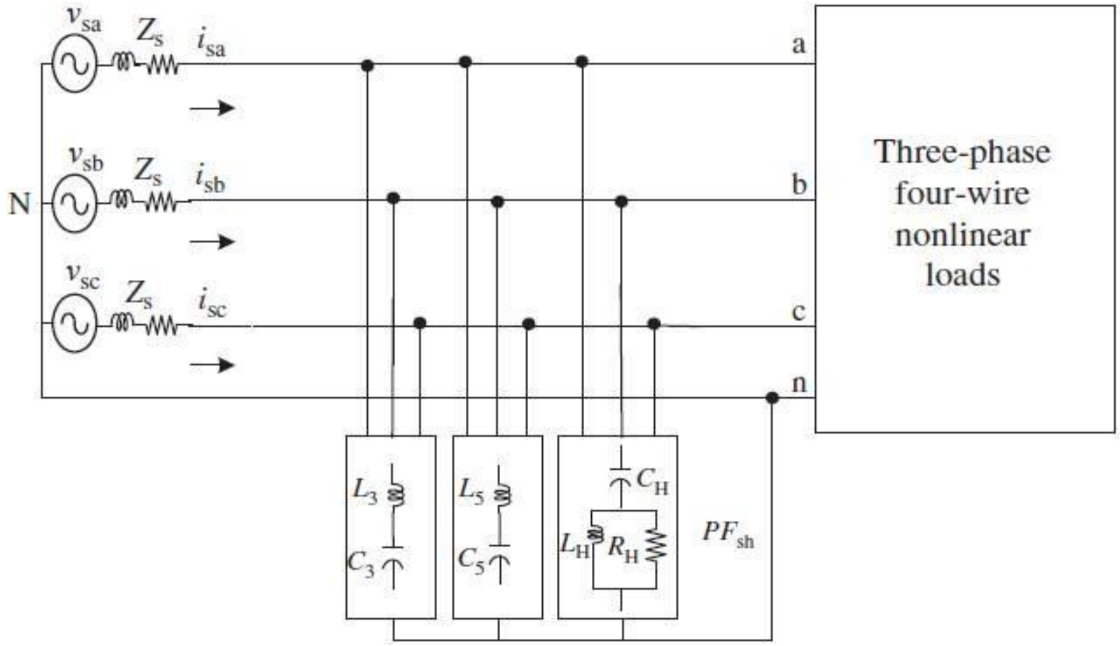


Fig. 4.45 A three-phase four-wire passive shunt filter

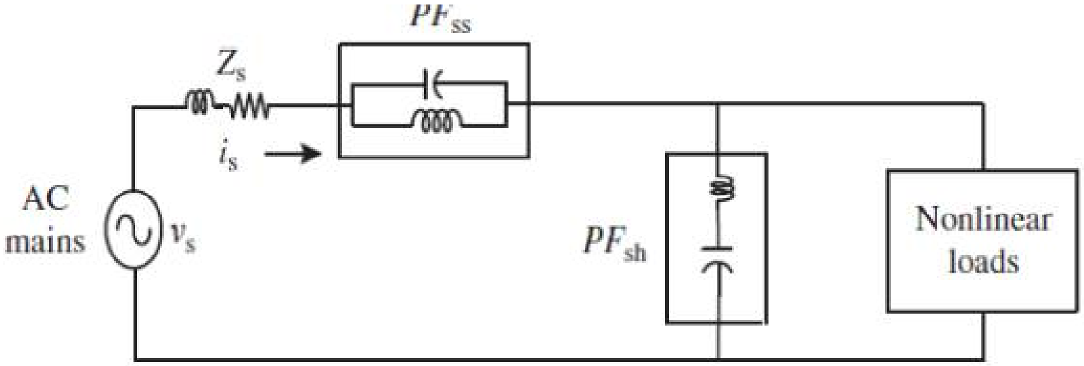


Fig. 4.46 A hybrid filter as a combination of passive series (PF_{ss}) and passive shunt (PF_{sh}) filters

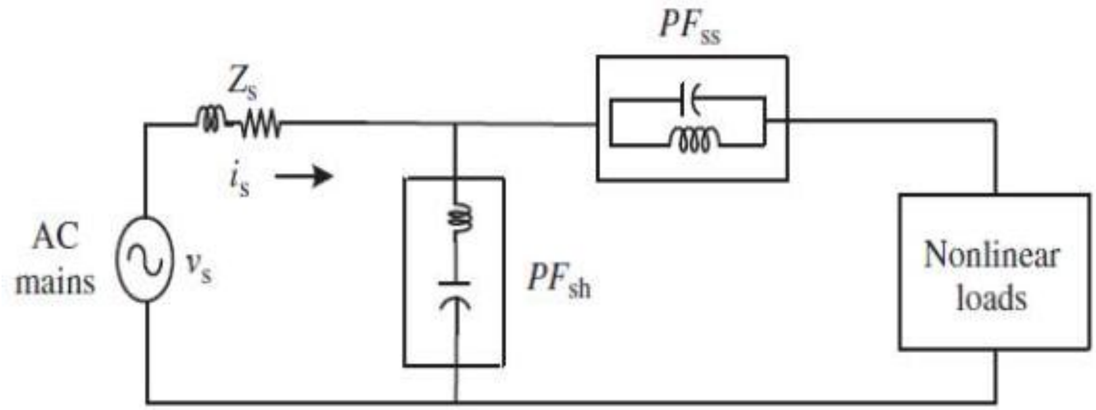


Fig. 4.47 A hybrid filter as a combination of passive shunt (PF_{sh}) and passive series (PF_{ss}) filters

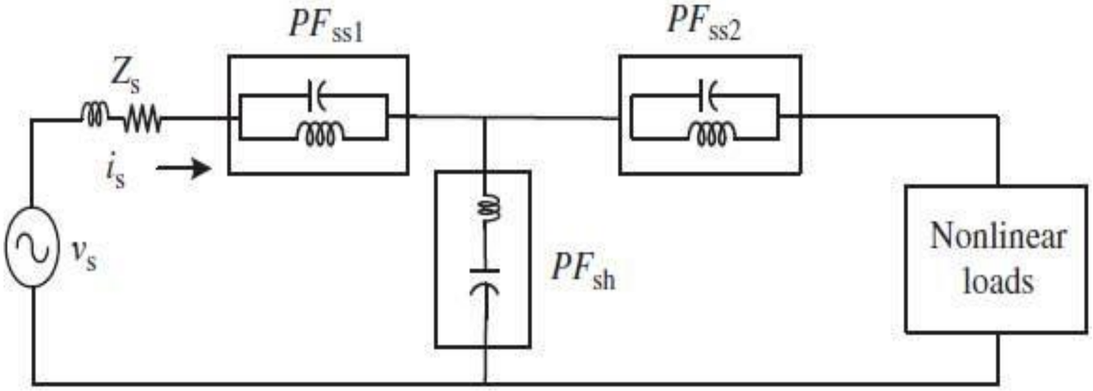


Fig. 4.48 A hybrid filter as a combination of passive series (PF_{ss1}), passive shunt (PF_{sh}), and passive series (PF_{ss2}) filters

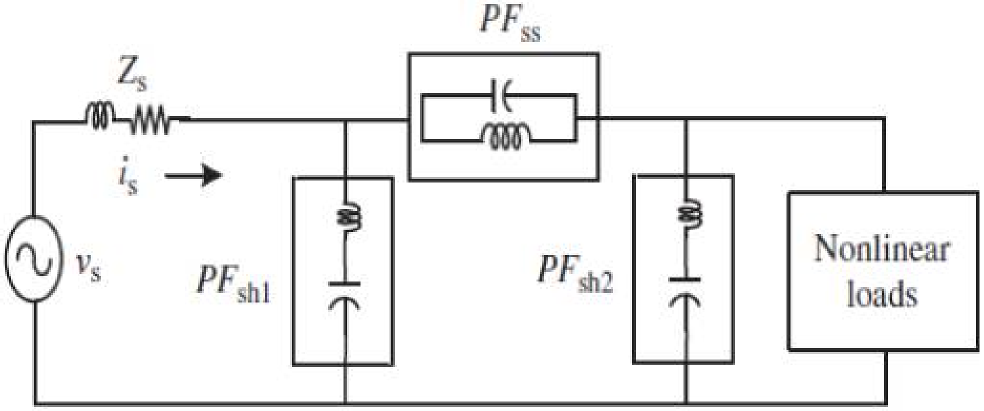


Fig. 4.49 A hybrid filter as a combination of passive shunt (PF_{sh1}), passive series (PF_{ss}), and passive shunt (PF_{sh2}) filters

Two-Wire PPFs:

Two-wire (single-phase) PPFs are used in all three modes, for example, series, shunt and a combination of both. Figures 4.40, 4.41 and 4.46 – 4.49 show the configurations of series, shunt and hybrid passive filters.

Three-Wire PPFs:

Three-phase three-wire nonlinear loads such as ASDs are one of the major applications of solid-state power converters and lately many ASDs incorporate passive filters in their front-end design. A large number of publications have appeared on three-wire PPFs with different configurations. All the configurations shown in figures 4.42 and 4.43 are developed, in three-wire PPFs, with three wires on the AC side and rectifier type nonlinear load.

Four-Wire PPFs:

A large number of single-phase loads may be supplied from the three-phase AC mains with a neutral conductor. They cause excessive neutral current, harmonic and reactive power burden, and unbalance. To reduce these problems, four-wire PPFs have been developed. Figures 4.44 and 4.45 show typical configurations of series and shunt PPFs. Detailed comparisons of the features of the passive filters are provided for different types of nonlinear loads.

4.10.3 Principle of Operation of Passive Power Filters

The basic principle of operation of passive power filters may be explained through their objectives, locations, connections, quality, sharpness, rating, size, cost, detuning, applications, and other factors.

The main objective of passive filters is to reduce harmonic voltages and currents in an AC power system to an acceptable level. The AC passive shunt filters also provide the leading reactive power required in most of the nonlinear loads. The DC harmonic filters are used to reduce only harmonics on the DC bus of the load in the system. The basic operating principle of a passive shunt harmonic filter is to absorb harmonic currents in a low-impedance path realized using a tuned series *LC* circuit as shown in Figure 4.50. Similarly, the basic operating principle of a passive series filter is to block harmonic currents entering the AC network by a passive tuned parallel *LC* circuit offering high impedance for harmonic currents as shown in Figure 4.40. Passive shunt filters are connected in parallel to the load and rated for the system voltage at PCC, whereas passive series filters are connected between the AC line and the load and rated for full load current. Passive filters are the engineering solution for harmonic reduction within an acceptable limit and not the elimination of harmonics. In case of passive shunt filters, harmonic voltages are required at PCC to flow the complete harmonic currents in passive series *RLC* circuits of the shunt filter. The passive shunt connected circuit absorbs a part of harmonic currents into it and a fraction of harmonic currents still flows in the network. Therefore, it only reduces harmonic currents and does not completely eliminate them.

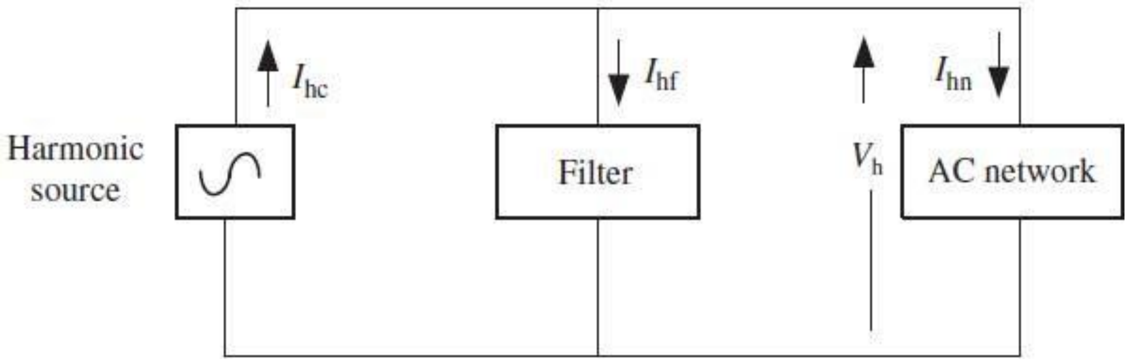


Fig. 4.50 A circuit for computation of harmonic currents and voltages on the AC side

4.10.4 Analysis and Design of Passive Power Filters

The analysis and design of passive power filters are normally considered together. It needs the data and nature of the nonlinear load for which a passive filter is to be designed and then a step-by-step procedure is adopted to design the passive filter. It is an iterative procedure because of several issues and constraints. The design procedure of a passive filter generally involves the following steps,

Estimate or record the input current frequency spectrum of the nonlinear load and its displacement power factor.

Obtain the frequency response of the power distribution equivalent impedance at the PCC where a passive filter is to be connected in the system.

Select the numbers, types, and tuned frequencies of passive filters (out of the tuned – single, double, triple, etc.; damped – first order, second order, and C-type filters; normally a C-type filter is recommended for low frequency and a high-pass filter for high frequency).

Appropriately assign the reactive power to be generated by each unit of the passive filter.

- Estimate the parameters of each unit of the passive filter.
- Evaluate the attenuation factor of each unit of the passive filter as a function of the frequency.
- Check the existence of resonance frequencies of each unit of the passive filter.
- If these resonance frequencies of passive filter units are close to current harmonics generated by the nonlinear load, then change the tuned frequency of the filter and

accordingly calculate new parameters of the passive filter to avoid the parallel resonance with the supply system.

- Validate the performance of the distribution system with filter scheme connected through simulation and estimate the harmonic distortion of voltage and current and displacement power factor.
- Iterate this design procedure of the passive filter till satisfactory performance is achieved for the distribution system in terms of total harmonic distortion (THD) of the current and voltage and power factor.

4.10.5 Modeling, Simulation and Performance of Passive Power Filters

Modeling and simulation of passive shunt and series filters are carried out to demonstrate their performance for their effectiveness and presence of various phenomena such as resonance through voltage and current waveforms. After the design of the passive filters, these are connected in the system configuration and waveform analysis is done through simulation to study their effect on the system and to observe their interactions with the system and occurrence of any phenomena such as parallel resonance considering all the practical conditions, which are not considered in the design of the passive filters. Earlier, the simulation study of these filters with the system has been quite cumbersome. However, with various available simulation tools such as MATLAB, PSCAD, EMTP, PSPICE, SABER, PSIM, ETAP and desilent, the simulation of the performance of these filters has become quite simple and straightforward.

4.10.6 Limitation of Passive Filters

- The passive filters are not adaptable to varying system conditions and remain rigid once they are installed in an application. The size and tuned frequency cannot be altered easily.
- The change in operating conditions of the system may result in detuning of the filter and it may cause increased distortion. Such a change may happen undetected provided there is online detection or monitoring in the system.
- The design of the passive filter is reasonably affected by the source impedance. For an effective filter design, its impedance must be less than the source impedance. It may result in large size of the filter in a stiff system with low source impedance, which may result in overcompensation of the reactive power. This overcompensation may

cause overvoltage on switching in and under voltage on switching out the passive filter.

- The passive filters are designed with a large number of elements and loss/damage of some of the elements may change its resonance frequencies. This may result in increased distortion in the distribution above the permissible limits.
- In case of large filters, the power losses may be substantial because of resistive elements.
- The parallel resonance due to interaction between the source and the filter can cause amplification of some characteristic and non characteristic harmonics. Such problems enforce constraints on the designer in selecting tuned frequency for avoiding such resonances.
- The size of the damped filter becomes large in handling the fundamental and harmonic frequencies.
- The environmental effects such as aging, deterioration, and temperature change and detune the filters in a random manner.
- In some cases, even the presence of a small DC component and harmonic current may cause saturation of the reactors of the filter.
- A special switching is required for switching in and switching out passive filters to avoid the switching transients.
- The grounded neutral of star connected capacitor banks may cause amplification of third harmonic currents in some cases.
- Special protective and monitoring devices are required in passive filters.

4.11 Shunt Active Power Filters

Solid-state control of AC power using diodes, thyristors, triacs and other semiconductor switches is widely employed to feed controlled power to electrical loads such as computers, printers, fax machines, copiers, TV power supplies, lighting devices especially vapor lamps consisting of magnetic or electronic ballasts, solid-state AC voltage controllers feeding fans, furnaces, adjustable speed drives (ASDs) consisting of solid-state controllers for both DC and AC motors, uninterruptible power supplies (UPS), high-frequency transformer-isolated welding machines, magnet power supplies, electrochemical industries such as electroplating, electromining and so on. Such solid-state controllers are also used in electric traction, high-voltage direct current (HVDC) systems, flexible alternating current transmission system (FACTS) and renewable electrical power generation. As nonlinear loads (NLLs), these solid-state converters draw harmonic currents and the reactive power component of the current from the AC mains.

In three-phase systems, they could also cause unbalanced currents and draw excessive neutral current. The injected harmonic currents, reactive power burden, and unbalanced and excessive neutral current cause low efficiency of distribution system, poor power factor, mal-operation of protection systems, power capacitor banks overloading and their nuisance tripping, noise and vibration in electrical machines, derating of distribution and user equipment, and so on. They also cause disturbance to other consumers and interference in nearby communication networks. Traditionally, passive L–C filters have been used to reduce harmonics and power capacitors have been employed to improve the power factor of the AC loads.

However, passive filters have the demerits of fixed compensation, large size, resonance, and so on. The increased severity of harmonic pollution in power networks has attracted attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipment generally known as active power filter (APF) is also called active power line conditioner (APLC), instantaneous reactive power compensator (IRPC), and active power quality conditioner (APQC). In recent years, many studies have also appeared on harmonics, reactive power, load balancing and neutral current compensation associated with linear and nonlinear loads. It is thus relevant to present the analysis, design and control of SAPF considering their increasing applications for the compensation of nonlinear loads.

4.11.1 State of the Art on Shunt Active Power Filters

The SAPF technology is now a mature technology for providing harmonic current compensation, reactive power compensation, and neutral current compensation in AC distribution networks. It has evolved in the past quarter century with development in terms of varying configurations, control strategies, and solid-state devices. Shunt active power filters are also used to regulate the terminal voltage and suppress voltage flicker in three-phase systems. These objectives are achieved either individually or in combination depending upon the requirements, control strategy, and configuration that need to be selected appropriately.

With the widespread use of solid-state control of AC power, the power quality issues have also become significant. A large number of publications are reported on the power quality survey, measurements, analysis, cause and effects of harmonics, and reactive power in the electric networks. Shunt active power filter is considered as an ideal device for mitigating power quality problems. The shunt active power filters are basically categorized into three types, namely, single-phase two-wire, three-phase three-wire and three-phase four-wire configurations, to meet the requirements of the three types of nonlinear loads on supply systems. Some single-phase loads such as domestic lights, ovens, TVs, computer power supplies, air conditioners, laser printers, and Xerox machines behave as nonlinear loads and cause power quality problems. Single-phase two-wire active power filters of varying configurations and control strategies have been investigated to meet the needs of single-phase nonlinear loads.

The problem of excessive neutral current is observed in three-phase four-wire systems mainly due to nonlinear unbalanced loads such as computer power supplies, fluorescent lighting, and so on. These problems of neutral current and unbalanced load currents in four-wire systems have been attempted to resolve through elimination/reduction of neutral current, harmonic compensation, load balancing and reactive power compensation.

One of the major factors in advancing the APF technology is the advent of fast, self-commutating solid state devices. In the initial stages, thyristors, bipolar junction transistors (BJTs) and power MOSFETs (metal–oxide–semiconductor field-effect transistors) have been used to develop APFs; later, SITs and GTOs have been employed to develop APFs. With the introduction of insulated gate bipolar transistors (IGBTs), the APF technology has got a real boost and at present it is considered as an ideal solid-state device for APFs. The improved sensor technology has also contributed to the enhanced performance of the APF. The availability of Hall effect sensors and isolation amplifiers at reasonable cost and with adequate ratings has improved the APF performance.

4.11.2 Classification of Shunt Active Filters

Shunt active power filters can be classified based on the type of converter used, topology and the number of phases. The converter used in the SAPF can be either a current source converter or a voltage source converter. Different topologies of SAPF can be realized by using various circuits of VSCs. The third classification is based on the number of phases: single-phase two-wire, three-phase three-wire, and three phase four-wire APF systems.

4.11.2.1 Converter Based Classification

Two types of converters are used to develop APFs. Figure 4.51 shows a SAPF using a current fed PWM (pulse-width modulation) converter or a CSC bridge. It behaves as a non sinusoidal current source to meet the harmonic current requirement of the nonlinear loads. A diode is used in series with the self commutating device (IGBT) for reverse voltage blocking. However, GTO-based circuit configurations do not need the series diode, but they have restricted frequency of switching. These CSC-based SAPFs are considered sufficiently reliable, but have higher losses and require higher values of parallel AC power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve the performance of SAPFs in higher ratings.

The other converter used in APF is a voltage-fed PWM converter or voltage source converter shown in Figure 4.52. It has a self-supporting DC voltage bus with a large DC capacitor. It is more widely used because it is lighter, cheaper, and expandable to multilevel and multistep versions to enhance the performance with lower switching frequencies. It is more popular in UPS-based applications because in the presence of AC mains, the same converter bridge can be used in SAPF to eliminate harmonics of critical nonlinear loads.

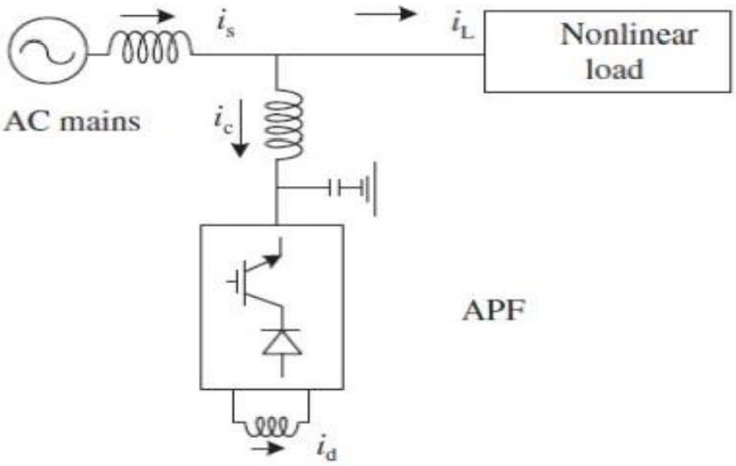


Fig. 4.51 A CSC-based SAPF

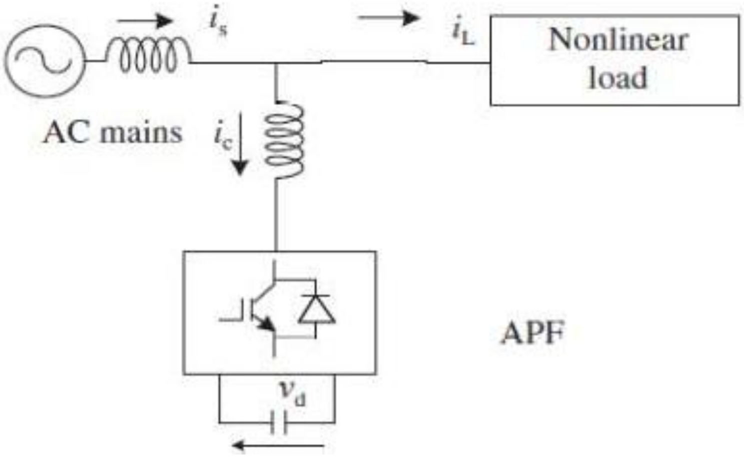


Fig. 4.52 A VSC-based SAPF

4.11.2.2 *Topology Based Classification*

SAPFs can also be classified based on topology, namely, half-bridge topology, full-bridge topology and H-bridge topology. Figures 4.53–4.56 show these topologies of SAPFs. The VSC-based half-bridge topology of SAPFs involves less number of solid-state devices and their control and hence is cheap and cost-effective. The VSC-based full-bridge topology of SAPFs is considered ideal for three-phase three wire and three-phase four-wire AC systems and it does not require transformers for isolation. The VSC based H-bridge topology of SAPFs consists of single-phase full H-bridges with two legs and four switching devices with independent control of each phase with unipolar switching to reduce the switching frequency and losses. Each H-bridge for each phase of VSC-based SAPFs needs a separate transformer for isolation, voltage matching and reliability from safety point of view, this is the most preferred configuration in SAPFs by the industries.

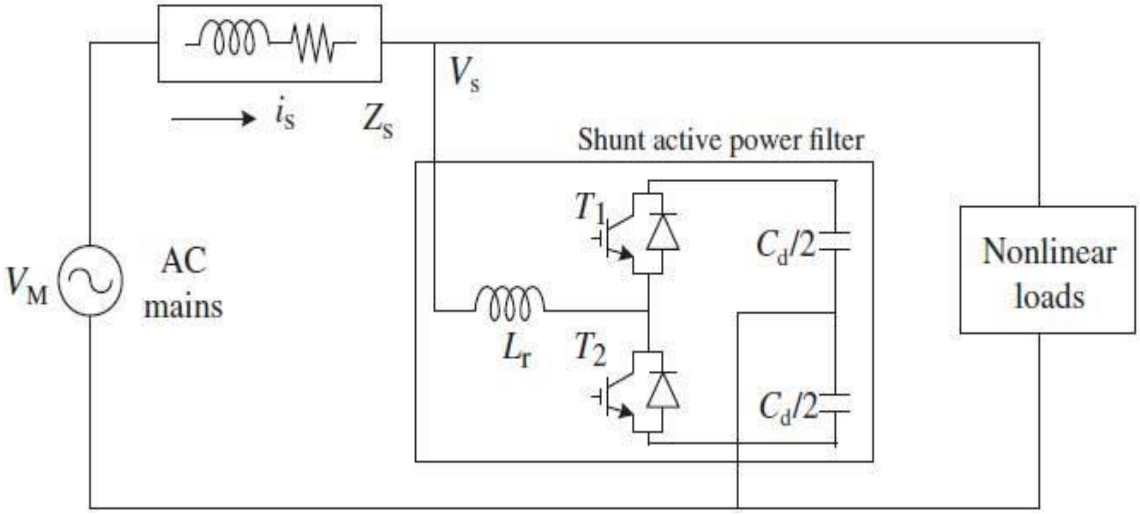


Fig. 4.53 Half-bridge topology of the VSC-based single-phase shunt active power filter

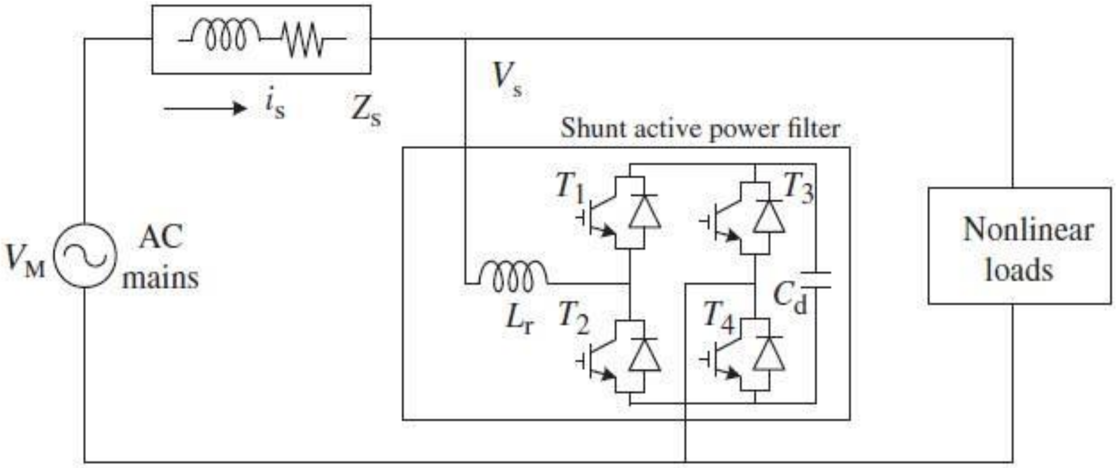


Fig. 4.54 Full-bridge topology of the VSC-based single-phase shunt active power filter

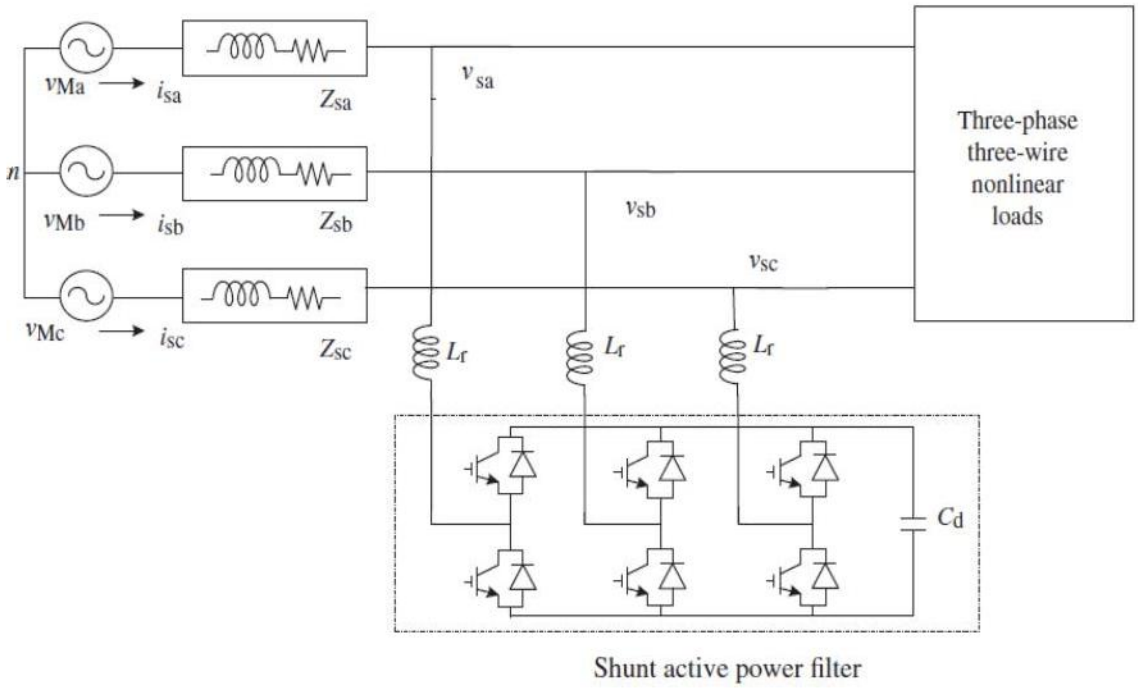


Fig. 4.55 A three-phase three-wire shunt active power filter

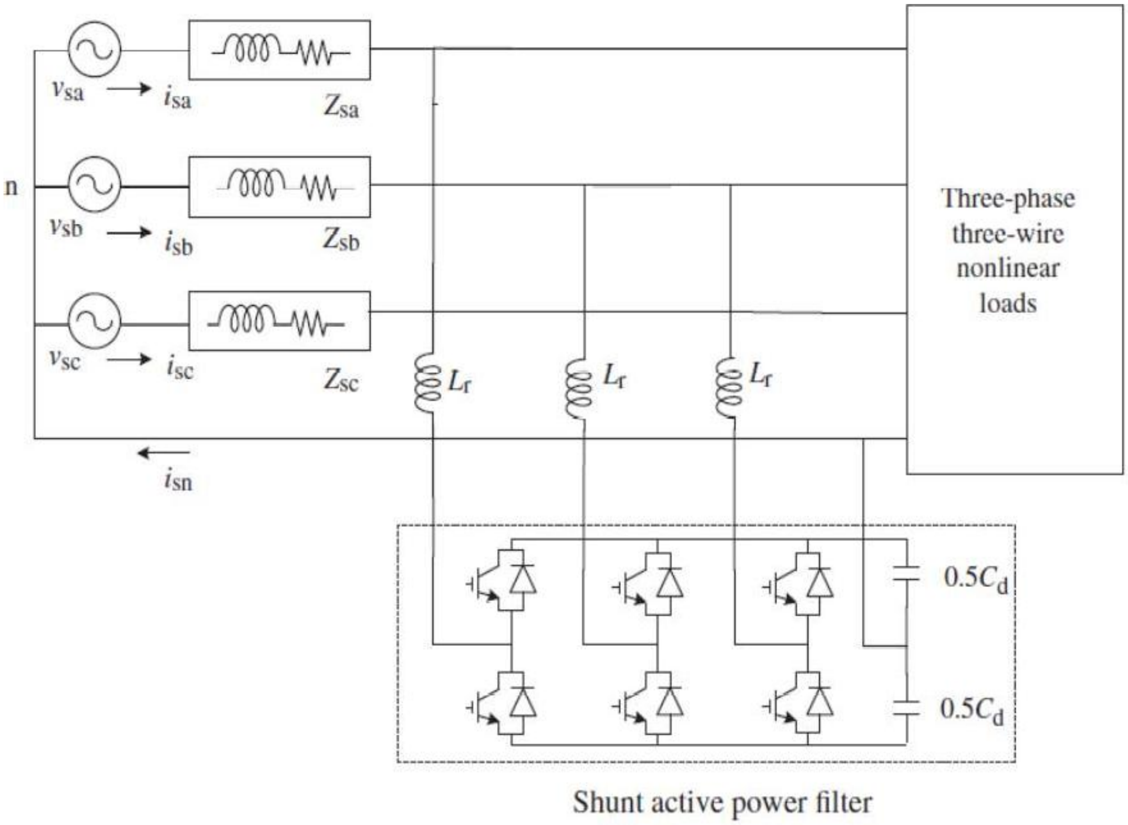


Fig. 4.56 A three-phase four-wire shunt active power filter with capacitor midpoint topology

4.11.2.3 *Supply System Based Classification*

This classification of SAPFs is based on the supply and/or the load system, namely, single-phase two wire, three-phase three-wire, and three-phase four-wire systems. There are many nonlinear loads such as domestic appliances connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral terminal, such as ASDs, fed from three-phase three-wire supply systems. There are many single-phase nonlinear loads distributed on three-phase four-wire supply systems, such as computers and commercial lighting Hence, these SAPFs may also be classified accordingly as two-wire, three-wire and four-wire SAPFs.

Two-Wire SAPFs:

Single-phase two-wire SAPFs are used in both converter configurations, namely, current source converter PWM bridge with inductive energy storage element and voltage source converter PWM bridge with capacitive DC bus energy storage element to form two-wire SAPF circuits. In some cases, active filtering is included in the power conversion stage to improve input characteristics at the supply end.

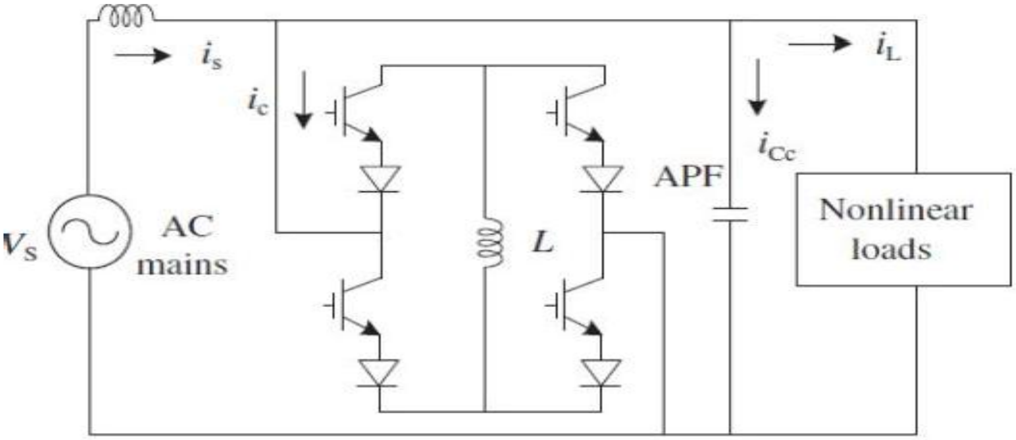


Fig. 4.57 A two-wire SAPF with a current source converter

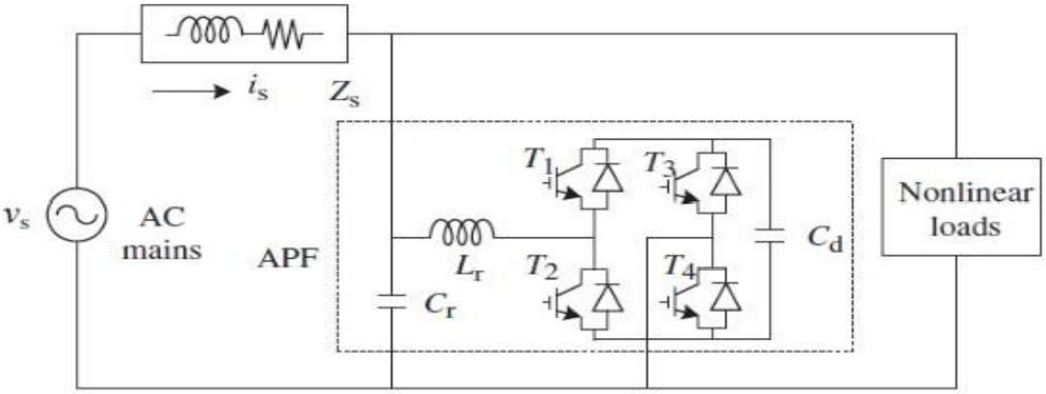


Fig. 4.58 A two-wire SAPF with a voltage source converter

Figures 4.57 and 4.58 show two detailed configurations of shunt active power filter with a current source converter using inductive storage element and a voltage source converter with capacitive DC bus energy storage element.

Three-Wire SAPFs:

Solid-state power converters have been widely used in three-phase three-wire nonlinear loads such as ASDs and lately many other electrical loads have also incorporated active power filters in their front design. A large number of publications have appeared on three-wire APFs with different configurations. All the configurations shown in figures 4.51–4.58 are developed in three-wire SAPFs, with three wires on the AC side and two wires on the DC side. SAPFs are developed in current fed type (Figure 4.51) or voltage fed type with single-stage (Figure 4.52) or multistep/multilevel and multi series configurations. Figure 4.59 shows a typical VSC-based three-wire SAPF. SAPFs are also designed with three single phase APFs with isolation transformers for proper voltage matching, independent phase control and reliable compensation with unbalanced systems.

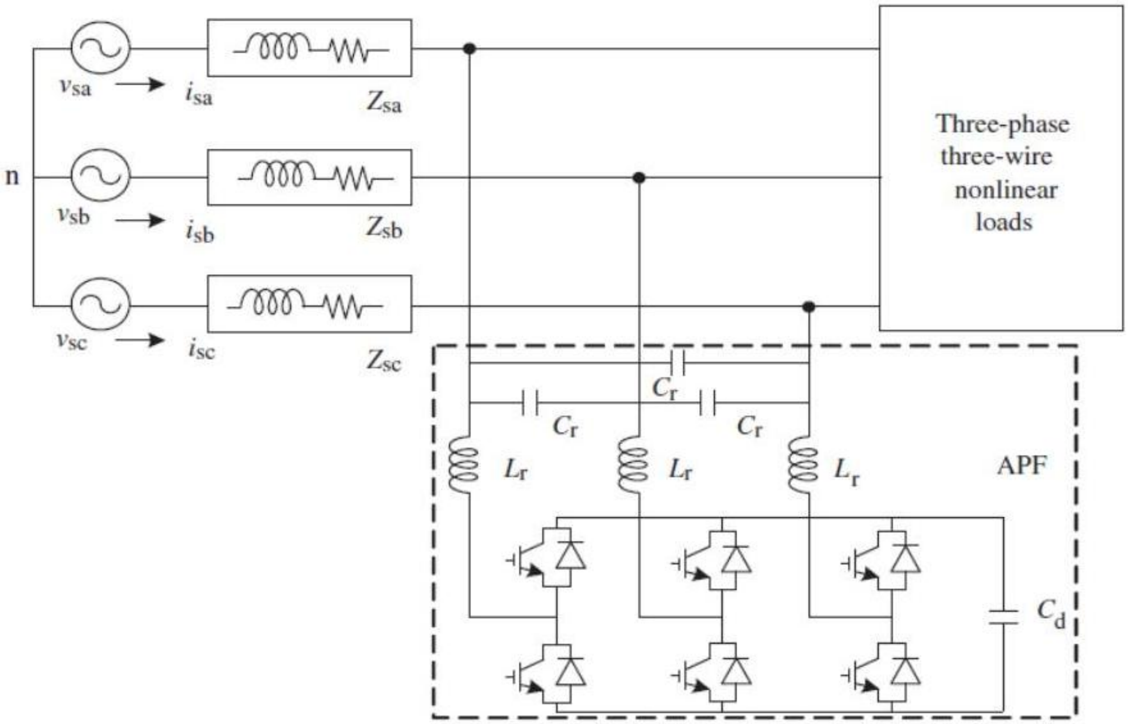


Fig. 4.59 A three-wire SAPF with a voltage source converter

Four-Wire SAPFs:

A large number of single-phase loads may be supplied from three-phase AC mains with a neutral conductor. They cause excessive neutral current, harmonics and reactive power burden and unbalanced currents. To reduce these problems, four-wire SAPFs have been used in four-wire distribution systems. They have been developed as active shunt mode with current fed converter and voltage fed converter.

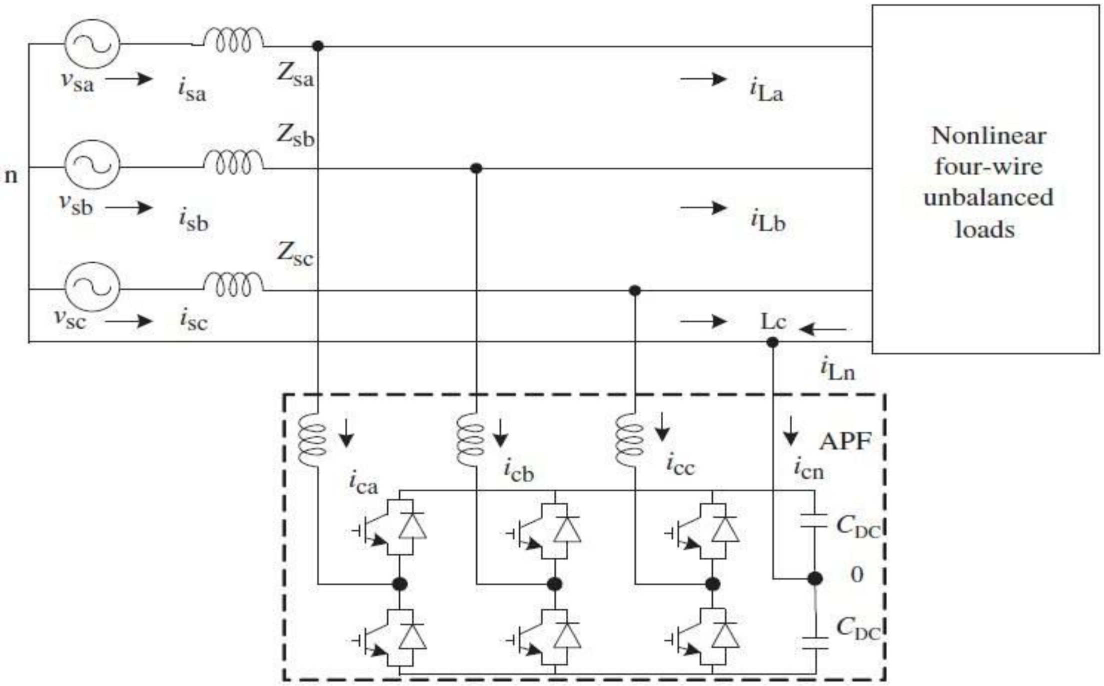


Fig. 4.60 A capacitor midpoint four-wire SAPF

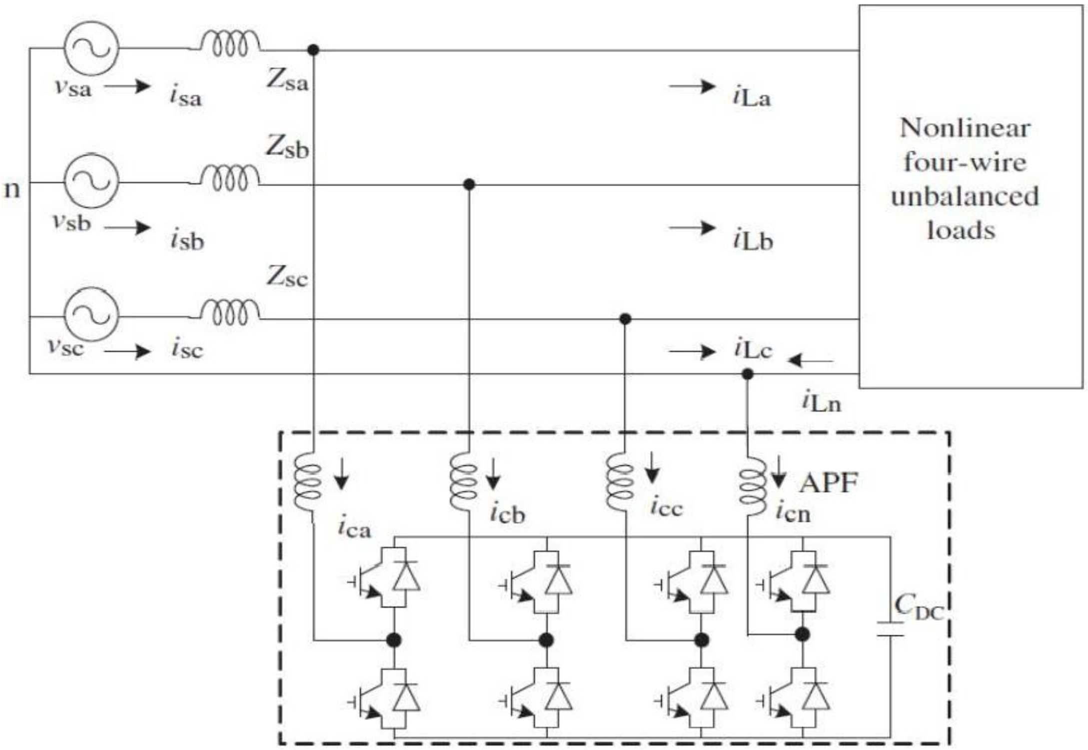


Fig. 4.61 A four-pole, four-wire SAPF

Figures 4.60–4.62 show three typical configurations of three-phase four-wire SAPFs. The first configuration of four-wire SAPFs is known as capacitor midpoint type used in smaller ratings. Here, the total neutral current flows through DC bus capacitors that are of large value. Figure 4.61 shows another configuration known as four-pole type, in which the fourth pole is used to stabilize the neutral terminal of the APF. A three single-phase H-bridge configuration as shown in figure 4.62 is quite common and this version uses a proper voltage matching for solid-state devices and enhances the reliability of the APF system.

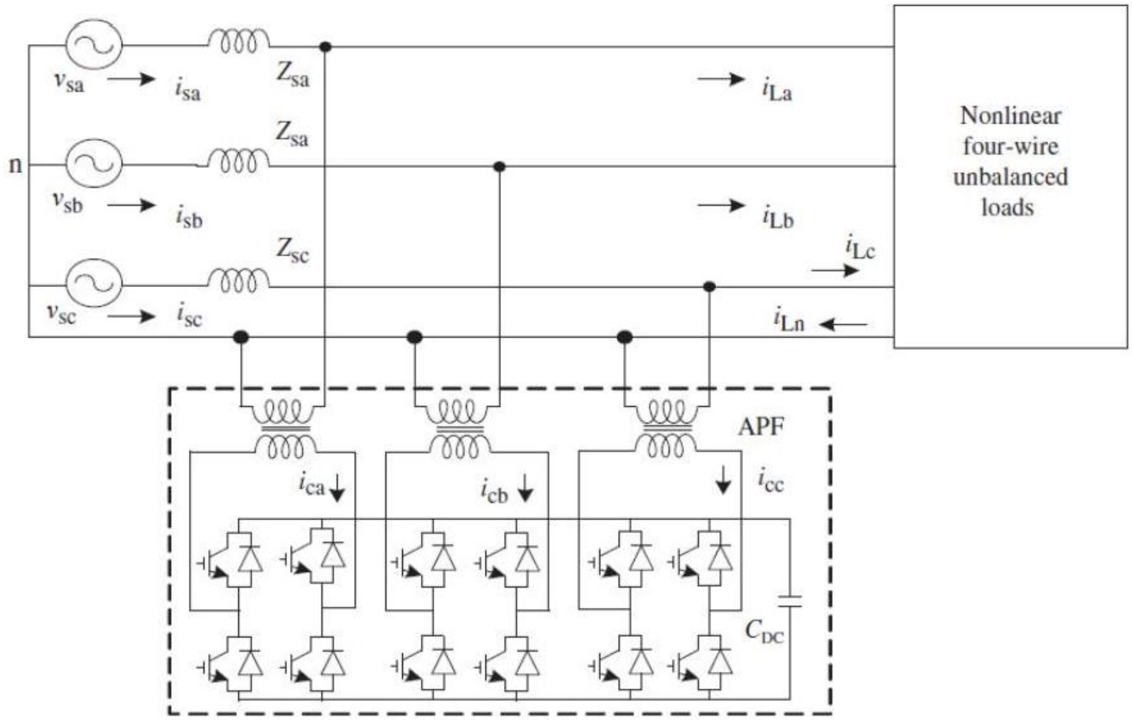


Fig. 4.62 A three H-bridge, four-wire SAPF

4.11.3 Principle of Operation of Shunt Active Power Filters

A fundamental circuit of SAPF for a three-phase, three-wire AC system with balanced/unbalanced NLL is shown in figure 4.59. An IGBT-based current-controlled voltage source converter (CC-VSC) with a DC bus capacitor is used as SAPF.

Using a control algorithm, the reference APF currents are directly controlled by estimating the reference APF currents. However, in place of APF currents, the reference currents may be estimated for an indirect current control of the VSC. The gating pulses to the APF are generated by employing hysteresis (carrier less PWM) or PWM (fixed frequency) current control over reference and sensed supply currents resulting in an indirect current control. Using SAPF, the supply current harmonics compensation, reactive power compensation and unbalanced currents compensation are achieved in all the control algorithms. In addition, zero voltage regulation (ZVR) at the point of common coupling (PCC) is also achieved by modifying the control algorithm suitably.

4.11.3.1 *Principle of Operation of Shunt Active Power Filters*

The main objective of shunt active power filters is to mitigate multiple power quality problems in a distribution system. SAPF mitigates most of the current quality problems, such as reactive power, unbalanced currents, neutral current, harmonics and fluctuations, present in the consumer loads or otherwise in the system and provides sinusoidal balanced currents in the supply along with its DC bus voltage control.

In general, a SAPF has a VSC connected to a DC bus and its AC side is connected in shunt normally across the consumer loads or across the PCC as shown in Figure 4.59. The VSC uses PWM current control. Therefore, it requires small ripple filters to mitigate switching ripples. It requires Hall Effect voltage and current sensors for feedback signals and normally a digital signal processor (DSP) is used to implement the required control algorithm to generate gating signals for the solid-state devices of the VSC of the SAPF. The VSC used as SAPF is normally controlled in PWM current control mode to inject appropriate currents into the system. The SAPF also needs many passive elements such as a DC bus capacitor, AC interacting inductors, and small passive filters.

4.11.3.2 *Control of Shunt Active Power Filters*

There are many control algorithms reported in the literature for the control of SAPFs, which are classified as time-domain and frequency-domain control algorithms. There are more than a dozen of time-domain control algorithms that are used for the control of SAPFs. A few of these time-domain control algorithms are as follows,

- Synchronous reference frame (SRF) theory, also known as d–q theory
- Unit template technique or proportional–integral controller-based theory
- Instantaneous reactive power theory, also known as PQ theory or α–β theory
- Instantaneous symmetrical component (ISC) theory
- Power balance theory (BPT)
- Neural network theory (Widrow’s LMS-based Adaline algorithm)
- Current synchronous detection (CSD) method
- I-cosΦ algorithm
- Singe-phase PQ theory

- Singe-phase DQ theory
- Enhanced phase locked loop (EPLL)-based control algorithm
- Conductance-based control algorithm
- Adaptive detecting algorithm, also known as adaptive interference canceling theory

Similarly, there are around the same number of frequency-domain control algorithms. Some of them are as follows,

- Fourier series theory
- Discrete Fourier transform theory
- Fast Fourier transform theory
- Recursive discrete Fourier transform theory
- Kalman filter-based control algorithm
- Wavelet transformation theory
- Stock well transformation (S-transform) theory
- Empirical decomposition (EMD) transformation theory
- Hilbert–Huang transformation theory

4.11.4 Analysis and Design of Shunt Active Power Filters

The design of three-phase three-wire shunt active power filters includes the design of the VSC and its other passive components. The shunt active power filter includes a VSC, interfacing inductors and a ripple filter. The design of the VSC includes the DC bus voltage level, the DC capacitance and the rating of IGBTs.

A three-phase three-wire shunt active power filter topology is considered for detailed analysis. Figure 4.59 shows a schematic diagram of one of the shunt active power filters for a three-phase three-wire distribution system. It uses a three-leg VSC-based shunt active power filter. The design of the shunt active power filter is discussed in the following sections through the example of a 50 kVA shunt active power filter.

4.11.5 Modeling, Simulation and Performance of Shunt Active Power Filters

The model of the SAPF is developed along with a non-stiff source, nonlinear loads and the VSC with other passive components. The nonlinear load is modeled using a three-phase uncontrolled rectifier with constant DC current. The VSC of the APF is modeled using

IGBT switches with a DC capacitor connected at the DC bus. The active filter is connected at PCC with a ripple filter and an interfacing inductor to eliminate high-frequency switching components. The switch-in response of the APF and load dynamics are implemented by incorporating circuit breaker models in the system. The simulation of three APFs with a three-wire and a four-wire system using MATLAB along with SIMULINK and SIM Power System toolboxes are described for the application of harmonics elimination, load balancing, and power factor correction.

4.12 Series Active Power Filters

There are a number of voltage quality problems in the AC mains nowadays, such as harmonics, sag, dip, flicker, swell, fluctuations, and imbalance and these problems increase losses in many loads and sometimes trip the sensitive loads causing loss of production. The DVRs (dynamic voltage restorers), which are mainly used for dynamic compensation of voltage quality problems such as sag, dip, flicker, swell, fluctuations, and imbalance, have already been explained in Chapter 5. However, the series active power filter (APF) protects the sensitive loads from these distortions (especially harmonics) in the voltage of the AC mains. As its name represents, a series active filter is expected to filter voltage harmonics appearing in the supply systems so that the loads are supplied with clean sinusoidal supply voltage.

Moreover, the solid-state control of AC power employing diodes, thyristors, and other semiconductor switches is extensively used to feed controlled power to electrical loads such as adjustable speed drives (ASDs), furnaces, computer power supplies, fax machines, copier, and printers. As nonlinear loads, the solid-state converters draw harmonics and reactive power components of current in addition to fundamental active power component of the current from the AC mains. Moreover, voltage-fed nonlinear loads (such as a diode rectifier with a large DC bus capacitor filter) used to realize the DC voltage source with the DC capacitor is increasingly used nowadays for feeding the voltage source inverter (VSI) in many applications. Such voltage-fed nonlinear loads draw peaky and discontinuous current and inject a large amount of harmonic currents into the AC mains. In such situations, series APFs are quite effective for harmonic current compensation with moderate rating. In current-fed nonlinear loads, a small-rating series active filter (approximately 3–5% of the load rating) is used along with a large-rating passive shunt filter to improve the filtering characteristics of the passive filter and the hybrid filter as a combination of these two filters is an adjustable solution for the harmonic compensation of varying loads. This type of filter is considered as a cost-effective filter especially in large rating.

4.12.1 State of the Art on Series Active Power Filters

The series APF technology is now a mature technology for providing compensation for harmonics present in the voltages and currents in AC networks. It has evolved in the past quarter century with development in terms of varying configurations, control strategies, and solid-state devices. The series active power filters are mainly used to eliminate voltage harmonics. In addition, they can be used to regulate the terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems, of course, with additional cost and rating. The series active power filters are also used to eliminate harmonic currents in voltage-fed nonlinear loads. Moreover, they are also used in current-fed nonlinear loads along with passive filters. These objectives of the series active power filters are achieved either individually or in combination depending upon the requirements and control strategy and configuration that need to be selected appropriately. This section describes the history of development and the current status of the series APF technology.

Following the widespread use of solid-state control of AC power, the power quality problems have become significant. The series active power filters are basically categorized into three types, namely, single-phase two-wire, three-phase three-wire, and three-phase four-wire configurations, to meet the requirements of the three types of nonlinear loads on supply systems. Single-phase loads such as domestic lights and ovens, television sets, computer power supplies, air conditioners, laser printers, and Xerox machines behave as voltage-fed nonlinear loads and cause substantial power quality problems. Single phase two-wire series active power filters are investigated in varying configurations and control strategies to meet the needs of single-phase nonlinear loads. Starting from 1976, many configurations of the series active power filter with current source converters (CSCs), voltage source converters (VSCs) and soon have been evolved for the compensation of voltage- and current-based power quality problems. Both current source converters with inductive energy storage and voltage source converters with capacitive energy storage are used to develop the single-phase series APFs.

One of the major factors in advancing the series APF technology is the advent of fast, self-commutating solid-state devices. In the initial stages, BJTs (bipolar junction transistors) and power MOSFETs (metal oxide semiconductor field-effect transistors) have been used to develop series APFs; later, SITs (static induction thyristors) and GTOs (gate turn-off thyristors) have been employed to develop series APFs. With the introduction of IGBTs (insulated gate bipolar transistors), the series APF technology has got a real boost and at present it is considered as an ideal solid-state device for series APFs. The improved sensor technology has also contributed to the enhanced performance of the series APFs. The availability of Hall Effect voltage and current sensors and isolation amplifiers at reasonable cost with adequate ratings has improved the performance of the series APFs.

4.12.2 Classification of Series Active Filters

Series active power filters can be classified based on the type of converter used, topology, and the number of phases. The converter can be either a current source converter or a voltage source converter. The topology can be circuit configurations used to develop the series APF, such as half bridge and full bridge. The third classification is based on the number of phases, for example, single-phase two-wire, three-phase three-wire, and three-phase four-wire series APF systems.

4.12.2.1 Converter-Based Classification of Series APFs

Two types of converters are used in the development of the series APFs. Figure 4.63 shows a single-phase series APF using a current source converter. It behaves as a non sinusoidal voltage source to meet the harmonic voltage requirement to feed clean sinusoidal voltage to the consumer loads. A diode is used in series with the self-commutating device (IGBT) for reverse voltage blocking. However, GTO-based configurations do not need the series diode, but they have restricted frequency of switching. They are considered sufficiently reliable, but have high losses and require high values of parallel AC power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings.

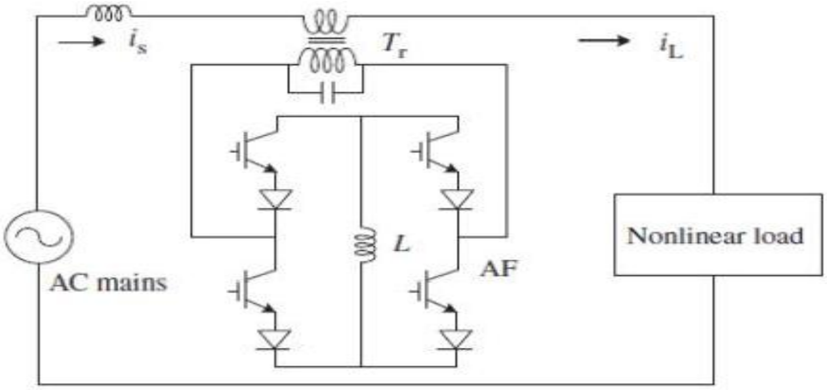


Fig. 4.63 A two-wire series APF with a current source converter

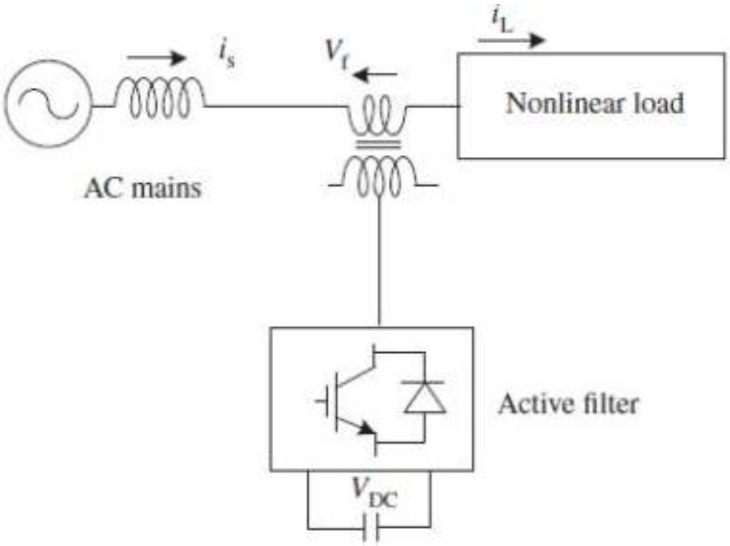


Fig. 4.64 A series APF with a voltage source converter

The other power converter used as a series APF is a voltage source converter shown in Figure 4.64. It has a self-supporting DC voltage bus with a large DC capacitor. It is more widely used because it is light, cheap and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies.

4.12.2.2 Topology-Based Classification of Series APFs

Series APFs can also be classified based on the topology used. Combinations of an active series filter and a passive shunt filter are known as hybrid filters. Figures 4.65 and 4.66 show half-bridge and full-bridge topologies of VSC-based series APFs. The active series filters are most widely used to eliminate voltage harmonics at the load end to provide clean power to consumer loads. They are also used to block harmonic currents of voltage-fed nonlinear loads, which effectively reduce voltage harmonics at PCC.

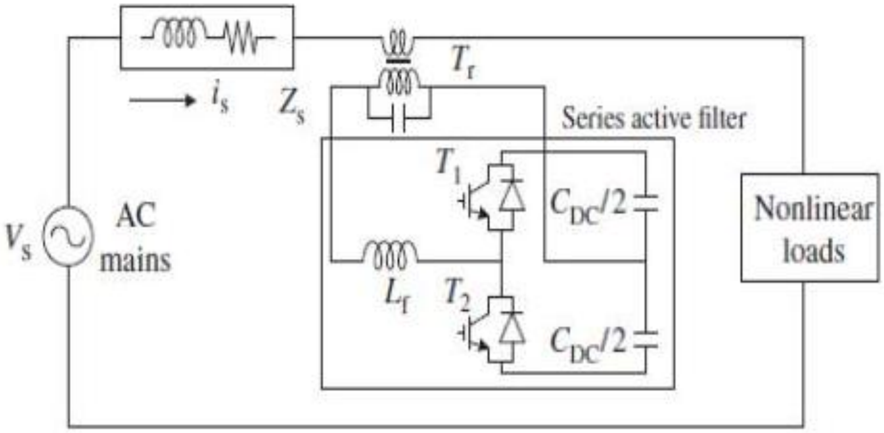


Fig. 4.65 Half-bridge topology of a VSC-based single-phase series filter

Figure 4.67 shows a basic block of a series active power filter. It is connected before the load in series with the AC mains, using a matching transformer, to eliminate voltage harmonics and to balance and regulate the terminal voltage across the load. It can also be used to reduce negative-sequence voltage and to regulate the voltage on three-phase systems but at the cost of additional rating. It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and/or passive shunt compensators.

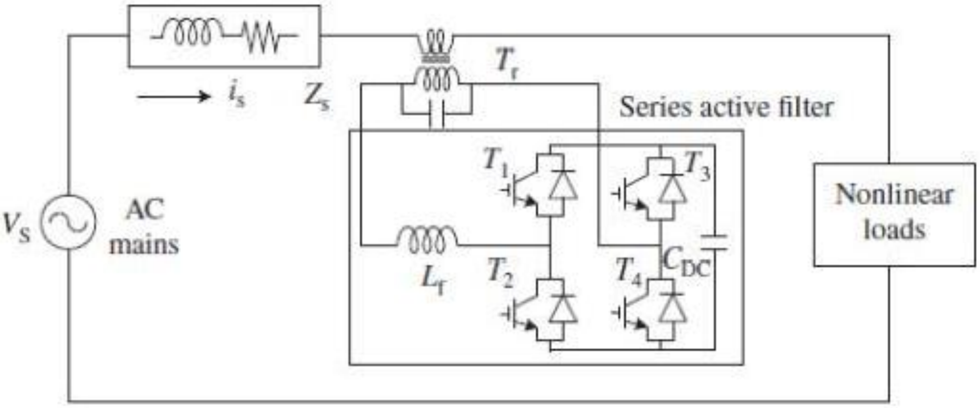


Fig. 4.66 Full-bridge topology of a VSC-based single-phase series filter

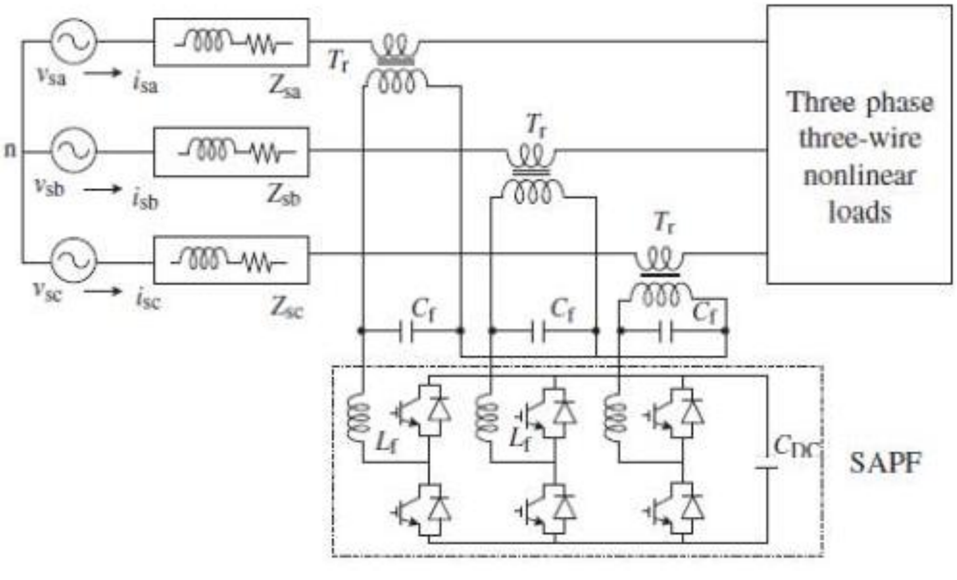


Fig. 4.67 A three-phase three-wire active series filter

4.12.2.3 Supply System-Based Classification of Series APFs

This classification of series APFs is based on the supply and/or the load system having single-phase (two wire) and three-phase (three-wire or four-wire) series APF systems. There are many nonlinear loads such as domestic appliances connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral terminal, such as ASDs fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on three-phase four-wire supply systems, such as computers and commercial lighting. Hence, the series APFs may also be classified accordingly as two-wire, three-wire, and four wire series APFs.

Two-Wire Series APFs:

Single-phase VSCs and CSCs are used as two-wire series active power filters. Both power converter configurations, current source converters with inductive energy storage elements and voltage source converters with capacitive DC bus energy storage elements are used to form two-wire series AF circuits. In some cases, active filtering is included in the power conversion stage to improve input characteristics at the supply end. Figures 4.65 and 4.66 show the configurations of series active power filters with voltage source converters. In the case of a series APF with a voltage source converter, sometimes the transformer is removed and the load is shunted with passive *LC* components. The series APF is normally used to eliminate voltage harmonics, spikes, sags, notches and so on.

Three-Wire Series APFs:

Three-phase three-wire nonlinear loads such as ASDs are one of the major applications of solid-state power converters and lately many ASDs incorporate active power filters in their front-end design. Figure 4.67 shows a three-wire series APF, with three wires on the AC side and two wires on the DC bus of the VSC used as the series APF. Series APFs are developed using CSCs as shown in figure 4.63. VSCs as shown in figure 4.64, or multistep/multilevel and multi series configurations. Series APFs are also designed with three single-phase APFs with isolation transformers for proper voltage matching, independent phase control and reliable compensation with unbalanced systems.

Four-Wire Series APFs:

A large number of single-phase loads may be supplied from three-phase AC mains with a neutral conductor. They cause excessive neutral current, injection of current harmonics and subsequently voltage harmonics, and unbalance. To reduce these problems, four-wire series APFs are used in four-wire distribution systems. They are developed as series active power filters in the typical configuration shown in Figure 4.68. A three single-phase VSC bridge configuration, shown in Figure 4.68, is quite common and this version allows proper voltage matching for solid-state devices and enhances the reliability of the APF system.

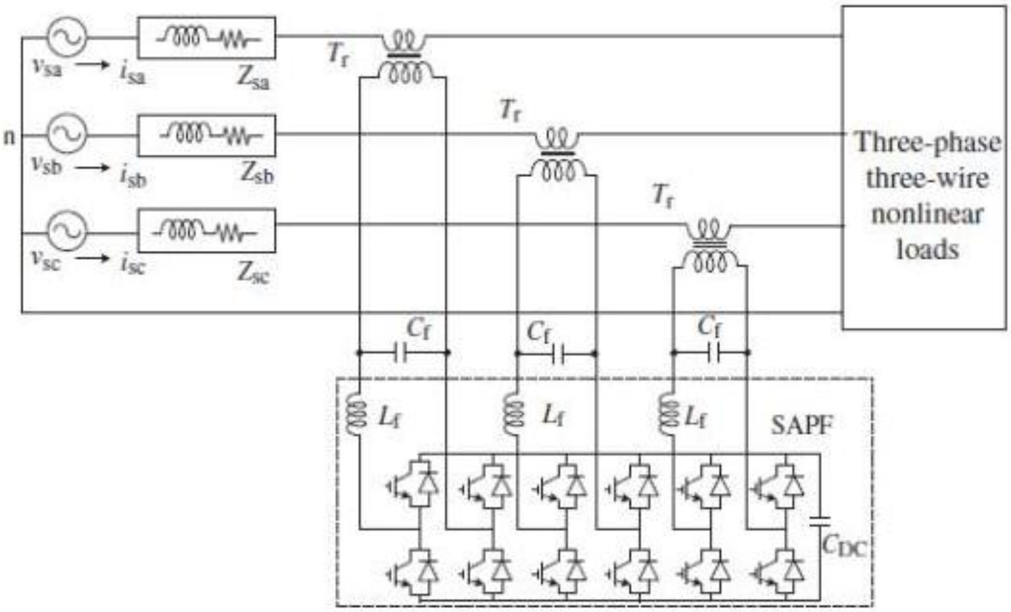


Fig. 4.68 A three-phase four-wire series active filter with three single-phase VSC bridge topology

4.12.3 Principle of Operation of Series Active Power Filters

The basic function of series active power filters is to mitigate most of the voltage-based power quality problems, mainly voltage harmonics present at PCC, and to provide sinusoidal balanced voltages even across linear loads with its self-supporting DC bus by injecting suitable voltages in series between the PCC and the load. The series active power filters are also found quite effective in eliminating harmonics in supply currents in voltage-fed nonlinear loads (such as a diode rectifier with a large DC bus capacitor filter) with quite small rating by injecting suitable voltages. In addition, the series APFs are also used in current-fed nonlinear loads along with passive filters to eliminate supply current harmonics.

These objectives of the series active power filters are achieved either individually or in combination depending upon the requirements and control strategy and configuration that need to be selected appropriately. A fundamental circuit of the series APF for a three-phase three-wire AC system is shown in figure 4.69. An IGBT-based voltage source converter (CC-VSC) with a DC bus capacitor is used as a series APF. Using a control algorithm, the reference voltages or currents are estimated and the sensed voltages or currents are directly controlled close to reference voltages or currents by the voltage source converter used as the series APF.

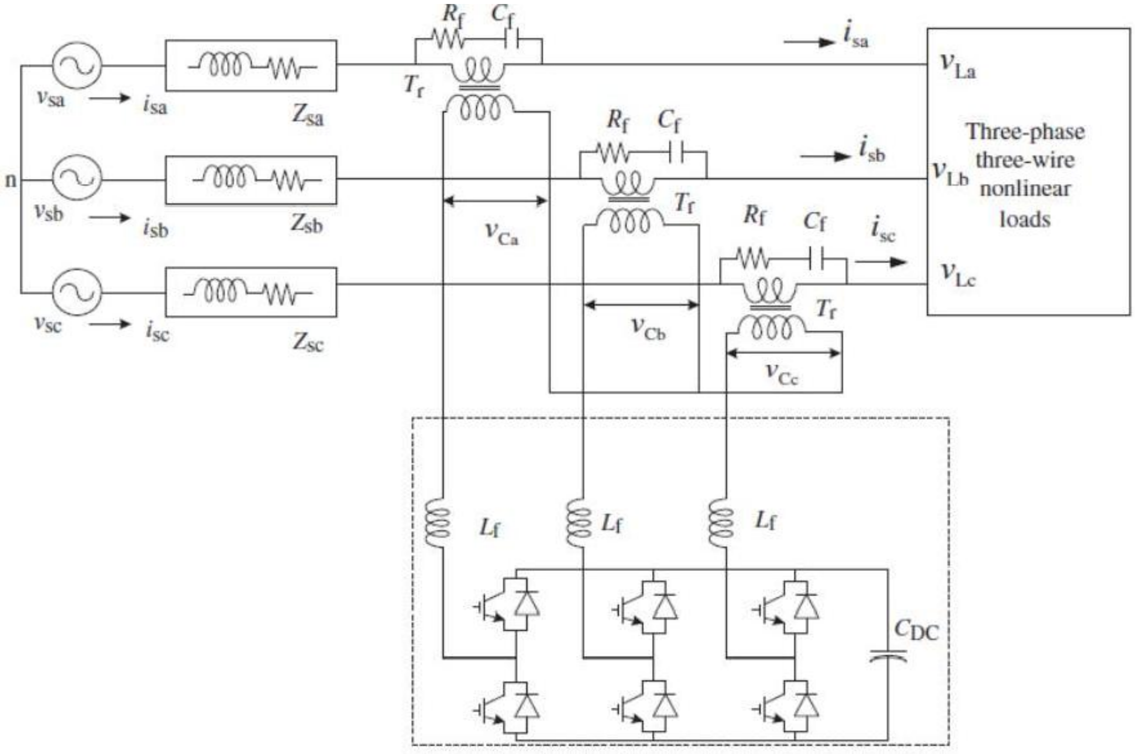


Fig. 4.69 System configuration of a three-phase series active filter

Principle of Operation of Series Active Power Filters:

Figure 4.69 shows the circuit diagram of a series active power filter system, which consists of a three phase VSC connected in series with three-phase supply through three single-phase coupling transformers. A three-phase VSC with a DC bus capacitor is used as a series active power filter. A small-rating *RC* filter is connected across secondary of each series transformer to eliminate high switching ripple content in the series active power filter injected voltage. The loads may include linear loads requiring elimination of voltage harmonics across them or voltage-fed nonlinear loads, such variable-frequency AC motor drives, as balanced harmonic-producing loads requiring elimination of supply current harmonics.

A single series filter may be installed at the PCC for multiple diverse types of loads for the elimination of voltage harmonics across them. However, such a configuration is susceptible to danger under short-circuit condition in utility line and thus requires an adequate protection. The series APF is controlled to eliminate harmonics in the three-phase supply currents or distortion and unbalance in the PCC voltages by injecting suitable voltage in series with the supply.

For the voltage-fed nonlinear loads, which consist of a capacitive filter and an equivalent load at the DC link of a three-phase diode rectifier, a series APF alone can effectively maintain sinusoidal supply currents. However, for the current-fed nonlinear loads, which consist of the series connection of a resistor and an inductor at the DC link of a three-phase diode rectifier or a three-phase thyristor bridge converter, a combined system of the shunt passive filters and a series active power filter needs to be employed to effectively maintain sinusoidal supply currents.

The control algorithm of the series active filter to eliminate current harmonics is suitable for both the series active filter and hybrid configurations of a series active power filter with a shunt passive filter. Moreover, for voltage-sensitive loads, to eliminate the voltage harmonics and unbalance and to maintain zero voltage regulation at PCC, the series APF is directly controlled to inject sufficient voltage in series with the supply; that is, the sum of supply voltage and injected voltage becomes sinusoidal with desired amplitude across the loads.

4.12.4 Analysis and Design of Series Active Power Filters

The analysis and design of the series active power filters include the detailed analysis for deriving the design equations for calculating the values of different components used in their circuit configurations. As already discussed in the previous section, there are a large number of topologies of the series active power filters; therefore, the design of a large number of circuit configurations is not practically possible to include here due to space constraints. In view of these facts, the step-by-step design procedure of a selected topology of a series active power filter is given here. The design of a three-phase three-wire series active power filter includes the design of a VSC, interfacing inductors, and a ripple filter. The design of the VSC includes the selection of the DC bus voltage level, the DC capacitance, and the rating of IGBTs.

4.12.5 Modeling, Simulation and Performance of Series Active Power Filters

The MATLAB-based models of different topologies of series APF systems are developed using SIMULINK and SIM Power Systems (SPS) toolboxes to simulate the performance of the series active power filters in single-phase and three-phase distribution systems. A large number of cases of the topologies of series active power filters are given in solved examples. Here, the performance of typical developed models of series APFs is illustrated with stiff supply under (a) linear load (b) nonlinear load and (c) DC link of the series APF connected to the DC bus of the load.

4.13 Hybrid Power Filters

Solid-state conversion of AC power using diodes and thyristors is widely adopted to control a number of processes such as adjustable speed drives (ASDs), furnaces, chemical processes such as electroplating, power supplies, welding and heating. The solid-state converters are also used in power industries such as HVDC transmission systems, battery energy storage systems, and interfacing renewable energy electricity generating systems. Some solid-state controllers draw harmonic currents and reactive power from the AC mains and behave as nonlinear loads. Moreover, in three-phase AC mains, they cause unbalance and excessive neutral current resulting in low power factor and poor efficiency of the system. In addition, they cause poor utilization of the distribution system, RFI and EMI noise, interference to the communication system, voltage distortion, disturbance to neighboring consumers, and poor power quality at the AC source due to notch, sag, swell, noise, spikes, surge, flicker, unbalance, low-frequency oscillations and malfunction of protection systems. Because of the severity of power quality problems, several standards are developed and are being enforced on the consumers, manufacturers, and utilities.

Moreover, the power community has become more conscious about these problems and a number of technology options are reported in the texts and research publications. Initially, lossless passive filters (*LC*) have been used to reduce harmonics and capacitors have been chosen for power factor correction of the nonlinear loads. But passive filters have the demerits of fixed compensation, large size, and resonance with the supply system. Active power filters (APFs) have been explored in shunt and series configurations to compensate different types of nonlinear loads. However, they have drawbacks that their rating sometimes is very close to the load (up to 80%) in some typical applications and thus they become a costly option for power quality improvement in a number of situations. Moreover, a single active power filter does not provide a complete solution for compensation in many cases of nonlinear loads due to the presence of both voltage and current-based power quality problems. However, many researchers have classified different types of nonlinear loads and have suggested various filter options for their compensation. Because of higher rating of APFs and cost considerations, the acceptability of the APFs by the users has faced a hindrance in practical situations. In response to these factors, a series of hybrid power filters

(HPFs) is evolved and extensively used in practice as a cost-effective solution for the compensation of nonlinear loads.

Moreover, the HPFs are found to be more effective in providing complete compensation of various types of nonlinear loads. The rating of active filters is reduced by adding passive filters to form hybrid filters, which reduces the overall cost, and in many instances they provide better compensation than either passive or active filters. Therefore, it is considered a timely attempt to present a broad perspective on the hybrid filter technology for the power community dealing with power quality issues.

4.13.1 State of the Art on Hybrid Power Filters

The technology of power filters is now a mature technology for compensating different types of nonlinear loads through current-based compensation and for improving the power quality of AC supply through voltage-based compensation techniques that eliminate voltage harmonics, sags, swell, notches, glitches, spikes, flickers, and voltage unbalance and provide voltage regulation. Moreover, these filters are also identified according to the nature of nonlinear loads such as voltage-fed loads (voltage stiff or voltage source on the DC side of the rectifier through the capacitive filter), current-fed loads (current stiff or current source on the DC side of the DC motor drive or current source for the CSI-fed AC motor drive) and a combination of both. Various topologies such as passive, active, and hybrid filters in shunt, series and a combination of both configurations for single-phase two-wire, three-phase three-wire, and three phase four-wire systems have been proposed using current source and voltage source converters to improve the power quality at the AC mains. As mentioned earlier, hybrid filters are a cost-effective and perfect solution for the compensation of nonlinear loads and for providing clean and ideal AC supply to a variety of loads. This section describes the chronological development and the current status of the HF technology.

Because of the extensive use of solid-state converters, the pollution level in the AC supply system is increasing rapidly and power quality has become an important area of research. A number of standards, surveys and texts have been published for improving the power quality and maintaining it to the prescribed level through different approaches in single-phase two-wire, three-phase three-wire and three phase four-wire systems. Moreover, hybrid filters are developed using one, two, or three passive and active filters either to improve their performance or to reduce the cost of the system compared with single active or passive filters. Lossless passive filters (*LC*) have been used for a long time as a combination of single tuned, double tuned, and damped high-pass filters either to absorb current harmonics by creating a harmonic valley in shunt with current-fed nonlinear loads (thyristor based DC motor drive, HVDC, DC current source for CSI, etc.) or to block harmonic currents by creating a harmonic dam in series with voltage-fed nonlinear loads. However, the passive filters have the limitations of fixed compensation and resonance with the supply system, which are normally overcome by using AFs). A single unit of AF normally has a high rating resulting in high cost and even does not provide complete compensation. The rating of active filters is reduced by adding passive filters to form hybrid filters, which reduces the overall cost and in many instances they provide better compensation than either passive or active filters. However, if one can afford the cost, then a hybrid of two active filters provides the perfect and best solution and thus it is known as a universal power quality conditioner or universal active power conditioner (UAPC). Therefore, the development in hybrid filter technology has been from a hybrid of passive filters to a hybrid of active filters that is from a cost-effective solution to a perfect solution.

In a single-phase system, there are a large number of nonlinear loads such as fluorescent lamps, ovens, TVs, computers, air conditioners, power supplies, printers, copiers and high-rating furnaces and traction systems. These loads are compensated using a hybrid of passive filters as a low-cost solution and a hybrid of active filters in the traction. A major amount of power is processed in a three-phase three-wire system either in ASDs in small rating to reasonable power level or in the HVDC transmission system in high power rating and they behave as nonlinear loads. These loads are also compensated by using either a group of passive filters or a combination of active and passive filters in different configurations depending upon their nature to the AC system, such as current-fed loads, voltage-fed loads, or a combination of both. Vastly distributed single-phase nonlinear loads cause power quality problems in a three-phase four-wire AC system and are compensated by using a number of passive filters, active filters or hybrid filters.

One of the major reasons for the advancement in hybrid filter technology using active filter elements is the development of fast self-commutating solid-state devices such as MOSFETs (metal-oxide semiconductor field-effect transistors) and IGBTs (insulated gate bipolar transistors). An improved and low cost sensor technology is also responsible for reducing the cost and improving the response of HPFs. Fast Half effect sensors and compact isolation amplifiers have resulted in HPFs with affordable cost. Another major factor that has contributed to the HPF technology is the evolution of microelectronics. The development of low-cost, high-accuracy, and fast digital signal processors (DSPs), microcontrollers and application-specific integrated circuits (ASICs) has made it possible to implement complex control algorithms for online control at an affordable price. A number of control theories of HPFs such as instantaneous reactive power theory (IRPT), synchronously rotating frame (SRF) theory, and many more with several low-pass, high-pass, and band-pass digital filters along with several closed-loop controllers such as proportional–integral (PI) controller and sliding mode controller (SMC) have been employed to implement hybrid filters. Moreover, many manufacturers are developing hybrid filters even in quite large power rating to improve the power quality of a variety of nonlinear loads.

4.13.2 Classification of Hybrid Filters

HPFs can be classified based on the number of elements in the topology, supply system, and type of converter used in their circuits. The supply system can be a single-phase two-wire, three-phase three-wire or three-phase four-wire system to feed a variety of nonlinear loads. The converter can be a VSC or a CSC to realize the APF part of the hybrid power filter with appropriate control. The number of elements in the topology can be either two, three or more, which may be either APFs or passive power filters (PPFs).

Here, the main classification is made on the basis of the supply system with further sub classification on the basis of filter elements. Figure 4.70 shows the proposed classification of hybrid power filters based on the supply system with topology as further sub classification. However, there is common sub classification in each case of the supply system. Therefore, major classification is made on the basis of number (two and three) and types of elements (passive and active filters) in different topologies in each case of the supply system. The hybrid filters consisting of two passive elements have two circuit configurations, as shown in figures 4.71 and 4.72 and those consisting of three passive elements also have two circuit configurations, as shown in figures 4.73 and 4.74.

The hybrid filters consisting of two elements, one active and one passive filter, have eight valid circuit configurations, as shown in Figures 4.75–4.82. Similarly, the hybrid filters consisting of three elements, two passive with one active and one passive with two active filter elements, have 18 valid circuit configurations each, resulting in 36 circuit configurations, as shown in figures 4.83–4.118. The hybrid filters consisting of two and three active filter elements have two circuit configurations each, as shown in Figures 4.119–4.122. The hybrid filters consisting of more than three elements are rarely used due to cost and complexity considerations and hence are not included here. The hybrid filters consisting of two and three active and passive elements result in 52 practically valid circuit configurations.

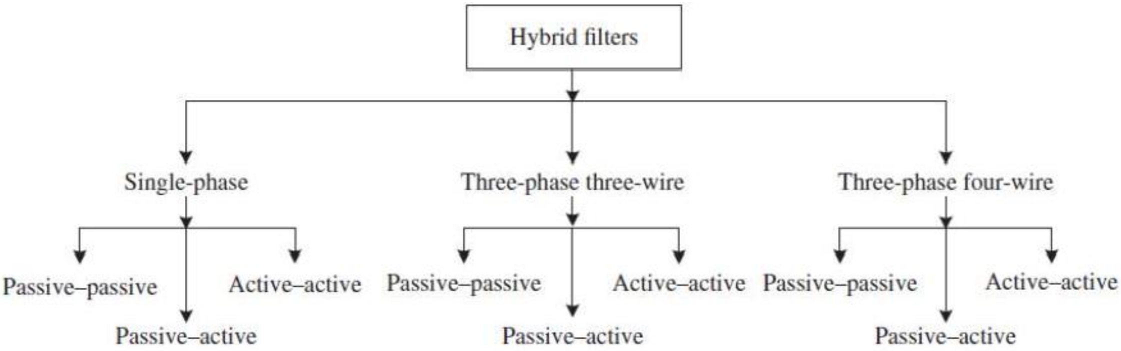


Fig. 4.70 Classification of hybrid filters for power quality improvement

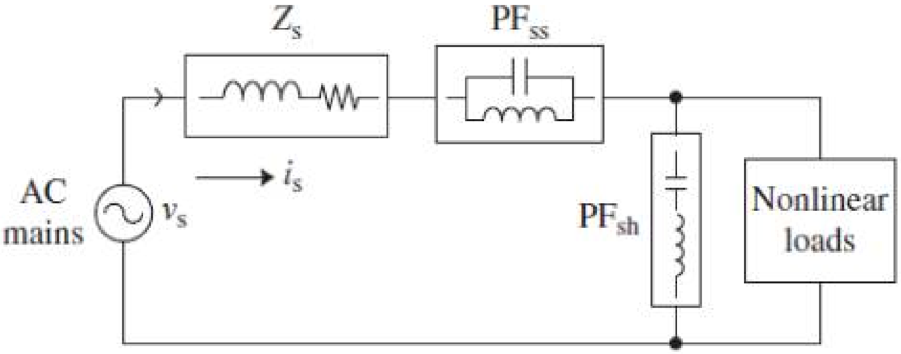


Fig. 4.71 A hybrid filter as a combination of passive series (PF_{ss}) and passive shunt (PF_{sh}) filters

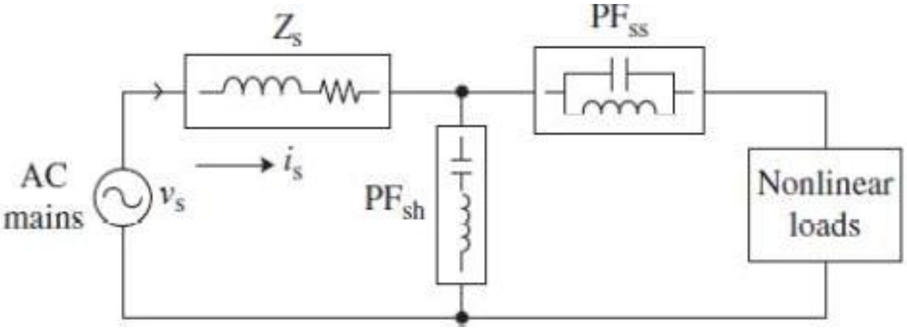


Fig. 4.72 A hybrid filter as a combination of passive shunt (PF_{sh}) and passive series (PF_{ss}) filters

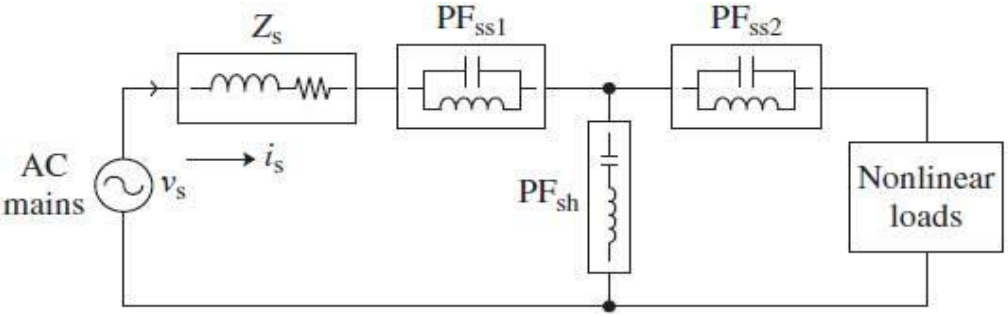


Fig. 4.73 A hybrid filter as a combination of passive series (PF_{ss1}), passive shunt (PF_{sh}), and passive series (PF_{ss2}) filters

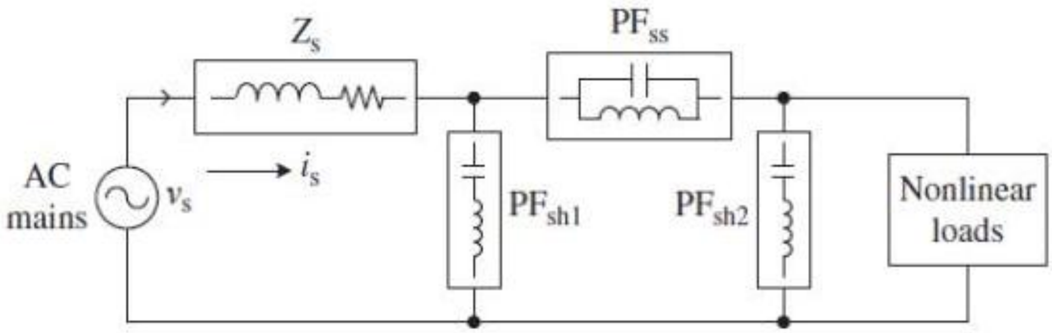


Fig. 4.74 A hybrid filter as a combination of passive shunt (PF_{sh1}), passive series (PF_{ss}), and passive shunt (PF_{sh2}) filters

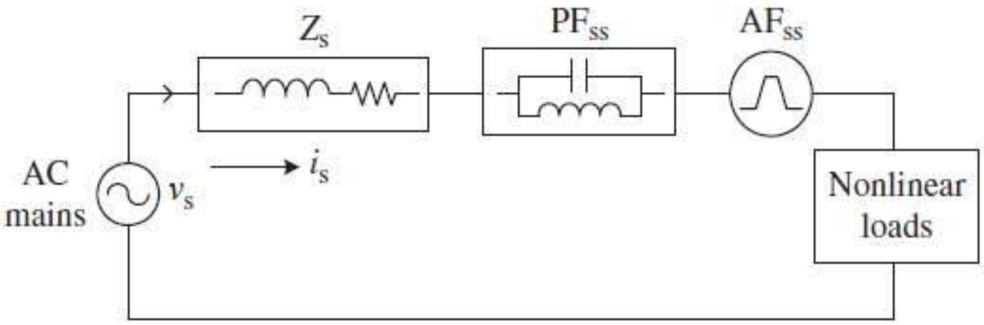


Fig. 4.75 A hybrid filter as a combination of series connected passive series (PF_{ss}) and active series (AF_{ss}) filters

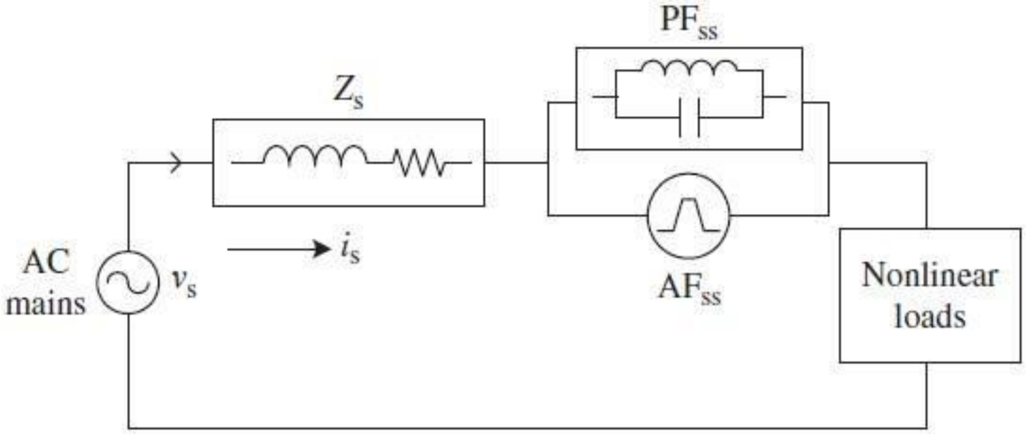


Fig. 4.76 A hybrid filter as a combination of parallel connected passive series (PF_{ss}) and active series (AF_{ss}) filters

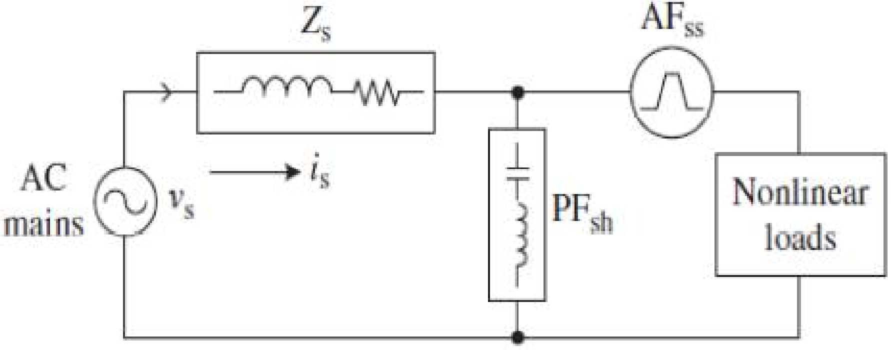


Fig. 4.77 A hybrid filter as a combination of passive shunt (PF_{sh}) and active series (AF_{ss}) filters

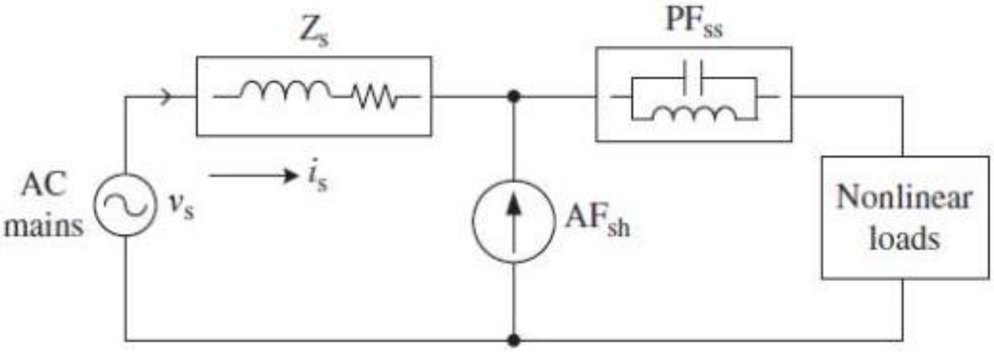


Fig. 4.78 A hybrid filter as a combination of active shunt (AF_{sh}) and passive series (PF_{ss}) filters

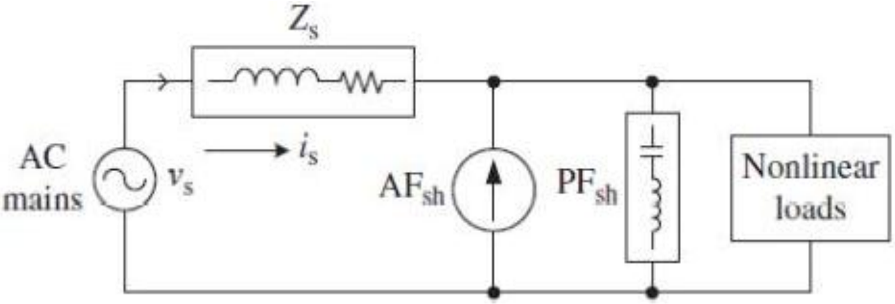


Fig. 4.79 A hybrid filter as a combination of active shunt (AF_{sh}) and passive shunt (PF_{sh}) filters

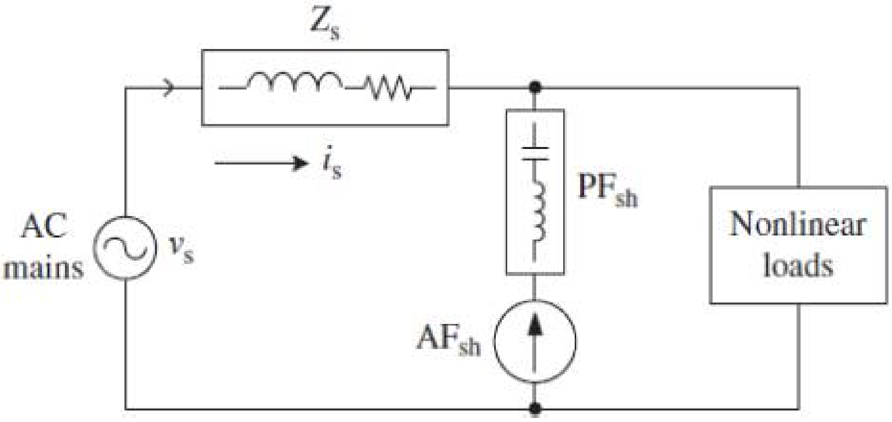


Fig. 4.80 A hybrid filter as a combination of series connected passive shunt (PF_{sh}) and active shunt (AF_{sh}) filters

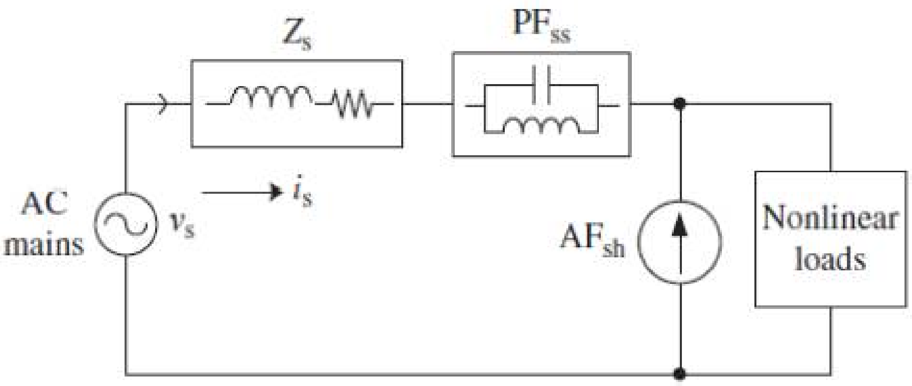


Fig. 4.81 A hybrid filter as a combination of passive series (PF_{ss}) and active shunt (AF_{sh}) filters

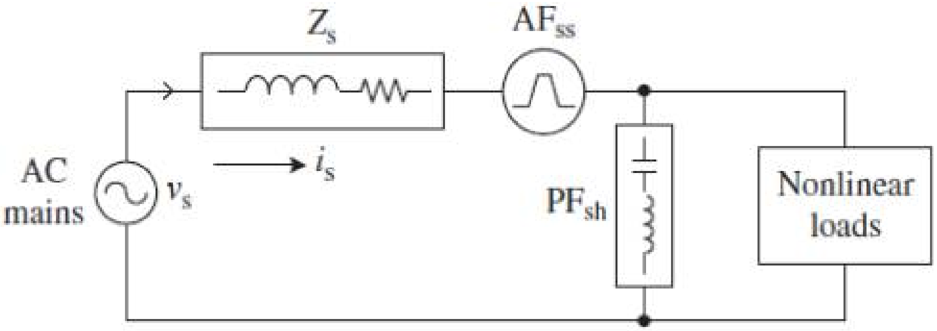


Fig. 4.82 A hybrid filter as a combination of active series (AF$_{ss}$) and passive shunt (PF$_{sh}$) filters

These 52 circuit configurations of hybrid filters are valid for each case of the supply system, for example, single-phase two-wire, three-phase three-wire, and three-phase four-wire AC systems. In each case of the supply system, four basic elements of the filter circuit, such as passive series (PF$_{ss}$), passive shunt (PF$_{sh}$), active series (AF$_{ss}$) and active shunt (AF$_{sh}$) are required to develop complete hybrid filter circuit configurations. However, there may be many more combinations such as active filter elements using current source converters or voltage source converters.

Normally, each passive filter element employs three tuned filters, the first two being of lowest dominant harmonics followed by a high-pass filter element. However, in some high-power applications such as HVDC systems, five tuned filter elements are used, the first four tuned for four lower dominant harmonics and fifth one as a high-pass filter element. In a passive series filter element (PF$_{ss}$), two lossless *LC* components are connected in parallel for creating a harmonic dam to block harmonic currents. All the three or five components of the passive series filter are connected in a series configuration. However, in a passive shunt filter element (PF$_{sh}$), two lossless *LC* components are connected in series for creating a harmonic valley to absorb harmonic currents. All the three or five components of the passive shunt filter (PF$_{sh}$) are connected in a parallel configuration.

Similarly, each active filter element employs a VSC preferably with a self-supporting DC bus having an electrolytic capacitor (C_d) and an AC inductor (L_r) along with an optional small AC capacitor (C_r) to form a ripple filter to eliminate the switching ripple. It may also use a CSC with inductive energy storage at DC link using current control along with shunt AC capacitors to form an active filter element. However, a VSC is normally preferred due to various advantages such low losses, small size, and low noise. Depending upon the supply system, the VSC-based active filter element may be single-phase two-arm H bridge, three-phase three-arm bridge, and three-phase four-arm, midpoint, or three single-phase VSC.

These units can be connected in series directly in single phase to reduce the cost or through injunction transformers usually with higher turns on the VSC side to form the active series filter element (AF_{ss}) for two-wire, three-wire and four-wire systems to act as a high active impedance to block harmonic currents and a low impedance for fundamental frequency current. In the same manner, the active shunt filter element (AF_{sh}) may be connected either directly or through step-down transformers to connect the VSC at optimum voltage to act as an adjustable sink for harmonic currents for three cases of the AC supply system.

There are 156 valid basic circuit configurations of HFs for all three cases of the supply system to suit majority of applications for improving the power quality of the system having either nonlinear loads or polluted AC supply. Moreover, there may be many more variations in the active or passive filter element, but the basic concept of HFs remains out of these circuit configurations.

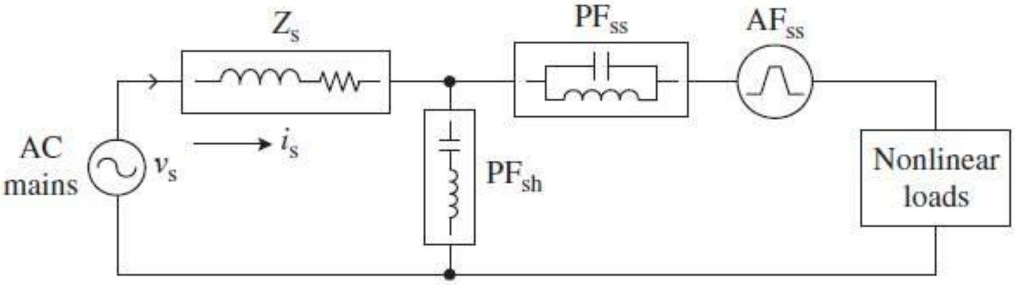


Fig 4.83 A hybrid filter as a combination of passive shunt (PF_{sh}), passive series (PF_{ss}) and active series (AF_{ss}) filters

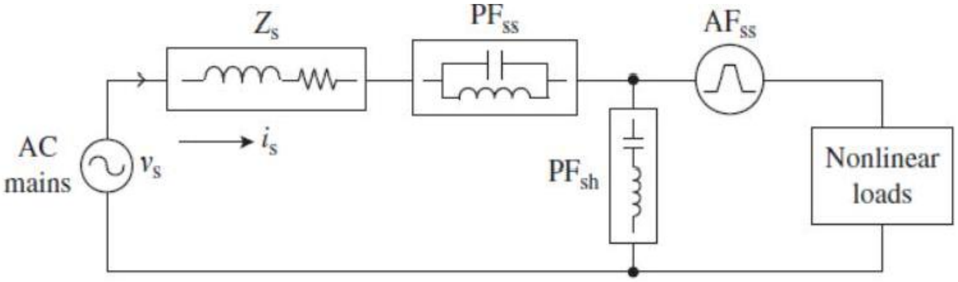


Fig. 4.84 A hybrid filter as a combination of passive series (PF_{ss}), passive shunt (PF_{sh}), and active series (AF_{ss}) filters

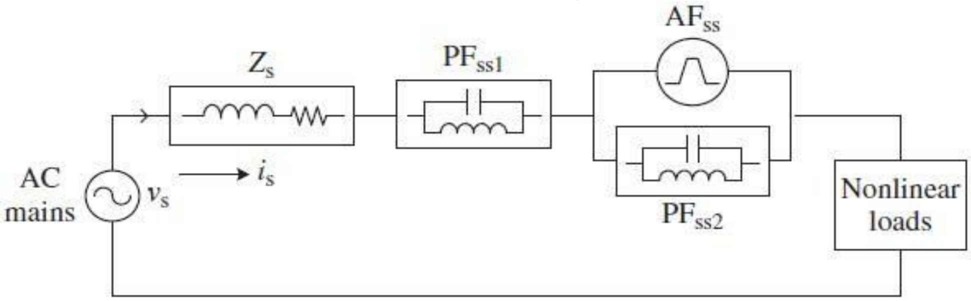


Fig. 4.85 A hybrid filter as a combination of passive series (PF_{ss1}) in series with a parallel connected active series (AF_{ss}) and passive series (PF_{ss2}) filters

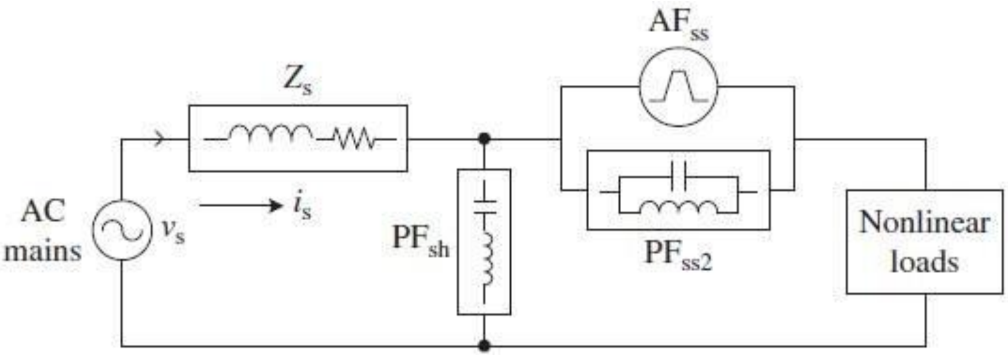


Fig. 4.86 A hybrid filter as a combination of passive shunt (PF$_{sh}$) and parallel connected active series (AF$_{ss}$) and passive series (PF$_{ss}$) filters

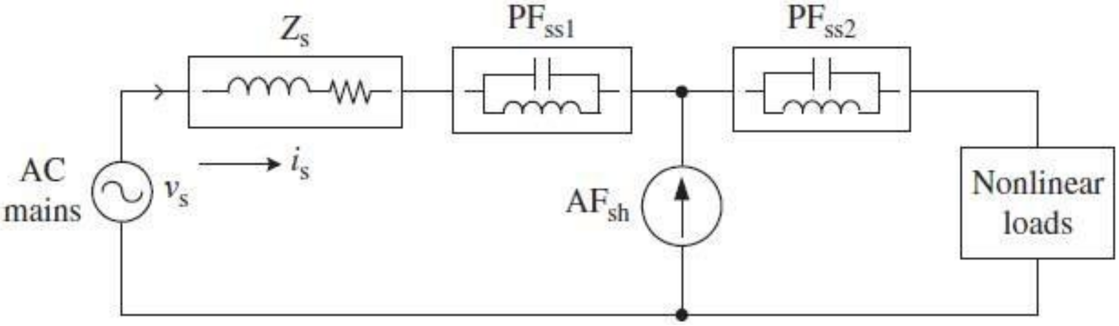


Fig. 4.87 A hybrid filter as a combination of passive series (PF$_{ss1}$), active shunt (AF$_{sh}$) and passive series (PF$_{ss2}$) filters

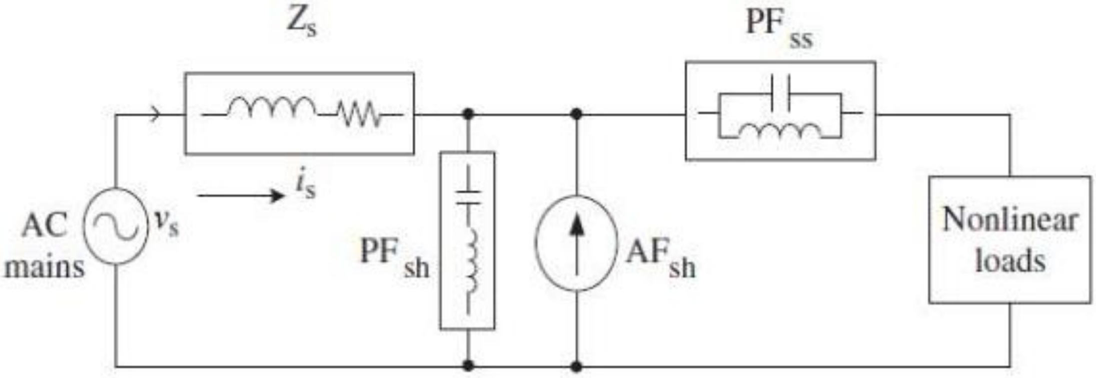


Fig. 4.88 Hybrid filter as a combination of parallel connected passive shunt (PF$_{sh}$) with active shunt (AF$_{sh}$) and passive series (PF$_{ss}$) Filters

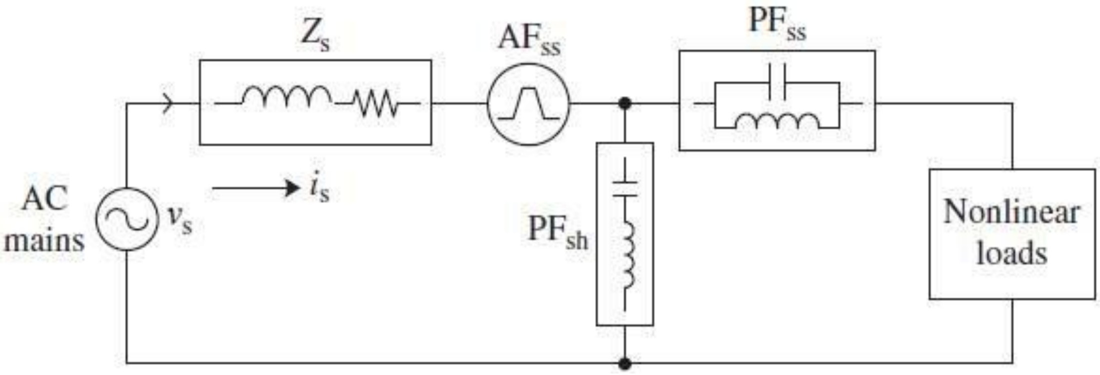


Fig. 4.89 A hybrid filter as a combination of active series (AF$_{ss}$), passive shunt (PF$_{sh}$) and passive series (PF$_{ss}$) filters

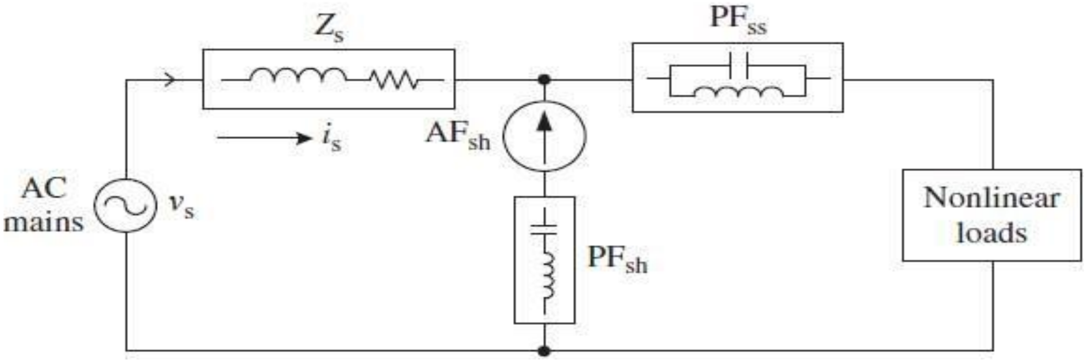


Fig. 4.90 A hybrid filter as a combination of series connected passive shunt (PF$_{sh}$) with active shunt (AF$_{sh}$) and passive series (PF$_{ss}$) filters

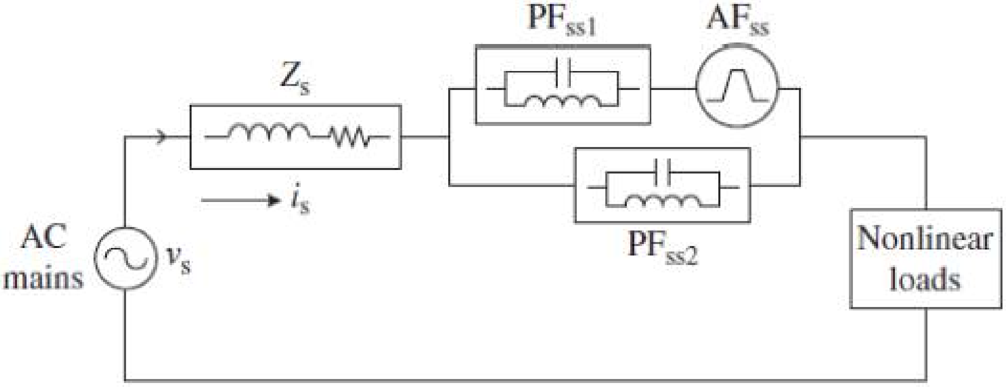


Fig. 4.91 A hybrid filter as a combination of series connected passive series (PF$_{ss1}$) with active series (AF$_{ss}$) in parallel with passive series (PF$_{ss2}$) filters

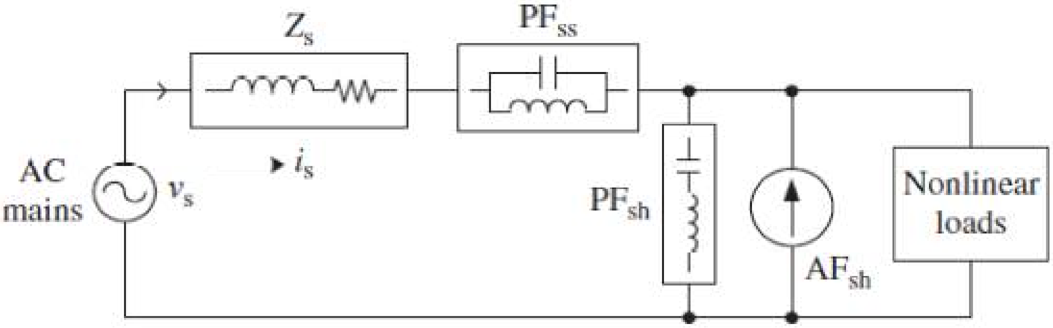


Fig. 4.92 A hybrid filter as a combination of passive series (PF$_{ss}$) and parallel connected passive shunt (PF$_{sh}$) with active shunt (AF$_{sh}$) filters

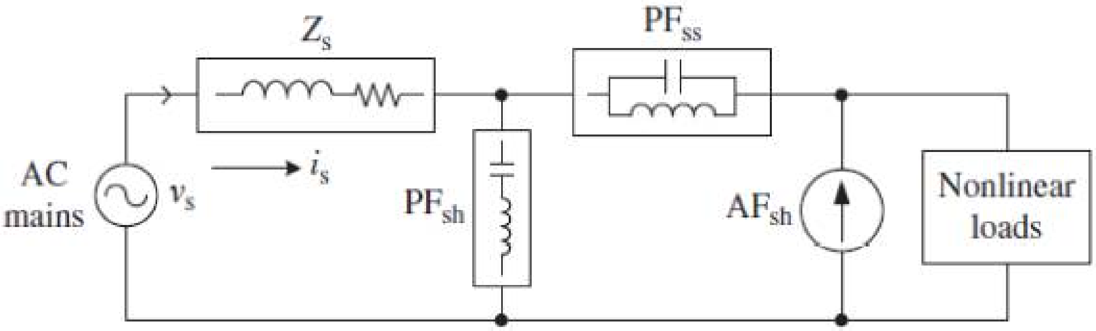


Fig. 4.93 A hybrid filter as a combination of passive shunt (PF$_{sh}$), passive series (PF$_{ss}$) and active shunt (AF$_{sh}$) filters

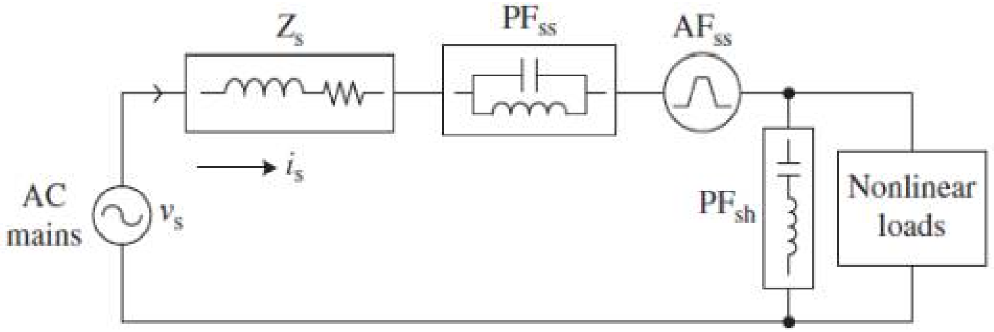


Fig. 4.94 A hybrid filter as a combination of series connected passive series (PF_{ss}) with active series (AF_{ss}) and passive shunt (PF_{sh}) filters

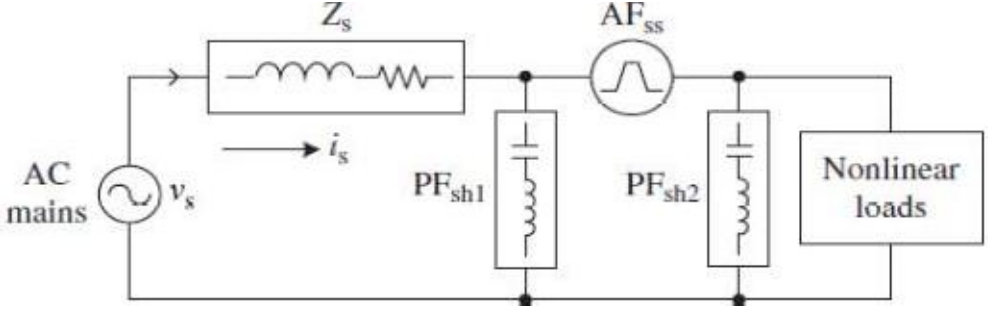


Fig. 4.95 A hybrid filter as a combination of passive shunt (PF_{sh1}), active series (AF_{ss}) and passive shunt (PF_{sh2}) filters

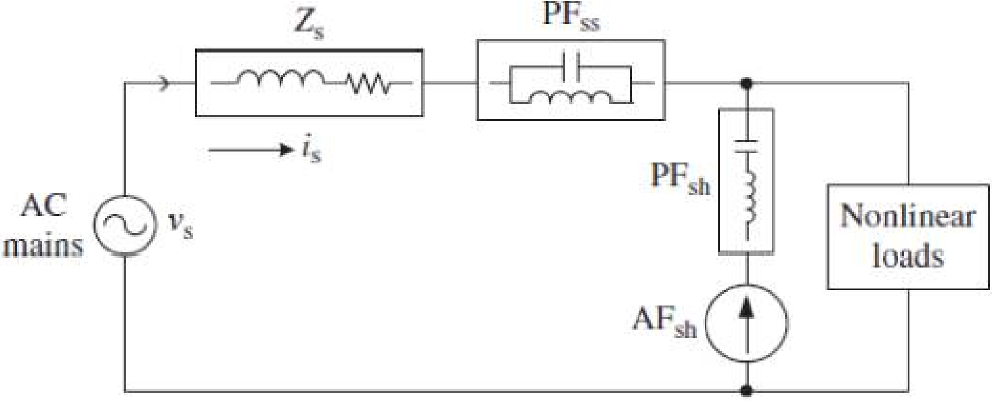


Fig. 4.96 A hybrid filter as a combination of passive series (PF_{ss}) and series connected passive shunt (PF_{sh}) with active shunt (AF_{sh}) filters

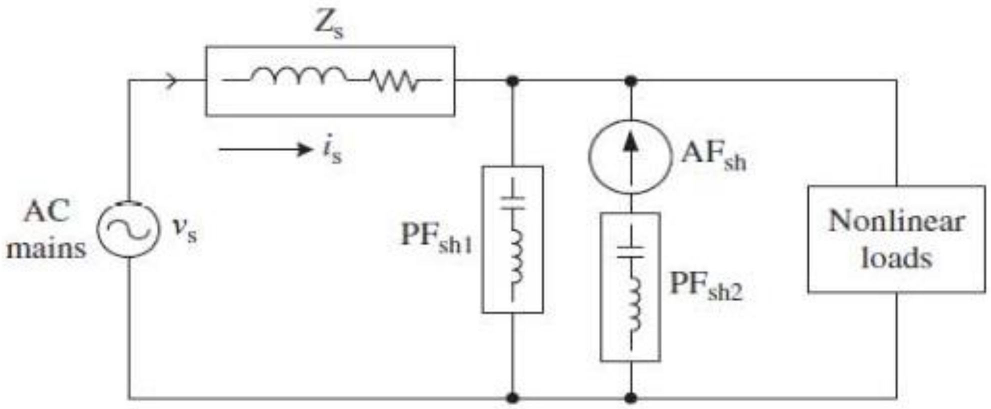


Fig. 4.97 A hybrid filter as a combination of passive shunt (PF_{sh1}) and series connected active shunt (AF_{sh}) with passive shunt (PF_{sh2}) filters

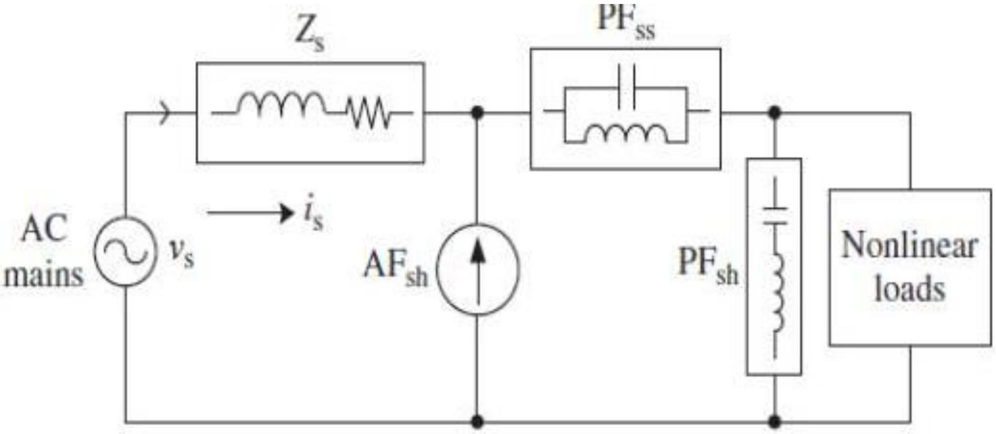


Fig. 4.98 A hybrid filter as a combination of active shunt (AF_{sh}), passive series (PF_{ss}) and passive shunt (PF_{sh}) filters

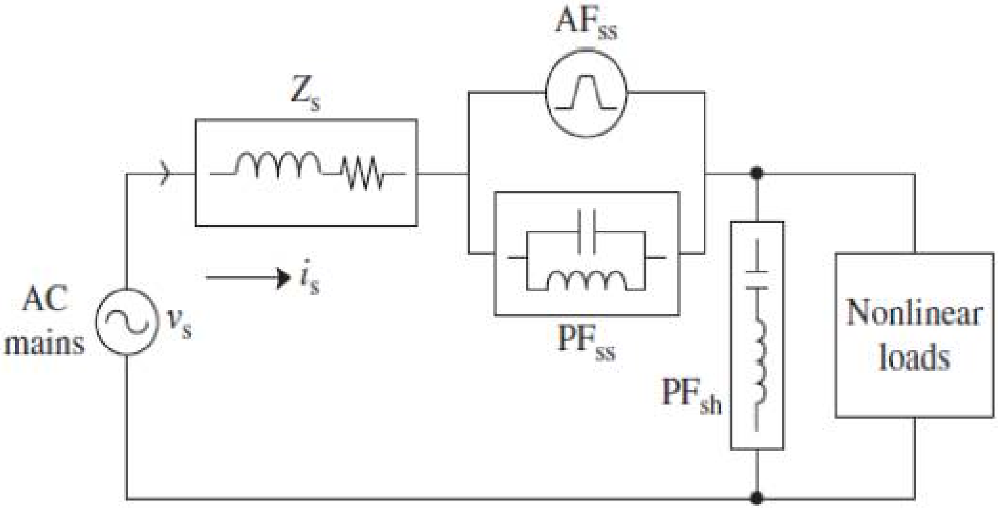


Fig. 4.99 A hybrid filter as a combination of parallel connected active series (AF_{ss}) with passive series (PF_{ss}) and passive shunt (PF_{sh}) filters

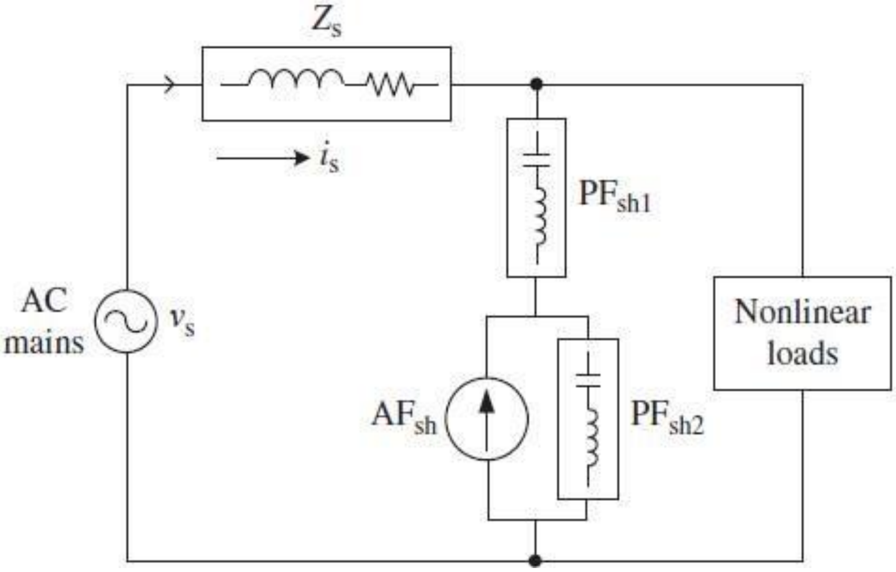


Fig. 4.100 A hybrid filter as a combination of passive shunt (PF_{sh1}) and parallel connected passive shunt (PF_{sh2}) with active shunt (AF_{sh}) filters

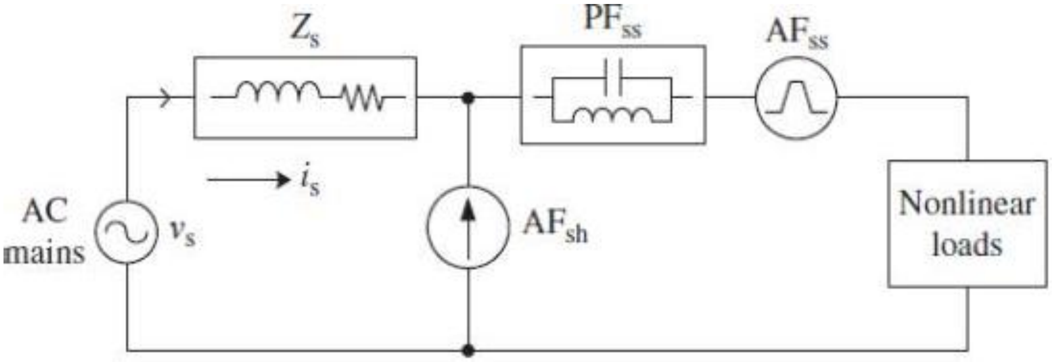


Fig. 4.101 A hybrid filter as a combination of active shunt (AF_{sh}), passive series (PF_{ss}) and active series (AF_{ss}) filters

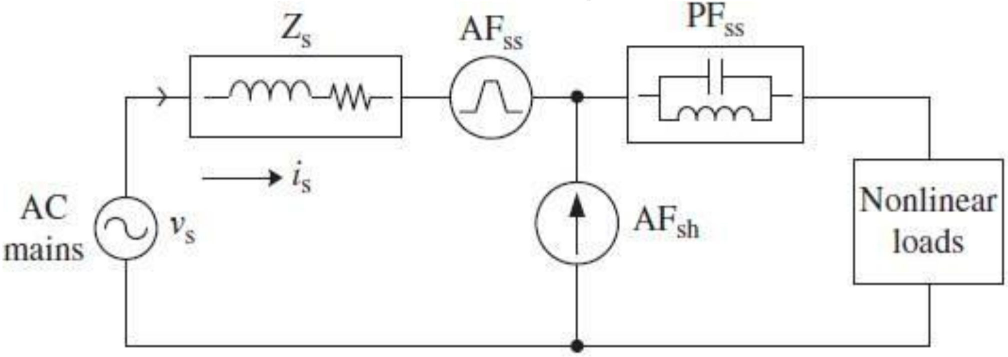


Fig. 4.102 A hybrid filter as a combination of active series (AF_{ss}), active shunt (AF_{sh}) and passive series (PF_{ss}) filters

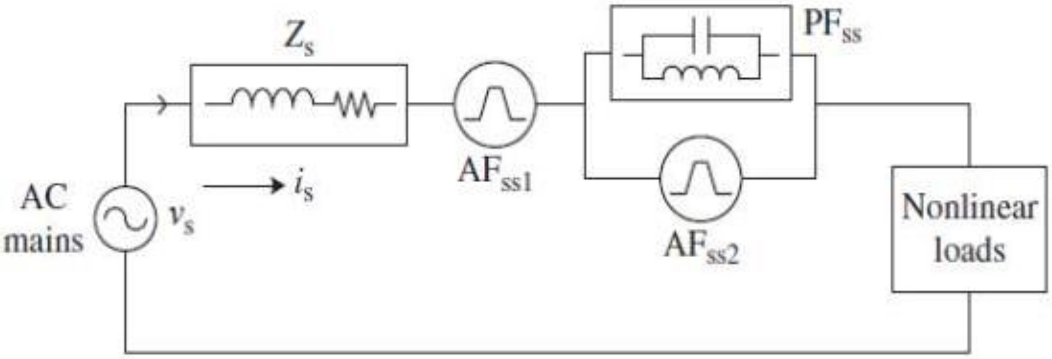


Fig. 4.103 A hybrid filter as a combination of active series (AF_{ss1}) and parallel connected passive series (PF_{ss}) with active series (AF_{ss2}) filters

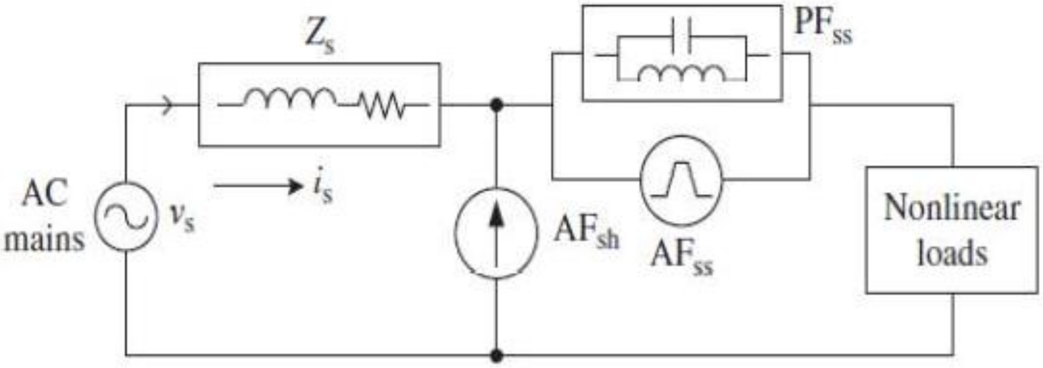


Fig. 4.104 A hybrid filter as a combination of active shunt (AF_{sh}) and parallel connected passive series (PF_{ss}) with active series (AF_{ss}) filters

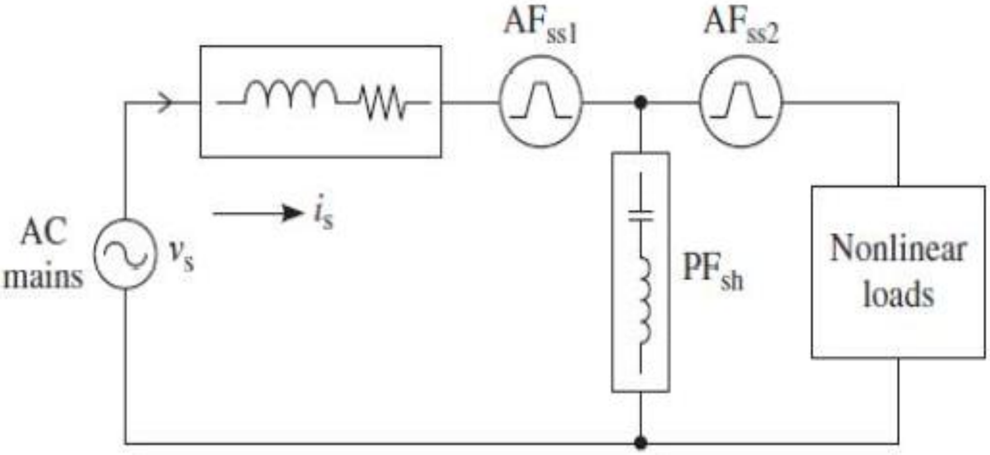


Fig. 4.105 A hybrid filter as a combination of active series (AF$_{ss1}$), passive shunt (PF$_{sh}$), and active series (AF$_{ss2}$) filters

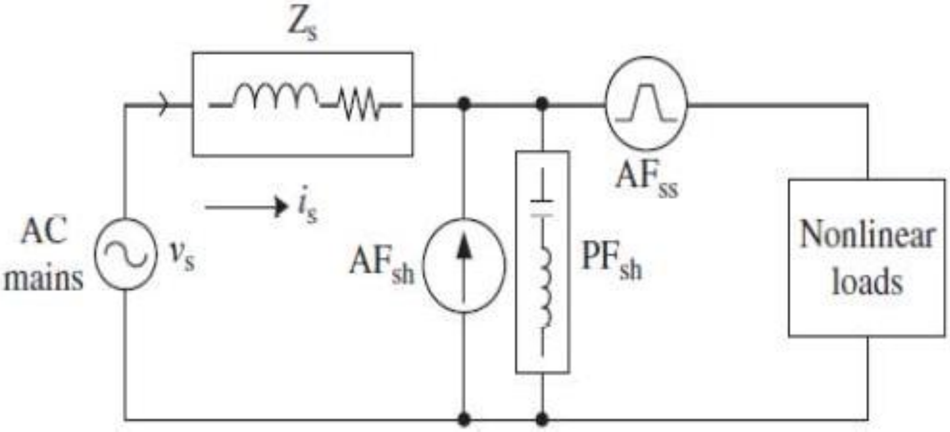


Fig. 4.106 A hybrid filter as a combination of active shunt (AF$_{sh}$), passive shunt (PF$_{sh}$) and active series (AF$_{ss}$) filters

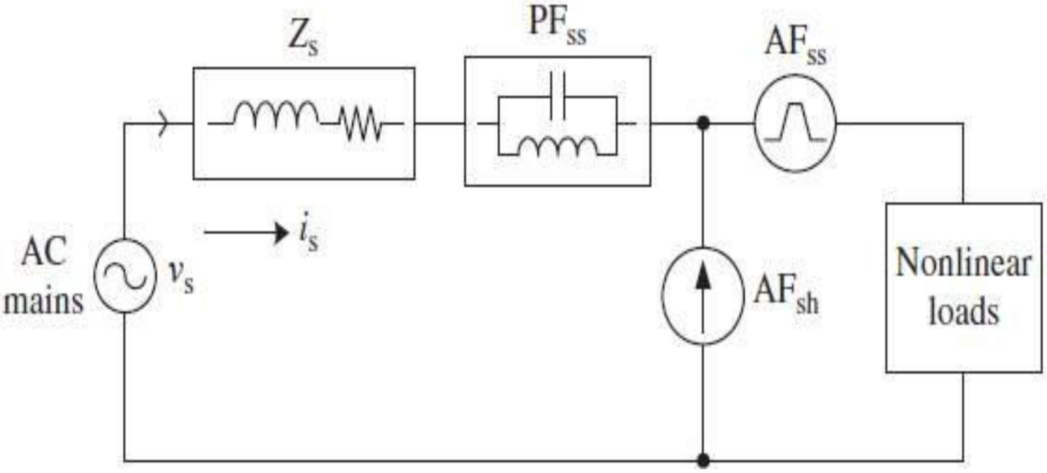


Fig. 4.107 A hybrid filter as a combination of passive series (PF$_{ss}$), active shunt (AF$_{sh}$) and active series (AF$_{ss}$) filters

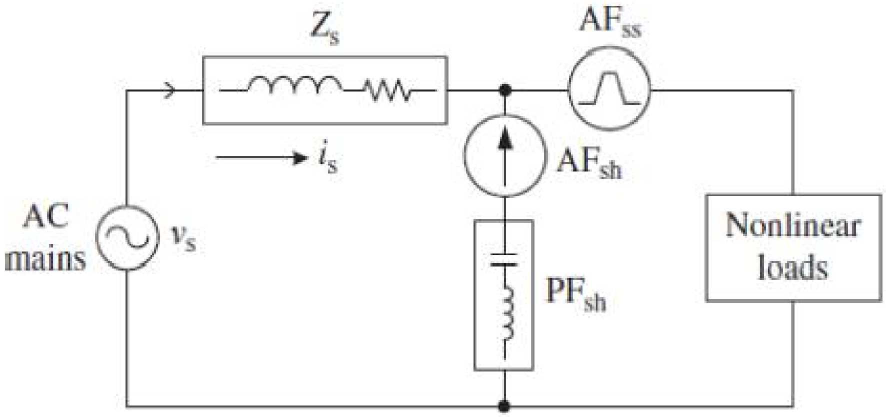


Fig. 4.108 A hybrid filter as a combination of series connected active shunt (AF_{sh}) with passive shunt (PF_{sh}) and active series (AFss) filters

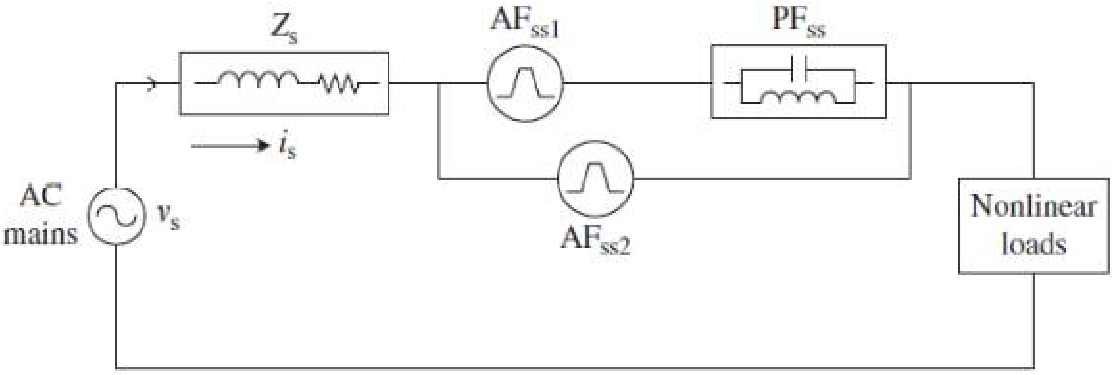


Fig. 4.109 A hybrid filter as a combination of active series (AF_{ss1}), passive series (PF_{ss}) and active series (AF_{ss2}) filters

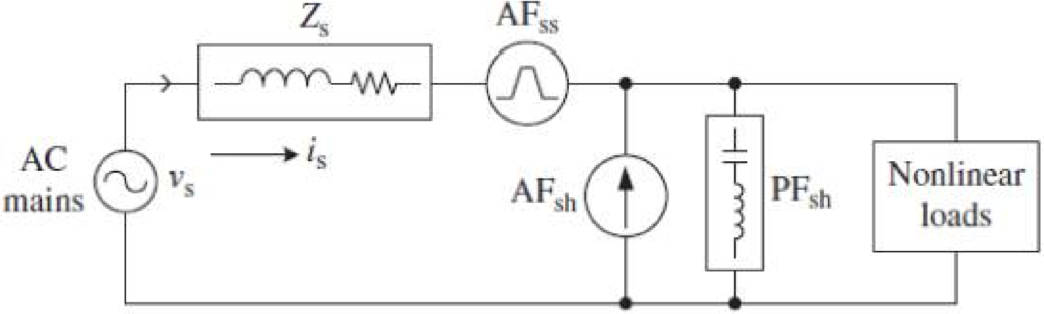


Fig. 4.110 A hybrid filter as a combination of active series (AF_{ss}), active shunt (AF_{sh}) and passive shunt (PF_{sh}) filters

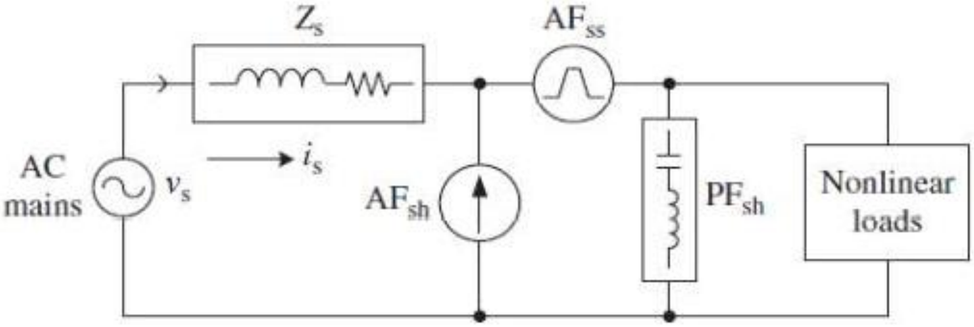


Fig. 4.111 A hybrid filter as a combination of active shunt (AF_{sh}), active series (AF_{ss}) and passive shunt (PF_{sh}) filters

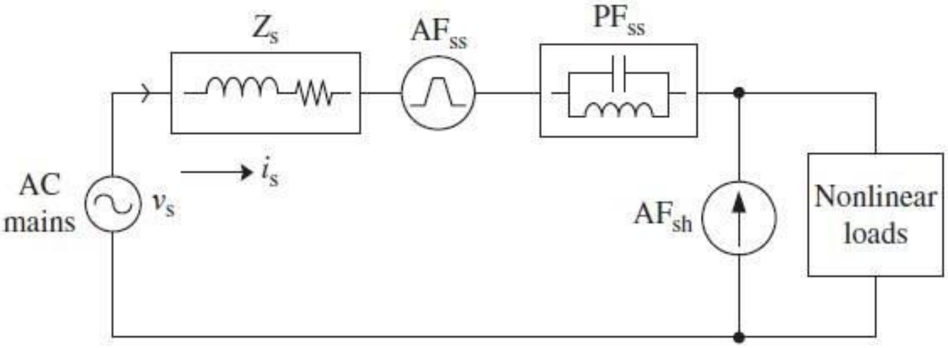


Fig. 4.112 A hybrid filter as a combination of active series (AF_{ss}), passive series (PF_{ss}) and active shunt (AF_{sh}) filters

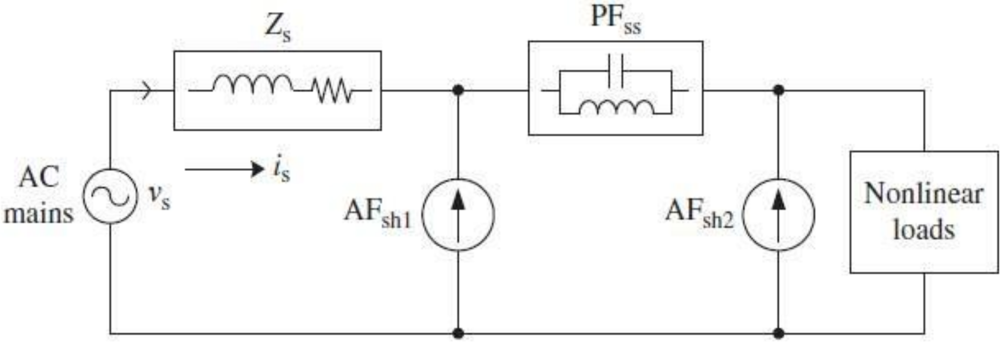


Fig. 4.113 A hybrid filter as a combination of active shunt (AF_{sh1}), passive series (PF_{ss}) and active shunt (AF_{sh2}) filters

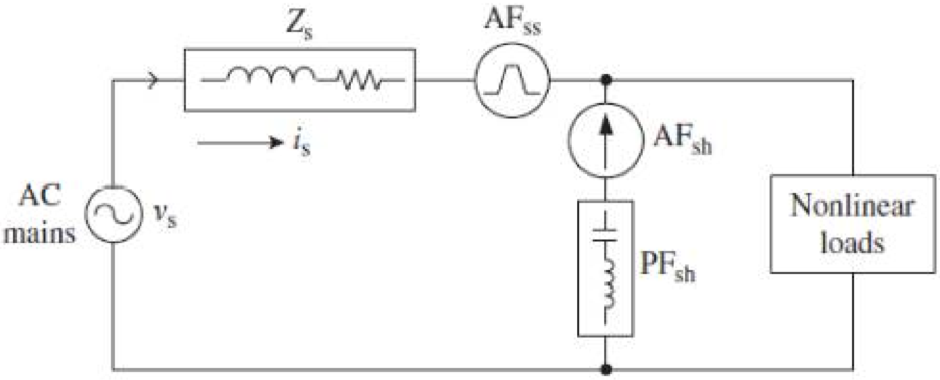


Fig. 4.114 A hybrid filter as a combination of active series (AF_{ss}) and series connected active shunt (AF_{sh}) and passive shunt (PF_{sh}) filters

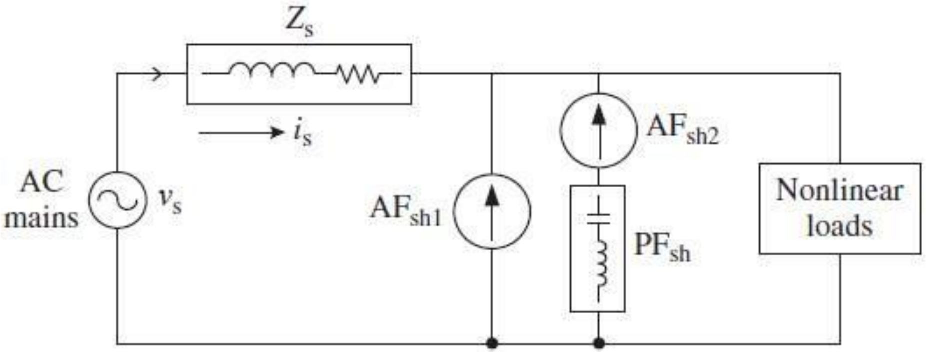


Fig. 4.115 A hybrid filter as a combination of active shunt (AF_{sh1}), series connected active shunt (AF_{sh2}) and passive shunt (PF_{sh}) filters

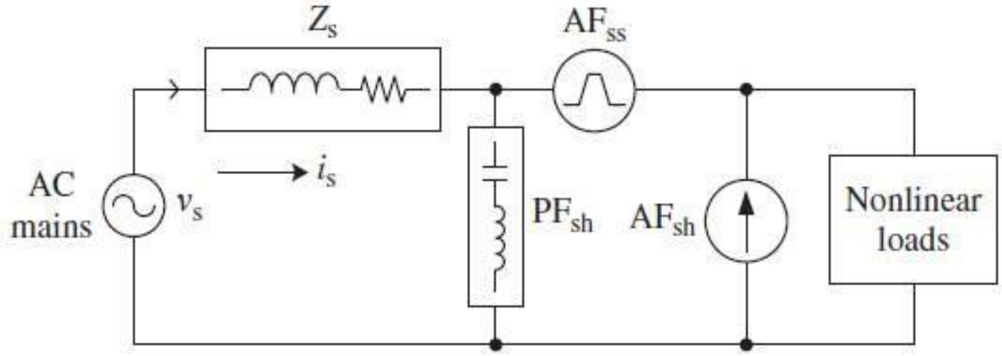


Fig. 4.116 A hybrid filter as a combination of passive shunt (PF$_{sh}$), active series (AF$_{ss}$) and active shunt (AF$_{sh}$) filters

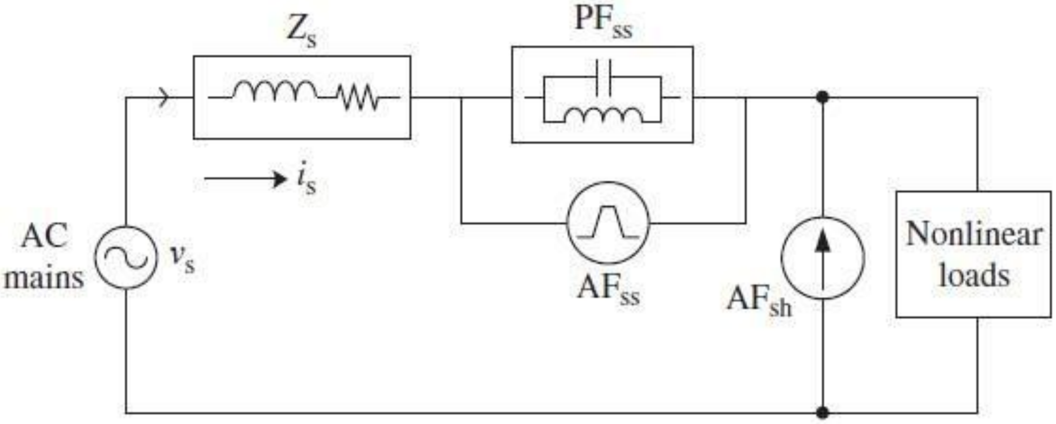


Fig. 4.117 A hybrid filter as a combination of parallel connected passive series (PF$_{ss}$) with active series (AF$_{ss}$) and active shunt (AF$_{sh}$) filters

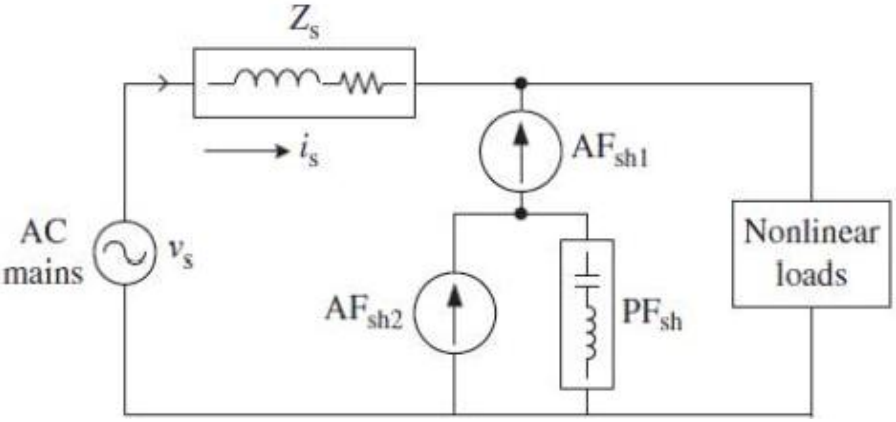


Fig. 4.118 A hybrid filter as a combination of active shunt (AF$_{sh1}$) in series with parallel connected active shunt (AF$_{sh2}$) and passive shunt (PF$_{sh}$) filters

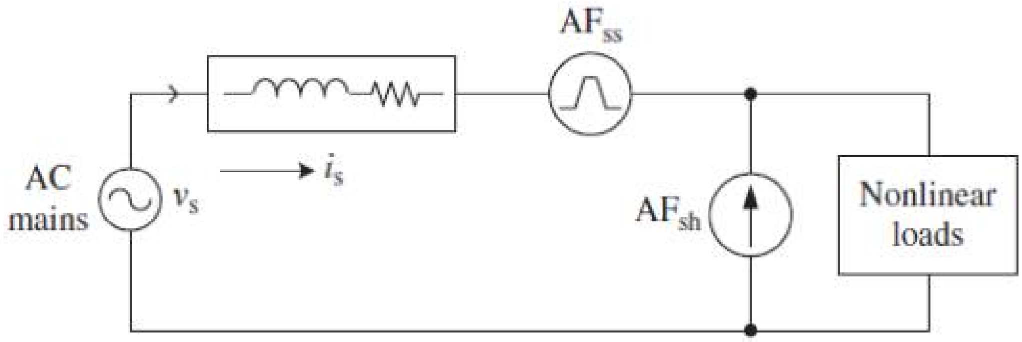


Fig. 4.119 A hybrid filter as a combination of active series (AF_{ss}) and active shunt (AF_{sh}) filters

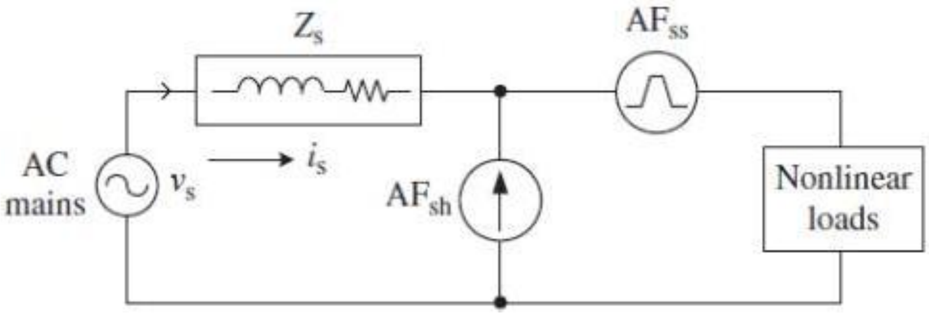


Fig. 4.120 A hybrid filter as a combination of active shunt (AF_{sh}) and active series (AF_{ss}) filters

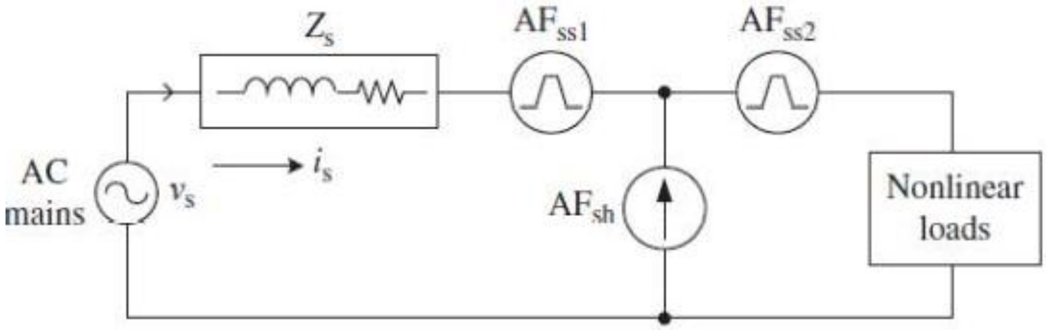


Fig. 4.121 A hybrid filter as a combination of active series (AF_{ss1}), active shunt (AF_{sh}) and active series (AF_{ss2}) filters

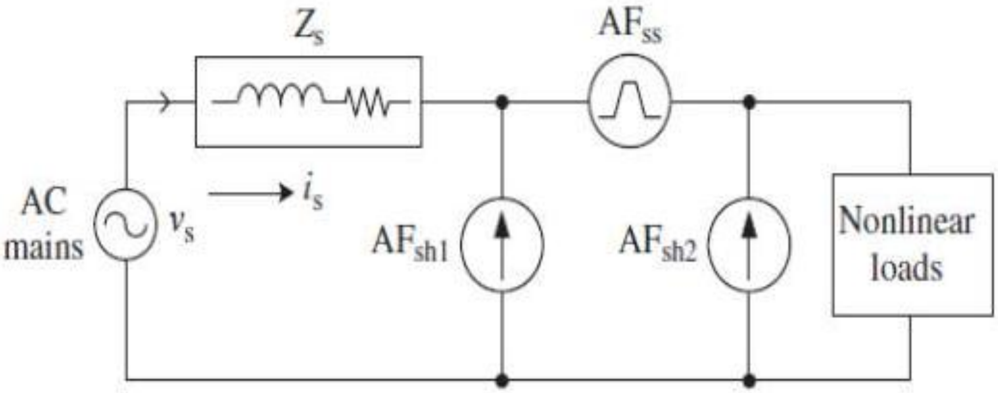


Fig. 4.122 A hybrid filter as a combination of active shunt (AF_{sh1}), active series (AF_{ss}) and active shunt (AF_{sh2}) filters

4.13.3 Principle of Operation and Control of Hybrid Power Filters

Many configurations of hybrid power filters have been discussed in the previous section for mitigating various power quality problems in addition to eliminating voltage and current harmonics. A large number of these configurations of hybrid power filters are reported in the literature for power quality improvement by compensation of various types of nonlinear loads.

Here mainly four configurations of hybrid power filters are discussed, which are most prominently used in practice as a combination of passive filters, a combination of active filters and a combination of an active filter and a passive filter to provide a cost-effective universal filter for mitigating multiple power quality problems caused by nonlinear loads and supply systems. Conceptually, these HPFs consist of

a) A combination of passive series (PF_{ss}) and passive shunt (PF_{sh}) filters (Figure 4.71)
b) A combination of series connected passive shunt (PF_{sh}) and active shunt (AF_{sh}) filters (Figure 4.80)
c) A combination of active series (AF_{ss}) and passive shunt (PF_{sh}) filters (Figure 4.82)
d) A combination of active series (AF_{ss}) and active shunt (AF_{sh}) filters (Figure 4.119)

Out of the 52 configurations of HPFs, these 4 configurations have been preferred due to a number of benefits and to meet the requirements of various types of nonlinear loads. Therefore, the principle of operation and control of HPFs are limited to these four hybrid power filters. However, a large number of configurations of HPFs are illustrated in numerical examples. Here, most of the concepts are given for three-phase HPFs, which can also be extended to single phase hybrid power filters.

4.13.4 Analysis and Design of Hybrid Power Filters

Since the considered configuration of the hybrid filter shown in Figure 11.55 consists of a passive filter along with a small active filter, its design consists of both the components. This design procedure involves the design of a passive filter for a voltage-fed load consisting of a diode rectifier with a filter capacitor and an equivalent resistive load of 25kW fed from a 415 V, 50 Hz three-phase supply system.

4.13.5 Modeling, Simulation and Performance of Hybrid Power Filters

The MATLAB-based models of different topologies of HPF systems are developed using SIMULINK and SIM Power Systems (SPS) toolboxes to simulate the performance of hybrid power filters in single-phase and three-phase distribution systems.

4.14 IEEE and IEC standards

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

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

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

The basis for limiting harmonic injections from individual customers is to avoid unacceptable levels of voltage distortions. Thus the current limits are developed so that the total harmonic injections from an individual customer do not exceed the maximum voltage distortion shown in Table 4.3. Table 4.3 shows harmonic current limits for various system voltages. Smaller loads (typically larger short-circuit ratio values) are allowed a higher percentage of harmonic currents than larger loads with smaller short-circuit ratio values. Larger loads have to meet more stringent limits since they occupy a larger portion of system load capacity. The current limits take into account the diversity of harmonic currents in which some harmonics tend to cancel out while others are additive. The harmonic current limits at the PCC are developed to limit individual voltage distortion and voltage THD to the values shown in Table 4.1. Since voltage distortion is dependent on the system impedance, the key to controlling voltage distortion is to control the impedance.

The two main conditions that result in high impedance are when the system is too weak to supply the load adequately or the system is in resonance. The latter is more common.

Therefore, keeping the voltage distortion low usually means keeping the system out of resonance. Occasionally, new transformers and lines will have to be added to increase the system strength. IEEE Standard 519-1992 represents a consensus of guidelines and recommended practices by the utilities and their customers in minimizing and controlling the impact of harmonics generated by nonlinear loads.

Table 4.3 Basis for Harmonic Current Limits

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

4.14.1 Overview of IEC Standards on Harmonics

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

Part 1: General

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

Part 2: Environment

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

Part 3: Limits

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

Part 4: Testing and measurement techniques

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

Part 5: Installation and mitigation guidelines

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

Part 6: Miscellaneous

These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

4.15 Summary

4.16 Review Questions

Short Answer Questions

1. Define harmonics?
2. Give at least two IEC standards for EMC.
3. Define harmonic indices?
4. Mention the devices for controlling harmonic distortion?
5. Give the IEC standard to define harmonics.
6. What is crest factor?
7. What kind of equipment is needed to measure distorted waveforms?
8. Define TDD
9. Define THD
10. What is the reason for existence of harmonic distortion?
11. What is voltage and current distortion?
12. Define inter harmonics.
13. Give at least two IEEE standards for harmonics.
14. What is the classification of active harmonic conditioner?

15. Mention the harmonic sources from industrial loads
16. State the principles of controlling harmonics.

Essay Questions

1. Explain briefly about fundamentals of waveform distortion and the effects of harmonic distortion.
2. Explain the principles of controlling harmonics and its standards and limitations.
3. Explain the power system response characteristics
4. Explain the principle of controlling harmonic distortion?
5. Explain Sources and effects of harmonic distortion.

UNIT – V

POWER QUALITY MONITORING

TOPICS COVERED: **Introduction – Monitoring Consideration – Monitoring as part of a facility site survey – Choosing Monitoring Locations – Options for Permanent Power Quality Monitoring Equipment – Sources of Disturbance – Power Quality Measurement Equipment – Disturbance Analyzers – Spectrum Analyzers and Harmonic Analyzers – Flicker Meters – Application of Expert Systems for Power Quality Monitoring – Basic Design of an expert system for monitoring applications – Future Applications.**

5.1 Introduction

Power quality monitoring is the process of gathering, analyzing, and interpreting raw measurement data into useful information. The process of gathering data is usually carried out by continuous measurement of voltage and current over an extended period. The process of analysis and interpretation has been traditionally performed manually, but recent advances in signal processing and artificial intelligence fields have made it possible to design and implement intelligent systems to automatically analyze and interpret raw data into useful information with minimum human intervention.

Power quality monitoring programs are often driven by the demand for improving the system wide power quality performance. Many industrial and commercial customers have equipment that is sensitive to power disturbances, and, therefore, it is more important to understand the quality of power being provided. Examples of these facilities include computer networking and telecommunication facilities, semiconductor and electronics manufacturing facilities, biotechnology and pharmaceutical laboratories, and financial data-processing centers. Hence, in the last decade many utility companies have implemented extensive power quality monitoring programs.

5.2 Monitoring Consideration

The monitoring objectives often determine the choice of monitoring equipment, triggering thresholds, methods for data acquisition and storage, and analysis and interpretation requirements. Several common objectives of power quality monitoring are summarized here.

Monitoring to characterize system performance:

This is the most general requirement. A power producer may find this objective important if it has the need to understand its system performance and then match that system performance with the needs of customers. System characterization is a proactive approach to power quality monitoring. By understanding the normal power quality performance of a system, a provider can quickly identify problems and can offer information to its customers to help them match their sensitive equipment's characteristics with realistic power quality characteristics.

Monitoring to characterize specific problems:

Many power quality service departments or plant managers solve problems by performing short-term monitoring at specific customer sites or at difficult loads. This is a reactive mode of power quality monitoring, but it frequently identifies the cause of equipment incompatibility, which is the first step to a solution.

Monitoring as part of an enhanced power quality service:

Many power producers are currently considering additional services to offer customers. One of these services would be to offer differentiated levels of power quality to match the needs of specific customers. A provider and customer can together achieve this goal by modifying the power system or by installing equipment within the customer's premises. In either case, monitoring becomes essential to establish the benchmarks for the differentiated service and to verify that the utility achieves contracted levels of power quality.

Monitoring as part of predictive or just-in-time maintenance:

Power quality data gathered over time can be analyzed to provide information relating to specific equipment performance. For example, a repetitive arcing fault from an underground cable may signify impending cable failure, or repetitive capacitor-switching restrikes may signify impending failure on the capacitor-switching device. Equipment maintenance can be quickly ordered to avoid catastrophic failure, thus preventing major power quality disturbances which ultimately will impact overall power quality performance.

The monitoring program must be designed based on the appropriate objectives, and it must make the information available in a convenient form and in a timely manner (i.e., immediately). The most comprehensive monitoring approach will be a permanently installed monitoring system with automatic collection of information about steady-state power quality conditions and energy use as well as disturbances.

5.2.1 Monitoring as part of a facility site survey

Site surveys are performed to evaluate concerns for power quality and equipment performance throughout a facility. The survey will include inspection of wiring and grounding concerns, equipment connections, and the voltage and current characteristics throughout the facility. Power quality monitoring, along with infrared scans and visual inspections, is an important part of the overall survey. The initial site survey should be designed to obtain as much information as possible about the customer facility. This information is especially important when the monitoring objective is intended to address specific power quality problems. This information is summarized here.

1. Nature of the problems (data loss, nuisance trips, component failures, control system malfunctions, etc.)
2. Characteristics of the sensitive equipment experiencing problems (equipment design information or at least application guide information)
3. The times at which problems occur
4. Coincident problems or known operations (e.g., capacitor switching) that occur at the same time
5. Possible sources of power quality variations within the facility (motor starting, capacitor switching, power electronic equipment operation, arcing equipment, etc.)
6. Existing power conditioning equipment being used
7. Electrical system data (one-line diagrams, transformer sizes and impedances, load information, capacitor information, cable data, etc.)

5.2.2 Determining what to monitor

Power quality encompasses a wide variety of conditions on the power system. Important disturbances can range from very high frequency impulses caused by lightning strokes or current chopping during circuit interruptions to long-term over voltages caused by a regulator tap switching problem. The range of conditions that must be characterized creates challenges both in terms of the monitoring equipment performance specifications and in the data-collection requirements. The methods for characterizing the quality of ac power are important for the monitoring requirements. For instance, characterizing most transients requires high-frequency sampling of the actual waveform. Voltage sags can be characterized with a plot of the RMS voltage versus time. Outages can be defined simply by time duration. Monitoring to characterize harmonic distortion levels and normal voltage variations requires steady-state sampling with results analysis of trends over time. Extensive monitoring of all the different types of power quality variations at many locations may be rather costly in terms of hardware, communications charges, data management, and report preparation. Hence, the priorities for monitoring should be determined based on the objectives of the effort. Projects to benchmark system performance should involve a reasonably complete monitoring effort.

5.2.3 Choosing Monitoring Locations

Obviously, we would like to monitor conditions at virtually all locations throughout the system to completely understand the overall power quality. However, such monitoring may be prohibitively expensive and there are challenges in data management, analysis, and interpretation. Fortunately, taking measurements from all possible locations is usually not necessary since measurements taken from several strategic locations can be used to determine characteristics of the overall system. Thus, it is very important that the monitoring locations be selected carefully based on the monitoring objectives.

5.2.4 Options for Permanent Power Quality Monitoring Equipment

Permanent power quality monitoring systems, such as the system illustrated in figure 5.1, should take advantage of the wide variety of equipment that may have the capability to record power quality information. Some of the categories of equipment that can be incorporated into an overall monitoring system include the following,

- **Digital fault recorders (DFRs):** These may already be in place at many substations. DFR manufacturers do not design the devices specifically for power quality monitoring. However, a DFR will typically trigger on fault events and record the voltage and current waveforms that characterize the event. This makes them valuable for characterizing rms disturbances, such as voltage sags, during power system faults. DFRs also offer periodic waveform capture for calculating harmonic distortion levels.
- **Smart relays and other IEDs:** Many types of substation equipment may have the capability to be an intelligent electronic device (IED) with monitoring capability. Manufacturers of devices like relays and re closers that monitor the current anyway are adding on the capability to record disturbances and make the information available to an overall monitoring system controller. These devices can be located on the feeder circuits as well as at the substation.

- **Voltage recorders:** Power providers use a variety of voltage recorders to monitor steady-state voltage variations on distribution systems. We are encountering more and more sophisticated models fully capable of characterizing momentary voltage sags and even harmonic distortion levels. Typically, the voltage recorder provides a trend that gives the maximum, minimum, and average voltage within a specified sampling window. With this type of sampling, the recorder can characterize a voltage sag magnitude adequately. However, it will not provide the duration with a resolution less than 2 sec.
- **In-plant power monitors:** It is now common for monitoring systems in industrial facilities to have some power quality capabilities. These monitors, particularly those located at the service entrance, can be used as part of a utility monitoring program. Capabilities usually include wave shape capture for evaluation of harmonic distortion levels, voltage profiles for steady-state RMS variations, and triggered wave shape captures for voltage sag conditions. It is not common for these instruments to have transient monitoring capabilities.

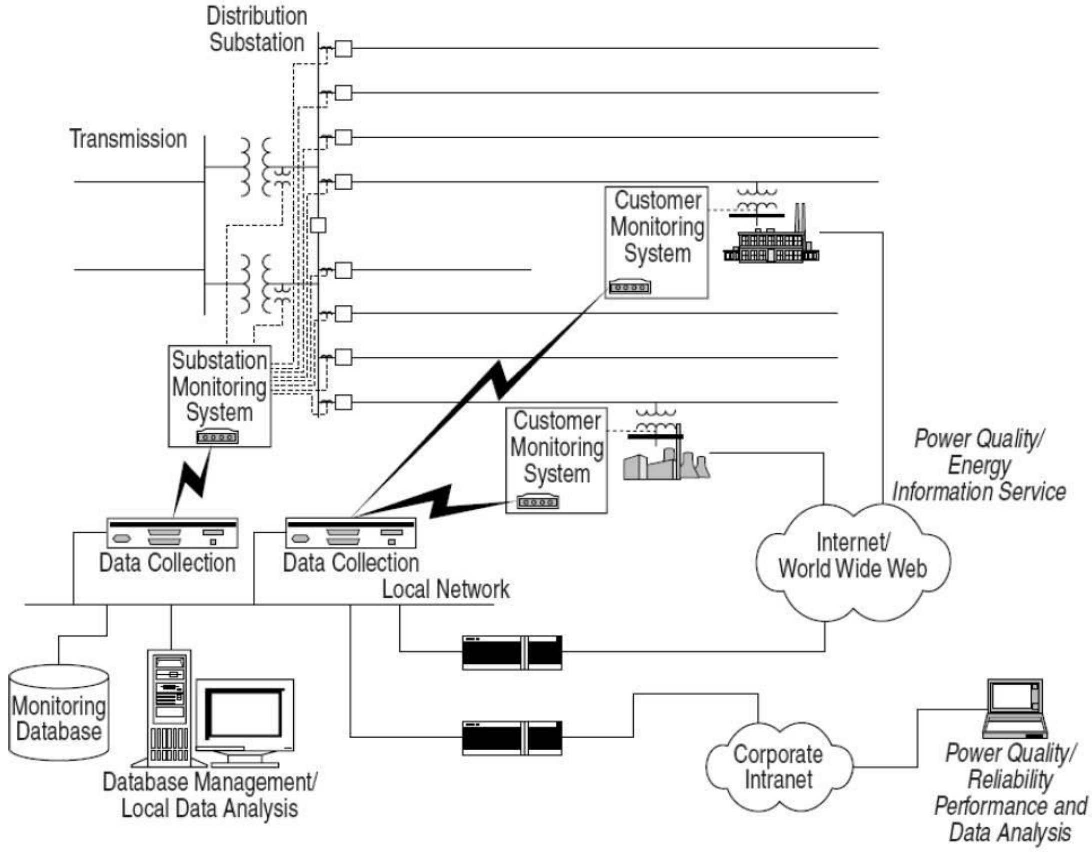


Fig. 5.1 Illustration of system power quality monitoring concept with monitoring at the substation and selected customer locations

5.2.5 Find the Sources of Disturbance

The first step in identifying the source of a disturbance is to correlate the disturbance waveform with possible causes. Once a category for the cause has been determined (e.g., load switching, capacitor switching, remote fault condition, recloser operation), the identification becomes more straightforward. The following general guidelines can help,

- High-frequency voltage variations will be limited to locations close to the source of the disturbance. Low-voltage (600 V and below) wiring often damps out high-frequency components very quickly due to circuit resistance, so these frequency components will only appear when the monitor is located close to the source of the disturbance.
- Power interruptions close to the monitoring location will cause a very abrupt change in the voltage. Power interruptions remote from the monitoring location will result in a decaying voltage due to stored energy in rotating equipment and capacitors.
- The highest harmonic voltage distortion levels will occur close to capacitors that are causing resonance problems. In these cases, a single frequency will usually dominate the voltage harmonic spectrum.

5.3 Power Quality Measurement Equipment

They include everything from very fast transient over voltages (microsecond time frame) to long-duration outages (hours or days time frame). Power quality problems also include steady-state phenomena, such as harmonic distortion, and intermittent phenomena, such as voltage flicker.

Types of instruments:

Although instruments have been developed that measure a wide variety of disturbances, a number of different instruments may be used, depending on the phenomena being investigated. Basic categories of instruments that may be applicable include,

Wiring and grounding test devices

- Multimeters
- Oscilloscopes
- Disturbance analyzers
- Harmonic analyzers and spectrum analyzers
- Combination disturbance and harmonic analyzers
- Flicker meters

- Energy monitors

Besides these instruments, which measure steady-state signals or disturbances on the power system directly, there are other instruments that can be used to help solve power quality problems by measuring ambient conditions,

1. Infrared meters can be very valuable in detecting loose connection sand overheating conductors. An annual procedure of checking the system in this manner can help prevent power quality problems due to arcing, bad connections, and overloaded conductors.
2. Noise problems related to electromagnetic radiation may require measurement of field strengths in the vicinity of affected equipment. Magnetic gauss meters are used to measure magnetic field strengths for inductive coupling concerns. Electric field meters can measure the strength of electric fields for electrostatic coupling concerns.
3. Static electricity meters are special-purpose devices used to measure static electricity in the vicinity of sensitive equipment. Electrostatic discharge (ESD) can be an important cause of power quality problems in some types of electronic equipment.

Regardless of the type of instrumentation needed for a particular test, there are a number of important factors that should be considered when selecting the instrument. Some of the more important factors include,

- Number of channels (voltage and/or current)
- Temperature specifications of the instrument
- Ruggedness of the instrument
- Input voltage range (e.g., 0 to 600 V)
- Power requirements
- Ability to measure three-phase voltages
- Input isolation (isolation between input channels and from each input to ground)
- Ability to measure currents
- Housing of the instrument (portable, rack-mount, etc.)
- Ease of use (user interface, graphics capability, etc.)
- Documentation
- Communication capability (modem, network interface)
- Analysis software

The flexibility (comprehensiveness) of the instrument is also important. The more functions that can be performed with a single instrument, the fewer the number of instruments required.

Wiring and grounding testers:

Many power quality problems reported by end users are caused by problems with wiring and/or grounding within the facility. These problems can be identified by visual inspection of wiring, connections, and panel boxes and also with special test devices for detecting wiring and grounding problems.

Important capabilities for a wiring and grounding test device include,

- Detection of isolated ground shorts and neutral-ground bonds
- Ground impedance and neutral impedance measurement or indication
- Detection of open grounds, open neutrals, or open hot wires
- Detection of hot/neutral reversals or neutral/ground reversals

Three-phase wiring testers should also test for phase rotation and phase-to-phase voltages. These test devices can be quite simple and provide an excellent initial test for circuit integrity. Many problems can be detected without the requirement for detailed monitoring using expensive instrumentation.

Multimeters:

After initial tests of wiring integrity, it may also be necessary to make quick checks of the voltage and/or current levels within a facility. Overloading of circuits, under voltage and overvoltage problems, and unbalances between circuits can be detected in this manner. These measurements just require a simple multi meter. Signals used to check for these include,

- Phase-to-ground voltages
- Phase-to-neutral voltages
- Neutral-to-ground voltages
- Phase-to-phase voltages (three-phase system)
- Phase currents
- Neutral currents

The most important factor to consider when selecting and using a multimeter is the method of calculation used in the meter. All the commonly used meters are calibrated to give an RMS indication for the measured signal. However, a number of different methods are used to calculate the RMS value. The three most common methods are,

1. **Peak method:** Assuming the signal to be a sinusoid, the meter reads the peak of the signal and divides the result by 1.414 (square root of 2) to obtain the rms.
2. **Averaging method:** The meter determines the average value of a rectified signal. For a clean sinusoidal signal (signal containing only one frequency), this average value is related to the RMS value by a constant.
3. **True RMS:** The RMS value of a signal is a measure of the heating that will result if the voltage is impressed across a resistive load. One method of detecting the true RMS value is to actually use a thermal detector to measure a heating value. More modern digital meters use a digital calculation of the RMS value by squaring the signal on a sample by-sample basis, averaging over the period, and then taking the square root of the result. These different methods all give the same result for a clean, sinusoidal signal but can give significantly different answers for distorted signals. This is very important because significant distortion levels.

5.4 Disturbance Analyzers

Disturbance analyzers and disturbance monitors form a category of instruments that have been developed specifically for power quality measurements. They typically can measure a wide variety of system disturbances from very short duration transient voltages to long-duration outages or under voltages. Thresholds can be set and the instruments left unattended to record disturbances over a period of time. The information is most commonly recorded on a paper tape, but many devices have attachments so that it can be recorded on disk as well.

There are basically two categories of these devices,

1. Conventional analyzers that summarize events with specific information such as overvoltage and under voltage magnitudes, sags and surge magnitude and duration, transient magnitude and duration, etc.
2. Graphics-based analyzers that save and print the actual waveform along with the descriptive information which would be generated by one of the conventional analyzers.

It is often difficult to determine the characteristics of a disturbance or a transient from the summary information available from conventional disturbance analyzers. For instance, an oscillatory transient cannot be effectively described by a peak and duration. Therefore, it is almost imperative to have the waveform capture capability of a graphics-based disturbance analyzer for detailed analysis of a power quality problem as shown in figure 5.2. However, a simple conventional disturbance monitor can be valuable for initial checks at a problem location.

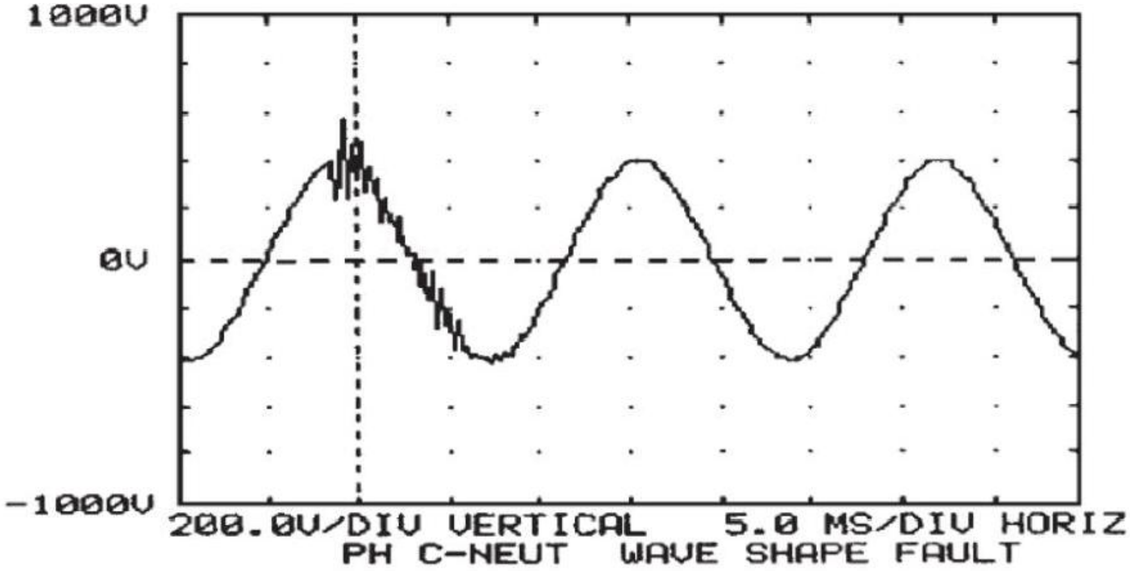


Fig. 5.2 Graphics-based analyzer output

5.5 Spectrum analyzers and Harmonic Analyzers

Harmonic analyzers have several capabilities. They capture harmonic waveforms and display them on a screen. They calculate the K factor to de rate transformers and the total harmonic distortion (THD) in percent of the fundamental. They also measure the corresponding frequency spectrum, i.e., the harmonic frequency associated with the current and voltage up to the fiftieth harmonic.

They display the harmonic frequency on a bar graph or as the signal’s numerical values. Some measure single-phase current and voltage while others measure three-phase current and voltage. All of them measure the power factor (PF). The power factor provides a measurement of how much of the power is being used efficiently for useful work. Some can store data for a week or more for later transfer to a PC for analysis.

This makes them powerful tools in the analysis of harmonic power quality problems. Some of the more powerful analyzers have add-on modules that can be used for computing fast Fourier transform (FFT) calculations to determine the lower-order harmonics. However, any significant harmonic measurement requirements will demand an instrument that is designed for spectral analysis or harmonic analysis. Important capabilities for useful harmonic measurements include Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.

- Capability to measure both magnitude and phase angle of individual harmonic components (also needed for power flow calculations).
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at least the 37th harmonic (this requirement is a combination of a high sampling rate and a sampling interval based on the 60-Hz fundamental).
- Capability to characterize the statistical nature of harmonic distortion levels (harmonics levels change with changing load conditions and changing system conditions).

There are basically three categories of instruments to consider for harmonic analysis:

1. **Simple meters:** It may sometimes be necessary to make a quick check of harmonic levels at a problem location. A simple, portable meter for this purpose is ideal. There are now several hand-held instruments of this type on the market. Each instrument has advantages and disadvantages in its operation and design. These devices generally use microprocessor-based circuitry to perform the necessary calculations to determine individual harmonics up to the 50th harmonic, as well as the RMS, the THD, and the telephone influence factor (TIF). Some of these devices can calculate harmonic powers (magnitudes and angles) and can upload stored waveforms and calculated data to a personal computer.
2. **General-purpose spectrum analyzers**: Instruments in this category are designed to perform spectrum analysis on waveforms for a wide variety of applications. They are general signal analysis instruments. The advantage of these instruments is that they have very powerful capabilities for a reasonable price since they are designed for a broader market than just power system applications. The disadvantage is that they are not designed specifically for sampling power frequency waveforms and, therefore, must be used carefully to assure accurate harmonic analysis. There are a wide variety of instruments in this category.
3. **Special-purpose power system harmonic analyzers:** Besides the general-purpose spectrum analyzers just described, there are also a number of instruments and devices that have been designed specifically for power system harmonic analysis. These are based on the FFT with sampling rates specifically designed for determining harmonic components in power signals. They can generally be left in the field and include communications capability for remote monitoring.

5.6 Flicker Meters

Over the years, many different methods for measuring flicker have been developed. These methods range from using very simple RMS meters with flicker curves to elaborate flicker meters that use exactly tuned filters and statistical analysis to evaluate the level of voltage flicker. This section discusses various methods available for measuring flicker.

Flicker standards: Although the United States does not currently have a standard for flicker measurement, there are IEEE standards that address flicker. IEEE Standards 141-19936 and 519-19927 both contain flicker curves that have been used as guides for utilities to evaluate the severity of flicker within their system. Both flicker curves, from Standards 141 and 519, are shown in figure 5.3. In other countries, a standard methodology for measuring flicker has been established. The IEC flicker meter is the standard for measuring flicker in Europe and other countries currently adopting IEC standards. The IEC method for flicker measurement, defined in IEC Standard 61000-4-158 (formerly IEC 868), is a very comprehensive approach to flicker measurement and is further described in "Flicker Measurement Techniques" below. More recently, the IEEE has been working toward adoption of the IEC flicker monitoring standards with an additional curve to account for the differences between 230-V and 120-V systems.

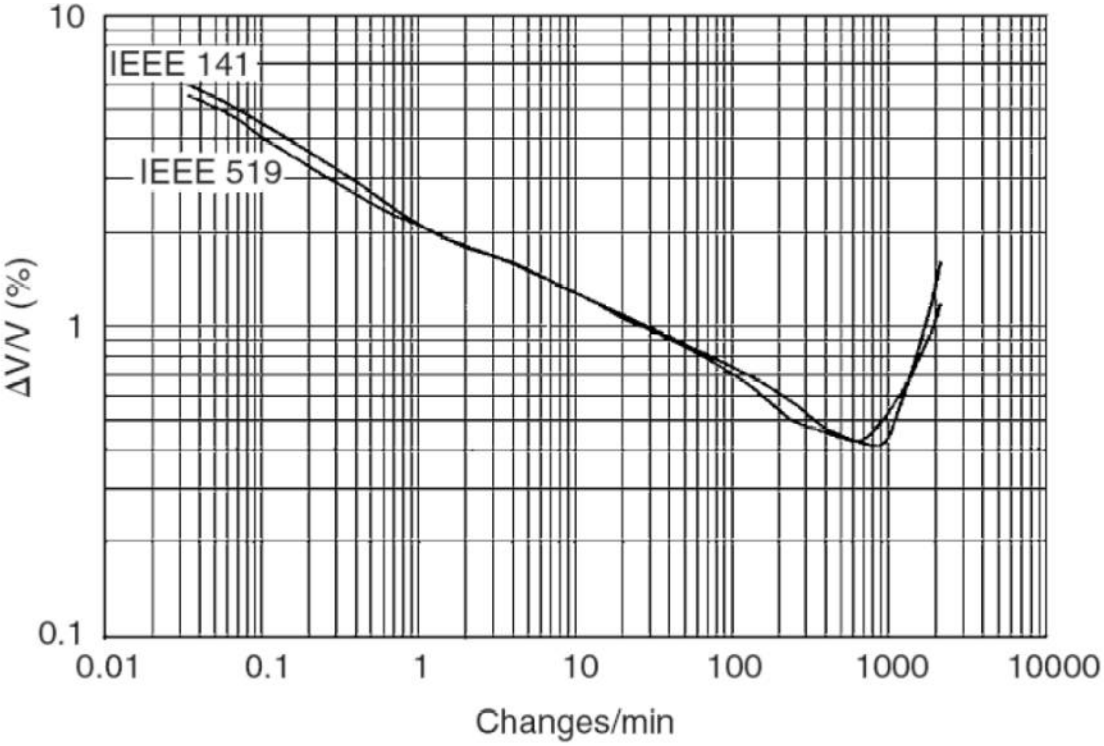


Fig. 5.3 Flicker curves from IEEE Standards 141 and 519

Flicker measurement techniques:

RMS strip charts: Historically, flicker has been measured using RMS meters, load duty cycle, and a flicker curve. If sudden RMS voltage deviations occurred with specified frequencies exceeding values found in flicker curves, such as one shown in figure 5.3, the system was said to have experienced flicker. A sample graph of RMS voltage variations is shown in figure 5.4 where large voltage deviations up to 9.0V RMS (V/V ± 8.0 percent on a 120-V base) are found. Upon comparing this to the flicker curve in Fig. 5.3, the feeder would be experiencing flicker, regardless of the duty cycle of the load producing the flicker, because any sudden total change in voltage greater than 7.0V RMS results in objectionable flicker, regardless of the frequency. The advantage to such a method is that it is quite simple in nature and the RMS data required are rather easy to acquire. The apparent disadvantage to such a method would be the lack of accuracy and inability to obtain the exact frequency content of the flicker.

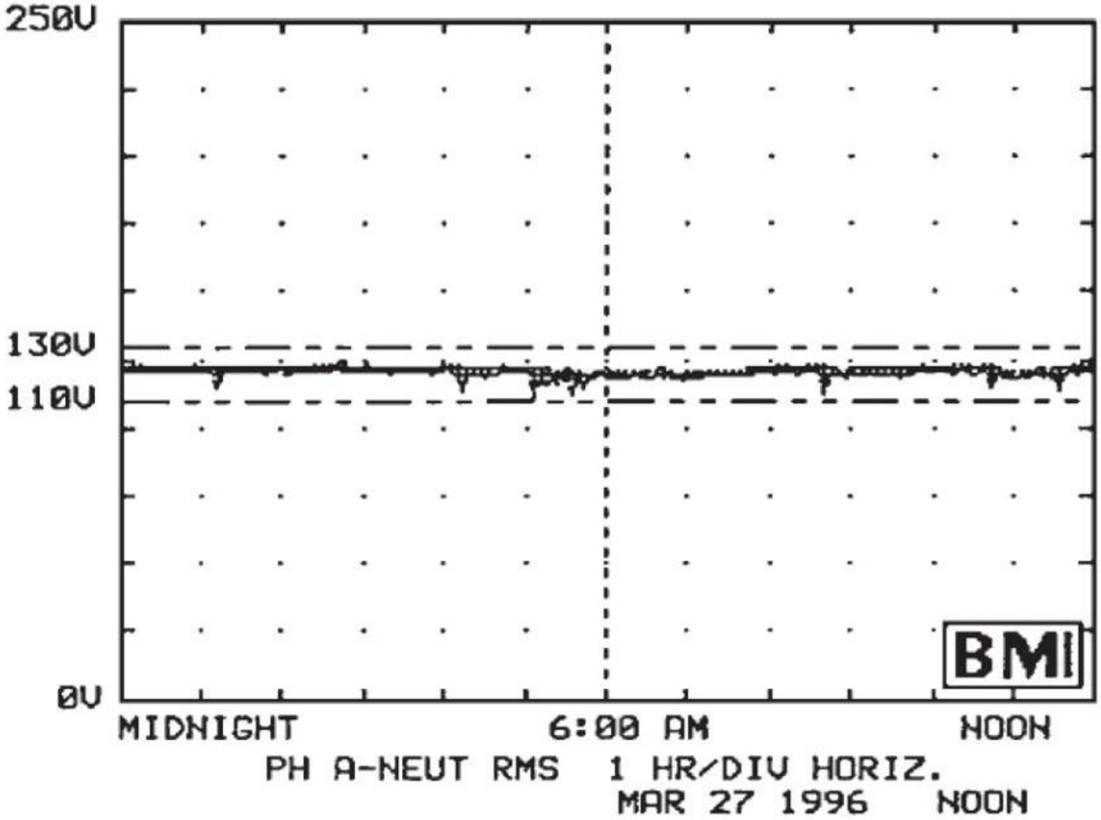


Fig.5.4 RMS voltage variations

Fast Fourier transforms: Another method that has been used to measure flicker is to take raw samples of the actual voltage waveforms and implement a fast Fourier transform on the demodulated signal (flicker signal only) to extract the various frequencies and magnitudes found in the data. These data would then be compared to a flicker curve. Although similar to using the rms strip charts, this method more accurately quantifies the data measured due to the magnitude and frequency of the flicker being known. The downside to implementing this method is associated with quantifying flicker levels when the flicker-producing load contains multiple flicker signals. Some instruments compensate for this by reporting only the dominant frequency and discarding the rest.

5.7 Application of Expert Systems for Power Quality Monitoring

Many advanced power quality monitoring systems are equipped with either off-line or on-line intelligent systems to evaluate disturbances and system conditions so as to make conclusions about the cause of the problem or even predict problems before they occur. The applications of intelligent systems or autonomous expert systems in monitoring instruments help engineers determine the system condition rapidly. This is especially important when restoring service following major disturbances.

The implementation of intelligent systems within a monitoring instrument can significantly increase the value of a monitoring application since it can generate information rather than just collect data. The intelligent systems are packaged as individual autonomous expert system modules, where each module performs specific functions. Examples include an expert system module that analyzes capacitors witching transients and determines the relative location of the capacitor bank, and an expert system module to determine the relative location of the fault causing voltage sag.

5.7.1 Basic Design of an Expert System for Monitoring Applications

The development of an autonomous expert system calls for many approaches such as signal processing and rule-based techniques along with the knowledge-discovery approach commonly known as data mining. Before the expert system module is designed, the functionalities or objectives of the module must be clearly defined. In other words, the designers or developers of the expert system module must have a clear understanding about what knowledge they are trying to discover from volumes of raw measurement data. This is very important since they will ultimately determine the overall design of the expert system module.

The process of turning raw measurement data into knowledge involves data selection and preparation, information extraction from selected data, information assimilation, and report presentation. These steps illustrated in figure 5.5 are commonly known as knowledge discovery or data mining.

The first step in the knowledge discovery is to select appropriate measurement quantities and disregard other types of measurement that do not provide relevant information. In addition, during the data selection process preliminary analyses are usually carried out to ensure the quality of the measurement. For example, an expert system module is developed to retrieve a specific answer, and it requires measurements of instantaneous three-phase voltage and current waveforms to be available.

The data-selection task is responsible for ensuring that all required phase voltage and current waveform data are available before proceeding to the next step. In some instances, it might be necessary to interpolate or extrapolate data in this step. Other preliminary examinations include checking any outlier magnitudes, missing data sequences, corrupted data, etc. Examination on data quality is important as the accuracy of the knowledge discovered is determined by the quality of data.

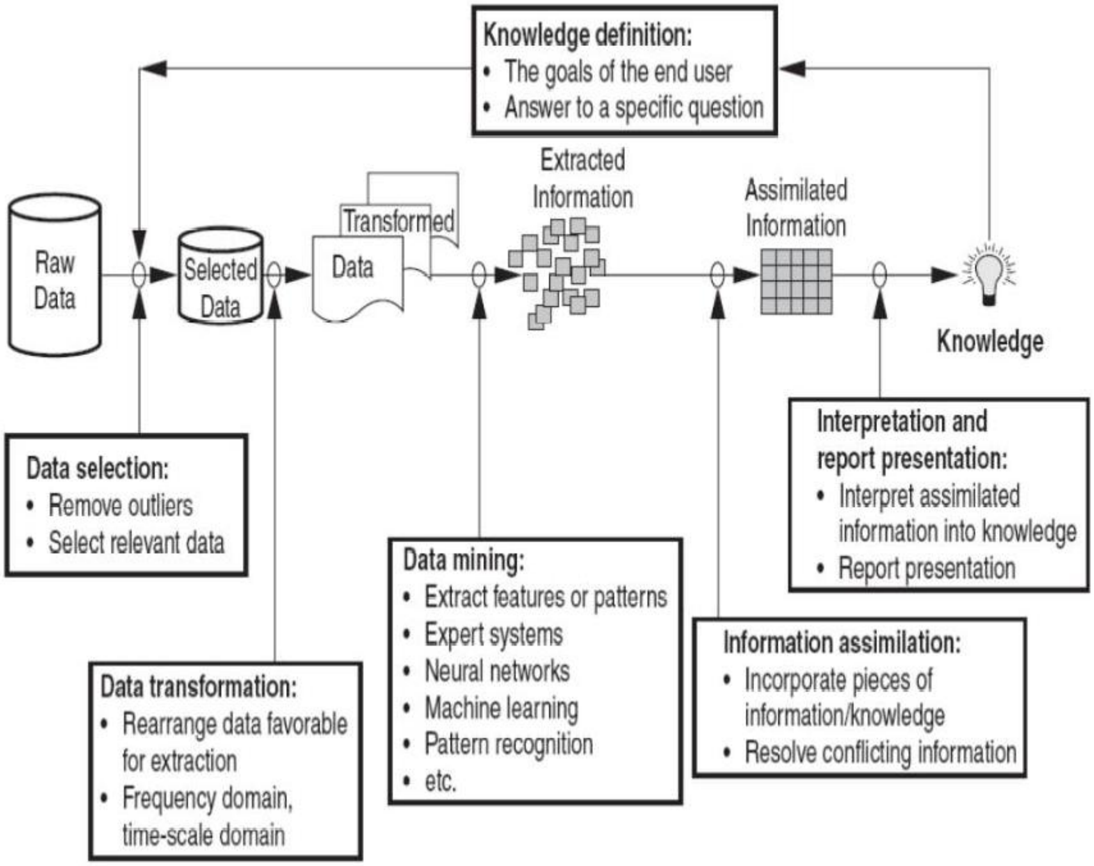


Fig. 5.5 Process of turning raw data into answers or knowledge

The second step attempts to represent the data and project them onto domains in which a solution is more favorable to discover. Signal-processing techniques and power system analysis are applied. An example of this step is to transform data into another domain where the information might be located. The Fourier transform is performed to uncover frequency information for steady-state signals, the wavelet transform is performed to find the temporal and frequency information for transient signals, and other transforms may be performed as well.

Now that the data are already projected onto other spaces or domains, we are ready to extract the desired information. Techniques to extract the information vary from sophisticated ones, such as pattern recognition, neural networks, and machine learning, to simple ones, such as finding the maximum value in the transformed signal or counting the number of points in which the magnitude of a voltage waveform is above a predetermined threshold value. One example is looking for harmonic frequencies of a distorted waveform. In the second step the waveform is transformed using the Fourier transform, resulting in a frequency domain signal.

A simple harmonic frequency extraction process might be accomplished by first computing the noise level in the frequency domain signal, and subsequently setting a threshold number to several fold that of the noise level. Any magnitude higher than the threshold number may indicate the presence of harmonic frequencies.

The data mining step usually results in scattered pieces of information. These pieces of information are assimilated to form knowledge. In some instances assimilation of information is not readily possible since some pieces of information conflict with each other. If the conflicting information cannot be resolved, the quality of the answer provided might have limited use. The last step in the chain is interpretation of knowledge and report presentation.

5.7.2 Future Applications

There are many applications for the intelligent power quality monitoring concept.
Some of the more important applications are listed in this section.

- Energy and demand profiling with identification of opportunities for energy savings and demand reduction.
- Harmonics evaluations to identify transformer loading concerns, sources of harmonics, problems indicating disoperation of equipment (such as converters), and resonance concerns associated with power factor correction.

- Voltage sag impacts evaluation to identify sensitive equipment and possible opportunities for process ride-through improvement.
- Power factor correction evaluation to identify proper operation of capacitor banks, switching concerns, resonance concerns, and optimizing performance to minimize electric bills.
- Motor starting evaluation to identify switching problems, inrush current concerns, and protection device operation.
- Short-circuit protection evaluation to evaluate proper operation of protective devices based on short-circuit current characteristics, time-current curves, etc.

5.8 Summary

5.9 Review Questions

Short Answer Questions

1. What are the importances of power quality monitoring?
2. What are the monitoring objectives?
3. What are the requirements of monitoring for a voltage regulation and unbalance?
4. What are the requirements of monitoring for a harmonic distortion?
5. What are the Characteristics of power line monitors?
6. What is the use of oscilloscope?
7. What is Spectrum analyzer?
8. What is FFT (or) digital technique used for harmonic analysis?
9. What is tracking generator?
10. What is the purpose of SVC?
11. What are the components of flicker meter?
12. What is total error?
13. What are the advantages of expert systems?

UNIT – VI

COMPENSATORS

TOPICS COVERED: **Introduction – Passive Shunt and Series Compensators – Active Shunt Compensator – Active Series Compensator – Unified Power Quality Compensator.**

6.1 Introduction

6.2 Passive Shunt and Series Compensators

Passive shunt and series compensators have been in the service since the inception of the AC supply system to improve the power quality of the power system by enhancing the efficiency and utilization of equipment in transmission and distribution networks. The passive compensators normally consist of lossless reactive elements such as capacitors and inductors with and without switching devices. The passive compensators are used for improving transient, steady state, and dynamic, voltage and angle stabilities. Moreover, these also help in reducing losses, enhancing the load ability, improving transmission capacity, damping power system oscillations, and mitigating sub synchronous resonance (SSR) and other contingency problems in transmission systems. The passive shunt and series compensators are also extensively used in distribution systems for improving the voltage profile at the point of common coupling (PCC), reducing losses, power factor correction (PFC), load balancing and neutral current compensation and for better utilization of distribution equipment. Ideally, the passive compensators can supply or absorb variable or fixed reactive power locally to mitigate the power quality problems. This chapter focuses on the concepts and methodologies of passive lossless compensation in distribution systems, especially on load compensation. It includes power factor correction, voltage regulation (VR), load balancing and neutral current compensation.

6.2.1 State of the Art on Passive Shunt and Series Compensators

Passive compensation is now a mature technology for providing reactive power compensation for power factor correction and/or voltage regulation, load balancing, and reduction of neutral current in AC networks. It has evolved during the past century with development in terms of varying configurations and requirements. Passive compensators are used for regulating the terminal voltage, suppressing voltage flicker, improving voltage balance, power factor correction, load balancing and neutral current mitigation in three-phase distribution systems. These objectives are achieved either individually or in combination depending upon the requirements and configurations that need to be selected appropriately.

The reactive power compensation employing lossless passive components in distribution systems has been used in practice for a long time for improving the voltage profile at the load end by the utilities and enhancing the power factor in the industries for avoiding the penalty by the utilities. In the early twentieth century, Steinmetz had investigated that an unbalanced single-phase resistive load may be realized as a balanced load using lossless passive elements in a three-phase supply system. This concept was later on extended in many directions such as balancing of three-phase unbalanced loads, power factor correction at the supply system, compensation of negative-sequence and zero-sequence currents, and voltage regulation. It has become quite important and relevant because in practice there are many single-phase and unbalanced loads such as traction, metros, furnaces, residential, and commercial loads. There are many methods to implement these compensators in practice for improving power quality, especially voltage quality, for the consumers nearby the fluctuating loads such as arc furnaces. Since these compensators are simple, cost effective, and easily realizable in practice, they are still used in large power rating.

6.2.2 Classification of Passive Shunt and Series Compensators

The passive compensators can be classified based on the topology and the number of phases. The topology can be shunt, series, or a combination of both. The other classification is based on the number of phases, such as two-wire (single-phase) and three or four-wire (three-phase) systems.

Topology Based Classification:

The passive compensators can be classified based on the topology, for example, series, shunt, or hybrid compensators. Figure 6.1 shows the examples of basic series, shunt, and hybrid compensators. Passive series compensators have limited applications in distribution systems as they affect the performance of the loads to a great extent and have resonance problems. The passive series compensators are used in transmission systems to improve power transfer capability, of course, with restricted capacity to avoid series resonance. The passive series compensators are also used in stand-alone self-excited induction generators for improving the voltage profile and enhancing the stability. In majority of the cases, mainly shunt compensators are used in practice as they are connected in parallel to the loads and do not disturb the operation of the loads. These are mainly used at the load end. So, current-based compensation is used at the load end. These inject equal compensating currents, opposite in phase, to cancel reactive power components of the load current for power factor correction at the point of connection. The passive shunt compensators are also used for voltage regulation and load balancing at the load end. These are also used as static VAR generators in the power system network for stabilizing and improving the voltage profile. The passive hybrid compensators shown in Figure 6.1 c and d as combinations of passive series and shunt elements in both short-shunt and long-shunt configurations are used in stand-alone self-excited induction generators for improving the voltage profile and enhancing the stability.

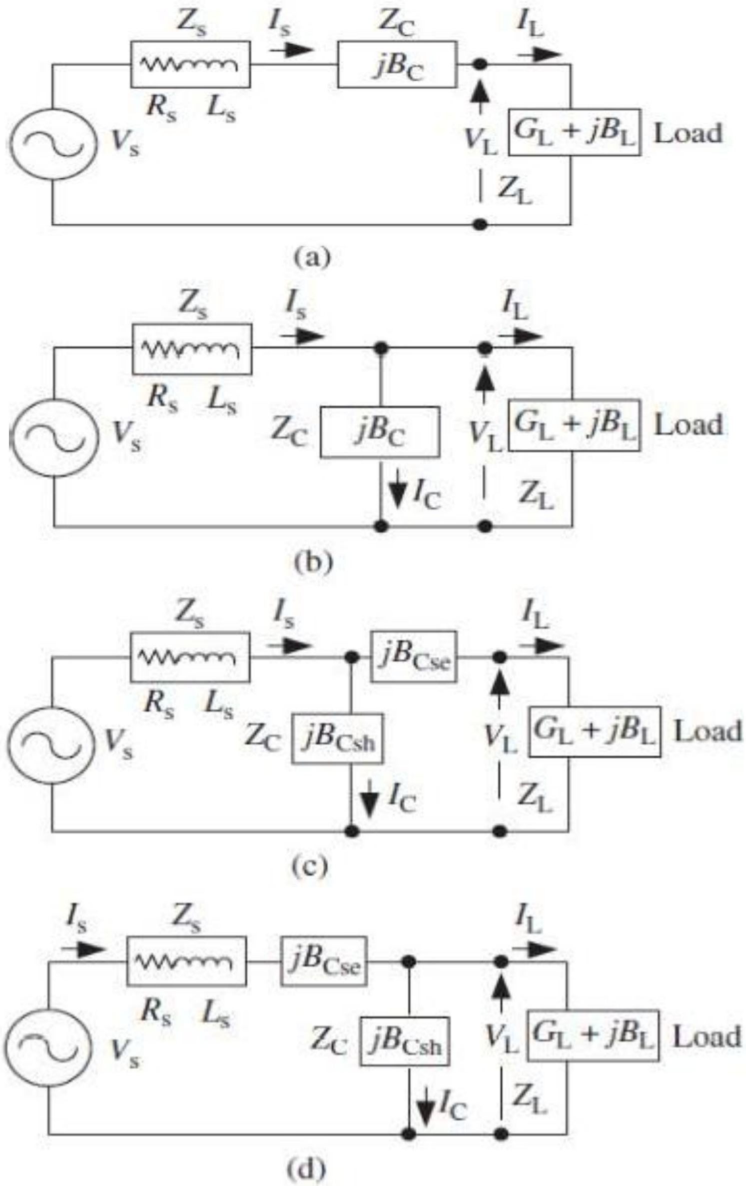


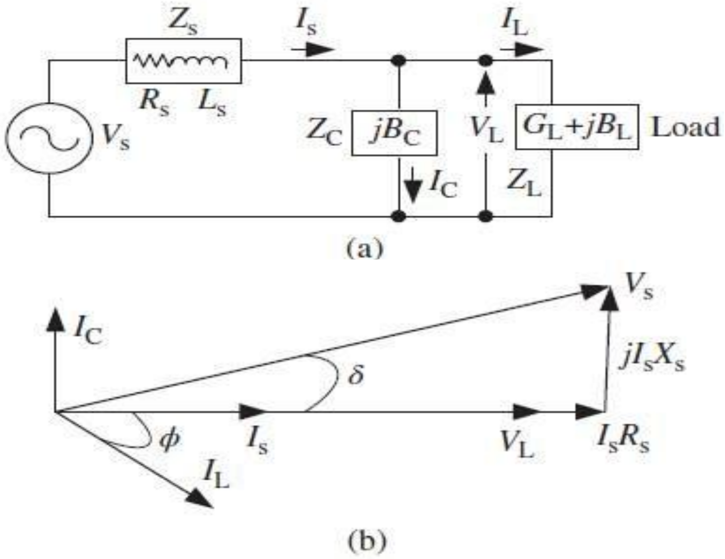
Fig. 6.1 Load compensation using (a) a series compensator (b) a shunt compensator (c) a short-shunt hybrid compensator (d) a long-shunt hybrid compensator

Supply System-Based Classification:

Mainly passive shunt compensators are used in the distribution system for reactive power compensation and load balancing, so these are studied in detail here. This classification of passive compensators is based on the supply and/or the load systems having single-phase (two-wire) and three-phase (three-wire and four-wire) systems. There are many varying loads such as domestic appliances connected to single-phase supply systems. Some three-phase unbalanced loads are without neutral terminal, such as AC motors, traction, metros, and furnaces fed from three-phase three-wire supply systems. There are many other single-phase loads distributed on three-phase four-wire supply systems, such as heating and lighting systems, among others. Hence, passive compensators may also be classified as single-phase two-wire, three-phase three-wire, and three-phase four-wire passive shunt compensators.

Two-Wire Passive Compensators:

Single-phase two-wire passive compensators are used in all three modes, that is, series, shunt and a combination of both. Figure 6.1 a–d shows four possible configurations of passive series, passive shunt and a combination of both as short-shunt and long-shunt configurations. Passive series compensators are normally used for reducing voltage sags, swell, fluctuations, and so on, while shunt compensators are used for voltage regulation or power factor correction using reactive power compensation. Therefore, shunt compensators are commonly used in the distribution systems. Figure 6.2 a–d shows a typical configuration of a passive shunt compensator along with its phasor diagrams for power factor correction and zero voltage regulation (ZVR) at the load end.



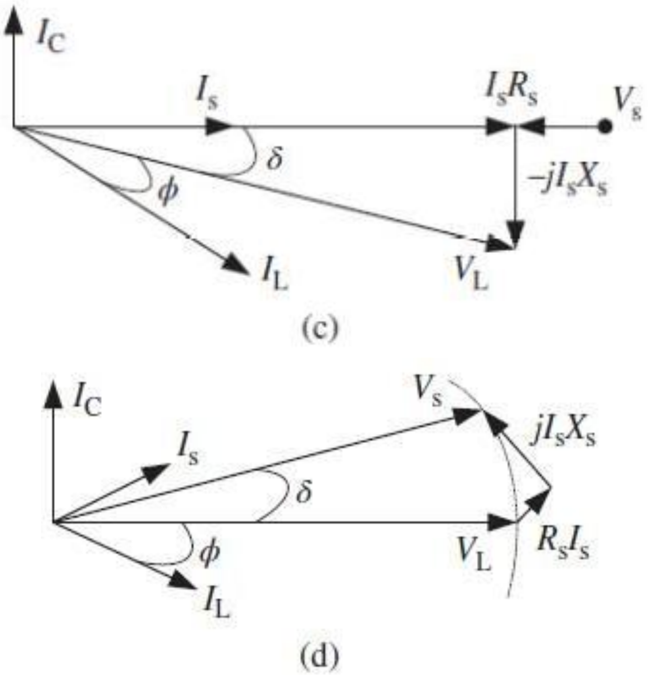
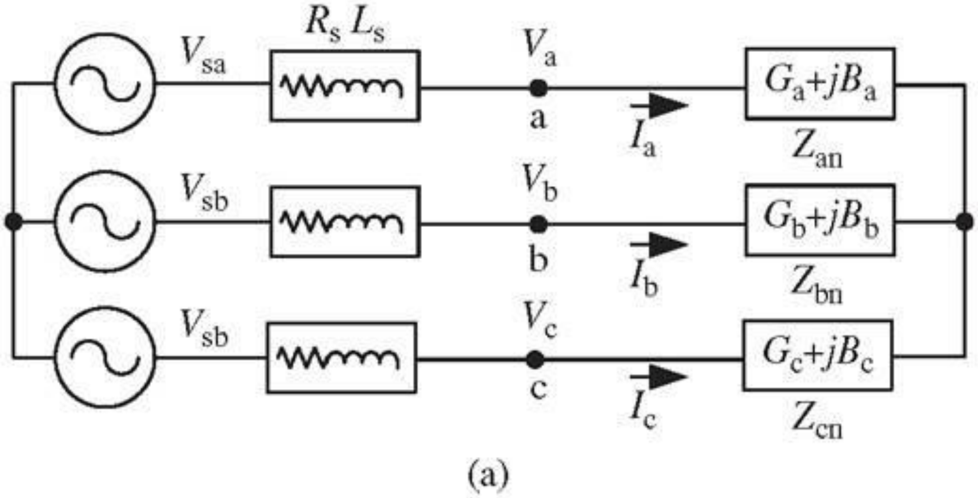
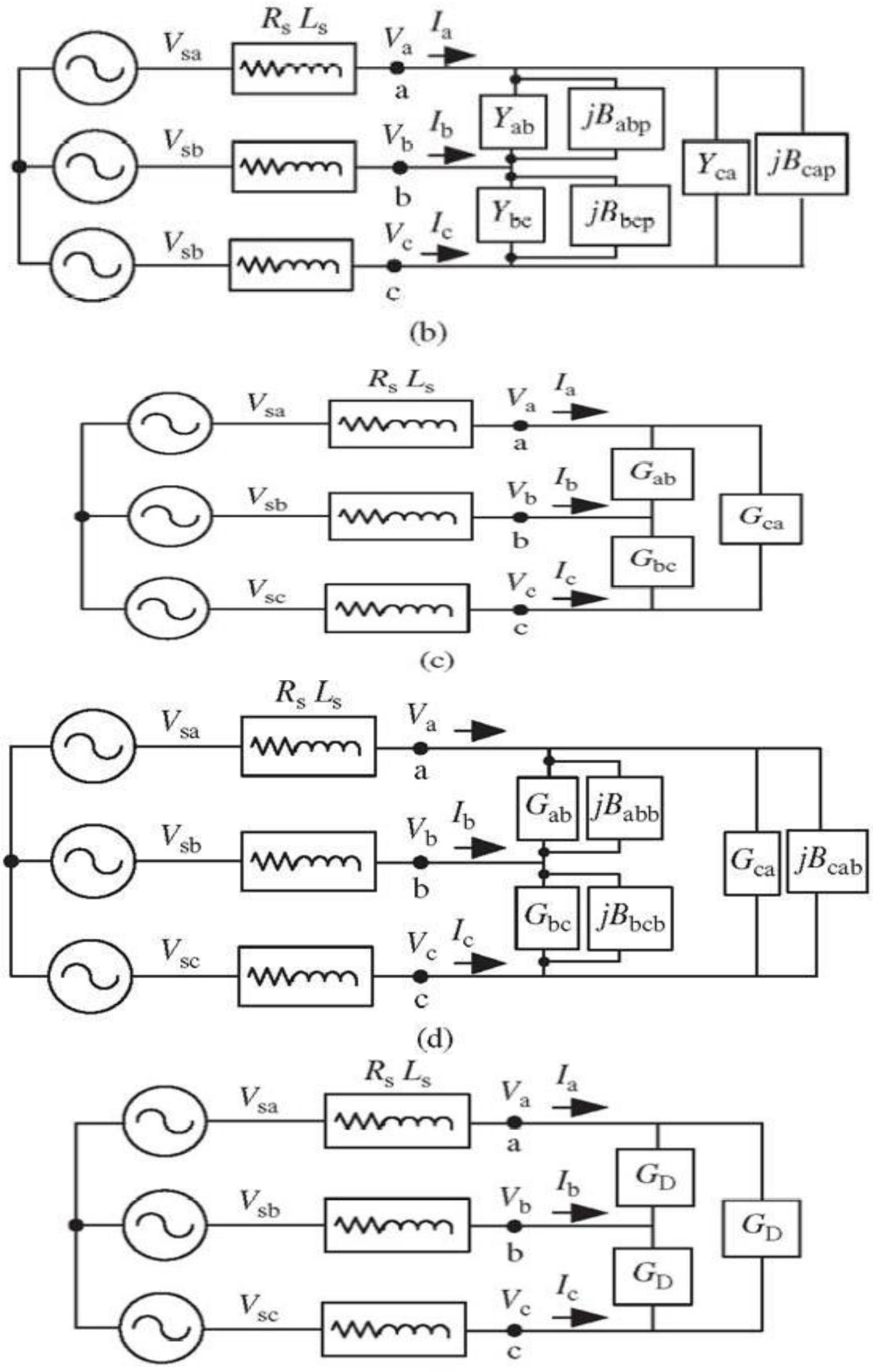


Fig. 6.2 (a) A shunt compensator (b) phasor diagrams for PFC at load terminals (c) phasor diagrams for PFC at substation (d) phasor diagrams for ZVR at load terminals

Three-Wire Passive Compensators:

Three-phase three-wire loads such as AC motors are one of the major applications. In addition, there are many unbalanced loads on a three-wire supply system such as traction, metros, and furnaces, which are fed from a three-wire supply system. Passive shunt compensators are also designed sometimes with isolation transformers for proper voltage matching, independent phase control, and reliable compensation in unbalanced systems. Figure 6.3 a–f shows typical configurations of a passive shunt compensator for power factor correction and zero voltage regulation at the load end.




V_{sa}
R_s L_s
V_a
I_a
a
Y_{ab}
jB_{abp}
Y_{ca}
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I_b
b
Y_{bc}
jB_{bcp}
V_{sb}
V_c
I_c
c
G_{ab}
G_{ca}
G_{bc}
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(b)

(c)

(d)

(e)

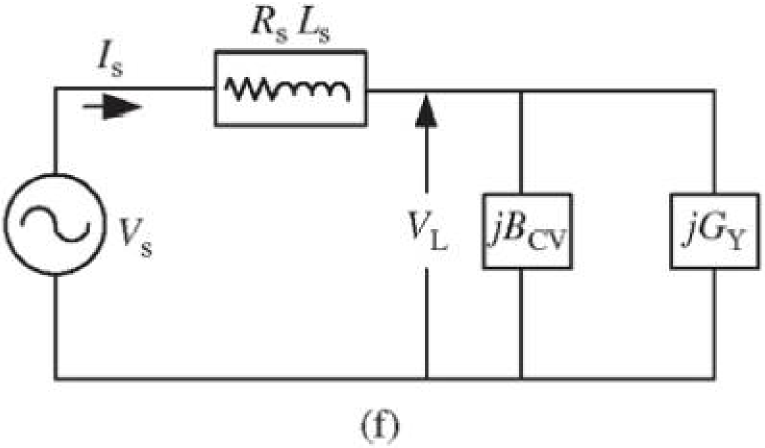
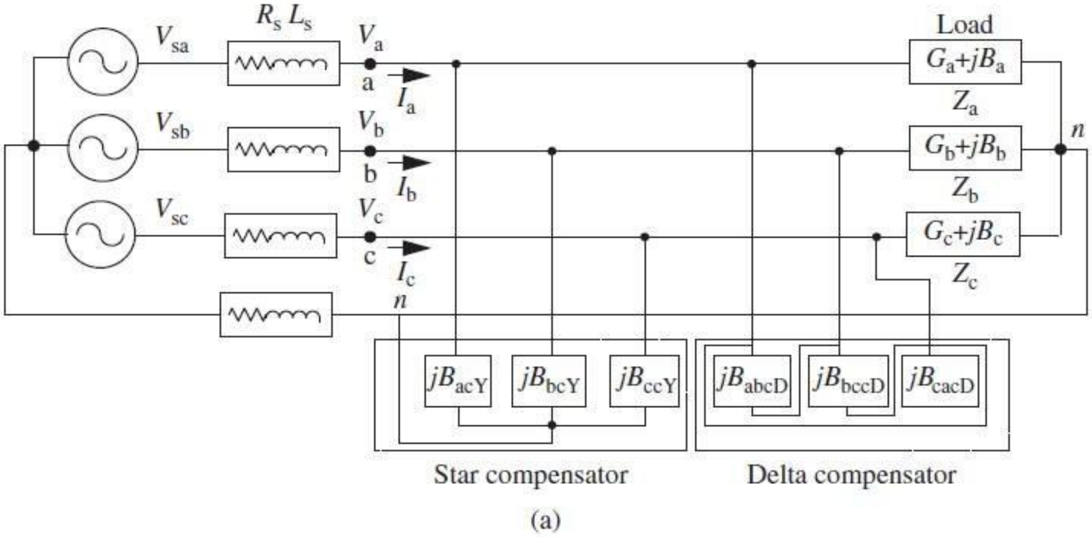


Fig.6.3 (a) A Three Phase three-wire star connected load with isolated neutral terminal
(b) Compensation for PFC of a three phase three-wire delta connected load as an equivalent of (a)
(c) An unbalanced delta connected unity power load after PFC at each phase load as an equivalent of (b)
(d) Load balancing of a delta connected unbalanced unity power load of (c)
(e) A balanced delta connected unity power load after compensation of load of (d)
(f) Compensation for ZVR of a per phase basis balanced star connected unity power load as an equivalent of (e)

Four-Wire Passive Shunt Compensators:

A large number of single-phase loads may be supplied from a three-phase AC distribution system with the neutral conductor. They cause neutral current and reactive power burden and unbalanced currents. To reduce these problems, four-wire passive compensators have been used in practice. Figure 6.4 a and b shows typical configurations of a passive shunt compensator with delta (D) and star (Y) connections of lossless passive elements for power factor correction and zero voltage regulation with neutral current mitigation at the load end.



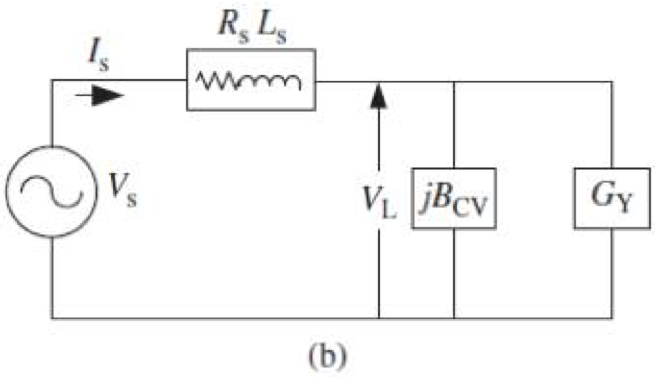


Figure 6.4 (a) Compensation for PFC, load balancing, and neutral current of a three-phase four-wire unbalanced load
(b) Compensation for ZVR of a per-phase basis balanced star connected load as an equivalent of (a)

6.2.3 Principle of Operation of Passive Shunt and Series Compensators

The main objectives of passive shunt compensators are to provide reactive power compensation for linear AC loads for improving the voltage profile (even for zero voltage regulation or power factor correction) at the AC mains in single-phase and three-phase circuits using lossless passive elements such as capacitors and inductors. In three-phase three-wire circuits, the passive shunt compensators using lossless passive elements also provide load balancing at the AC mains in addition to ZVR or PFC. Moreover, in three phase four-wire circuits, the passive shunt compensators using lossless passive elements also provide neutral current mitigation at the AC mains in addition to load balancing, ZVR, or PFC. This aspect of passive shunt compensators has been perceived long back and used in practice for a long time, even before the introduction of solid-state control. However, with the introduction of solid-state control, their performance is further improved in terms of response, flexibility, reliability, and so on. It is mainly known as classical load compensation and used in many applications such as furnaces, traction, metros, industries and distribution systems. Nowadays, the passive shunt compensators are also used in distributed, stand-alone, and renewable power generating systems.

The passive compensators are also used in a series configuration and a combination of shunt and series configurations depending upon application and their effectiveness. The passive series compensators are used for voltage regulation and enhancing power flow control in transmission systems. The passive series compensators are more effective in large power transmission systems. However, they have much severe resonance problems than passive shunt compensators; therefore, they are used cautiously and up to a certain part of compensation to avoid such divesting resonance problems. In a hybrid configuration, the series elements are used with shunt elements in some applications such as stand-alone self-excited induction generators. However, the series compensators are connected in series with the loads and affect the voltage across the loads; thus, they are not very popular in distribution systems.

6.2.4 Analysis and Design of Passive Shunt Compensators

In recent years, there has been an increased demand for the compensators to compensate large rating loads such as arc furnaces, traction, metros, commercial lighting and air conditioning. If these loads are not compensated, then these create system unbalance and lead to fluctuations in the supply voltages. Therefore, such a supply system cannot be used to feed sensitive loads such as computers and electronic equipment. However, the importance of balanced load on the supply system has already been felt long back. The unbalanced loads cause neutral current and reactive power burden, which in turn result in low system efficiency, poor power factor and disturbance to other consumers.

The passive shunt and series compensators are used for reactive power compensation for power factor correction or voltage regulation in single-phase systems. In addition, these are used for load balancing in three-phase three-wire systems. In three-phase four-wire systems, the passive compensators are also used for neutral current compensation along with load balancing and reactive power compensation for power factor correction or voltage regulation.

6.2.4.1 Analysis and Design of Single-Phase Passive Shunt Compensators

Single-phase passive shunt compensators are used for power factor correction or zero voltage regulation across the loads. Figure 6.2 a–d shows the circuit of a shunt compensator along with its phasor diagrams for these two cases. The rating of the compensator may be estimated using the system data and given load data, for which compensation is to be made.

Analysis and Design of Shunt Compensators for Power Factor Correction:

Normally for the power factor correction of the load at the AC mains, a passive shunt compensator is used as it is connected directly across the load to be compensated. This shunt compensator does not affect the voltage across the loads to a great extent. Passive series compensators can also improve/correct the power factor, but they may affect the voltage across the load depending upon the load power factor and its current magnitude; therefore, they are not much preferred in the distribution system.

Analysis and Design of Shunt Compensators for Zero Voltage Regulation:

In many situations, it is considered relevant to maintain the load terminal voltage equal to the AC mains voltage (for zero voltage regulation) by using a compensator connected at the load end. It means to recover the voltage drop in the distribution feeder. It has the following advantages,

- Avoids the voltage swells caused by capacitor switching.
- Reduces the voltage sags due to common feeder faults.
- Controls the voltage fluctuations caused by customer load variations.
- Reduces the frequency of mechanical switching operations in load tap changing (LTC) transformers and mechanically switched capacitors for drastic reduction in their maintenance.
- Enhances the load ability of the system, especially for improving the stability of the load such as an induction motor under major disturbances.

6.2.4.2 Analysis and Design of Three-Phase Three-Wire Passive Shunt Compensators

Three-phase passive compensators may be used for power factor correction or zero voltage regulation along with load balancing by connecting lossless passive elements across the unbalanced three-phase three-wire loads. The rating of the lossless passive elements of the comparator may be estimated using the system data and given load data, for which compensation is to be made as given in the following section.

Analysis and Design of Shunt Compensators for Power Factor Correction:

Any three-phase unbalanced ungrounded star connected load, which is shown in figure 6.3 (a), may be transformed to a three-phase unbalanced delta connected load as shown in figure 6.3 (b) by star–delta transformation as follows,

$$Y_{ab} = {}^{1}/_{Z_{ab}} = {}^{Z_{cn}}/_{(Z_{an}Z_{bn} + Z_{bn}Z_{cn} + Z_{cn}Z_{an})}$$

$$Y_{ba} = {}^{1}/_{Z_{ba}} = {}^{Z_{an}}/_{(Z_{an}Z_{bn} + Z_{bn}Z_{cn} + Z_{cn}Z_{an})}$$

$$Y_{ca} = {}^{1}/_{Z_{ca}} = {}^{Z_{bn}}/_{(Z_{an}Z_{bn} + Z_{bn}Z_{cn} + Z_{cn}Z_{an})}$$

where Z_{an}, Z_{bn} and Z_{cn} are three-phase load impedances of any three-phase unbalanced ungrounded star connected load. Therefore, any three-phase unbalanced ungrounded star connected load, shown in figure 6.3a, may be converted to an equivalent three-phase delta connected unbalanced reactive load shown in figure 6.3b.

6.2.4.3 Analysis and Design of Three-Phase Four-Wire Passive Shunt Compensators

Three-phase four-wire passive shunt compensators may be used for power factor correction or zero voltage regulation along with load balancing by connecting lossless passive elements across the unbalanced three-phase four-wire loads. The rating of the lossless passive elements of the compensator may be estimated using the system data and given load data.

6.2.5 Modeling, Simulation and Performance of Passive Shunt and Series Compensators

Modeling and simulation of passive shunt and series compensators are carried out to demonstrate their performance for their effectiveness and basic understanding of load compensation through voltage and current waveforms. After design of the passive compensators, these are connected in the system configuration and waveform analysis is done through simulation to study their effect on the system and to observe their interactions with the system and occurrence of any phenomena such as subsynchronous resonance and parallel resonance considering all the practical conditions, which are not considered in the design of the passive compensators. Earlier, the simulation study of these compensators with the system has been quite cumbersome. However, with various available simulation packages such as MATLAB, PSCAD, EMTP, PSPICE, SABER, PSIM, ETEPP and desilent, the simulation of the performance of these compensators has become quite simple and straightforward. Nowadays, for a particular application, after the design of these compensators, their performance is studied in simulation before these are implemented in practice.

6.3 Active Shunt Compensator

Present-day AC distribution systems are facing a number of power quality problems, especially due to the use of sensitive equipment in most of the industrial, residential, commercial, and traction applications. These power quality problems are classified as voltage and current quality problems in distribution systems. The custom power devices (CPDs), namely, DSTATCOMs (distribution static compensators), DVRs (dynamic voltage restorers), and UPQCs (unified power quality conditioners) are used to mitigate some of the problems depending upon the requirements. Out of these CPDs, DSTATCOMs are extensively used for mitigating the current-based power quality problems. There are a number of current-based power quality problems such as poor power factor, or poor voltage regulation, unbalanced currents and increased neutral current. Therefore, depending upon the problems, the configuration of the DSTATCOM is selected in the practice. With the objective of mitigating the current-based power quality problems especially in distribution systems, this chapter focuses on the configurations, design, control algorithms, modeling and illustrative examples of DSTATCOMs.

These problems further aggravate in the presence of harmonics either in the voltage or in the currents. The shunt active compensators are also reported with some modifications as cost-effective shunt active power filters to eliminate harmonic currents in nonlinear loads. Of course, the main objective of shunt active power filters has been to eliminate harmonic currents at the PCC (point of common coupling) voltage normally created by nonlinear loads.

6.3.1 State of the Art on DSTATCOMs

The DSTATCOM technology is now a mature technology for providing reactive power compensation, load balancing and/or neutral current and harmonic current compensation (if required) in AC distribution networks. It has evolved in the past quarter century with development in terms of varying configurations, control strategies and solid-state devices. These compensating devices are also used to regulate the terminal voltage, suppress voltage flicker, and improve voltage balance in three-phase systems. These objectives are achieved either individually or in combination depending upon the requirements and the control strategy and configuration that need to be selected appropriately.

In AC distribution systems, current-based power quality problems have been faced for a long time in terms of poor power factor, poor voltage regulation, load unbalancing, and enhanced neutral current. Classical technology of using power capacitors and static VAR compensators using TCRs (thyristor controlled reactors) and TSCs (thyristor switched capacitors) has been used to mitigate some of these power quality problems. However, DSTATCOM technology is considered the best technology to mitigate all the current-based power quality problems.

DSTATCOMs are basically categorized into three types, namely, single-phase two-wire, three-phase three-wire, and three-phase four-wire configurations, to meet the requirements of three types of consumer loads on supply systems. Single-phase loads such as domestic lights and ovens, TVs, computer power supplies, air conditioners, laser printers, and Xerox machines cause power quality problems. Single-phase two-wire DSTATCOMs have been investigated in varying configurations and control strategies to meet the needs of single-phase systems. Starting from 1984, many configurations have been developed and commercialized for many applications. Both current source converters (CSCs) with inductive energy storage and voltage source converters (VSCs) with capacitive energy storage are used to develop single phase DSTATCOMs.

6.3.2 Classification of DSTATCOMs

DSTATCOMs can be classified based on the type of converter used, topology, and the number of phases. The converter used in the DSTATCOM can be either a current source converter or a voltage source converter. Different topologies of DSTATCOMs can be realized by using transformers and various circuits of VSCs. The third classification is based on the number of phases, namely, single-phase two wire, three-phase three-wire, and three-phase four-wire systems.

6.3.2.1 Converter-Based Classification

Two types of converters are used to develop DSTATCOMs. Figure 6.5 shows a DSTATCOM using a CSC bridge. A diode is used in series with the self-commutating device (IGBT) for reverse voltage blocking. However, GTO-based DSTATCOM configurations do not need the series diode, but they have restricted frequency of switching. They are considered sufficiently reliable, but have high losses and require high values of parallel AC power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve the performance of DSTATCOMs in higher power ratings.

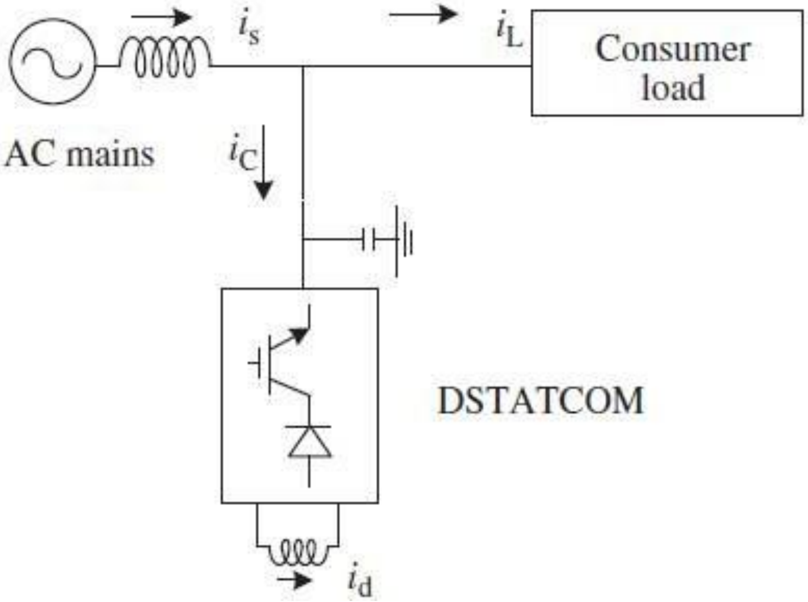


Fig. 6.5 A CSC-based DSTATCOM

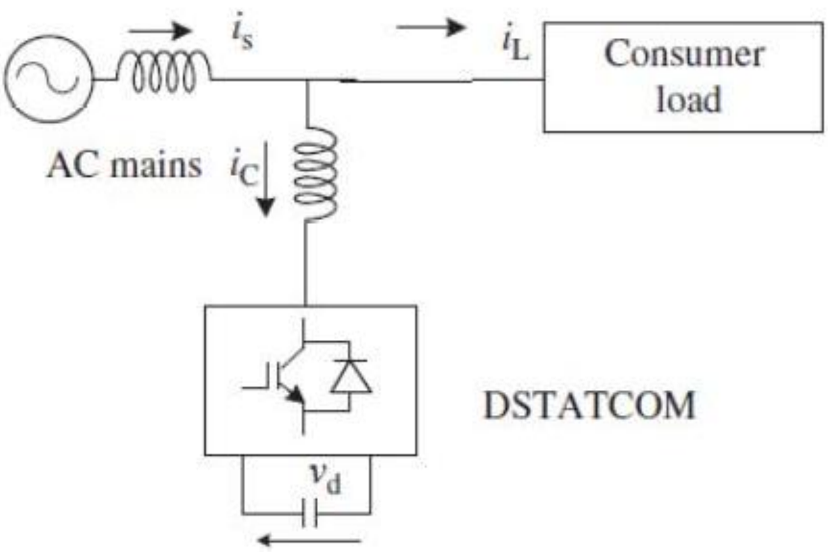


Fig. 6.6 A VSC-based DSTATCOM

The other converter used in a DSTATCOM is a voltage source converter shown in Figure 6.6. It has a self-supporting DC voltage bus with a large DC capacitor. It is more widely used because it is light, cheap and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies.

6.3.2.2 Topology-Based Classification

DSTATCOMs can also be classified based on the topology, for example, VSCs without transformers, VSCs with non-isolated transformers, and VSCs with isolated transformers. DSTATCOMs are also used as advanced static VAR generators (STATCOMs) in the power system network for stabilizing and improving the voltage profile. Therefore, a large number of circuits of DSTATCOMs with and without transformers are evolved for meeting the specific requirements of the applications.

6.3.2.3 Supply System-Based Classification

This classification of DSTATCOMs is based on the supply and/or the load system, for example, single phase two-wire, three-phase three-wire, and three-phase four-wire systems. There are many varying loads such as domestic appliances connected to single-phase supply systems. Some three-phase loads are without neutral terminals, such as traction, furnaces, and ASDs (adjustable speed drives) fed from three wire supply systems. There are many single-phase loads distributed on three-phase four-wire supply systems, such as computers and commercial lighting. Hence, DSTATCOMs may also be classified accordingly as two-wire, three-wire, and four-wire DSTATCOMs.

Two-Wire DSTATCOMs:

Two-wire (single-phase) DSTATCOMs are used in both converter configurations, a CSC bridge with inductive energy storage elements and a VSC bridge with capacitive DC bus energy storage elements, to form two-wire DSTATCOM circuits.

Figure 6.7 shows a configuration of a DSTATCOM with a CSC bridge using inductive energy storage elements. A similar configuration based on a VSC bridge with capacitive energy storage at its DC bus is obtained by considering only two wires (phase and neutral terminals) as shown in Figure 6.8.

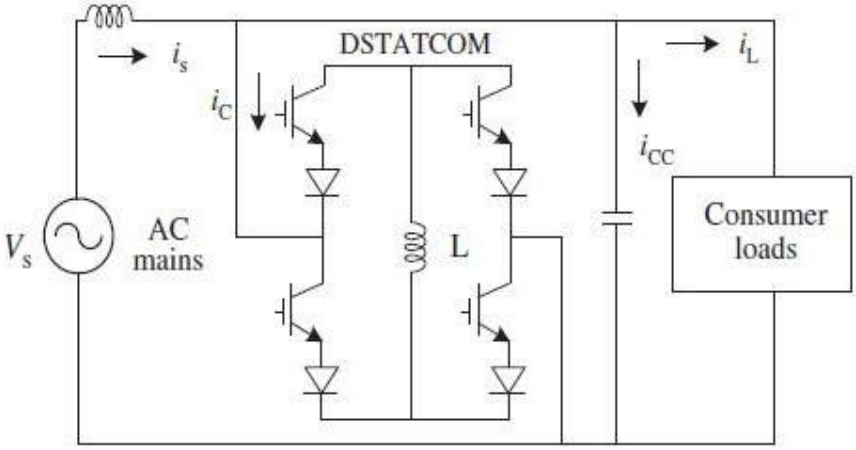


Fig. 6.7 A two-wire DSTATCOM with a CSC

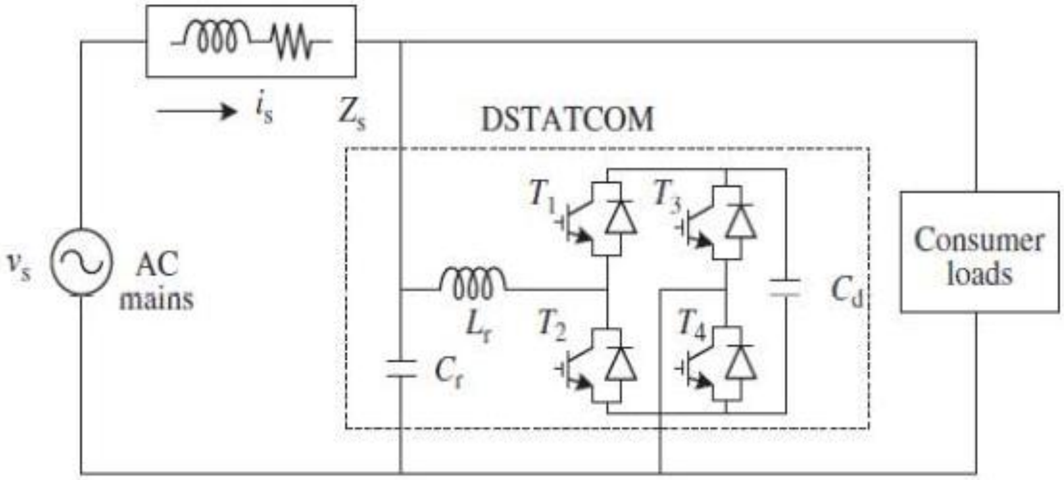


Fig. 6.8 A two-wire DSTATCOM with a VSC

Three-Wire DSTATCOMs:

There are various configurations of capacitor-supported DSTATCOMs based on the type of VSC used and auxiliary circuits. The classification of three-phase three-wire DSTATCOMs is shown in Figure 6.9, consisting of isolated and non-isolated VSC-based topologies of DSTATCOMs. The non-isolated configurations include three-leg VSC-based

DSTATCOMs and two-leg VSC-based DSTATCOMs, these circuit configurations are shown in Figures 6.10 and 6.11, respectively.

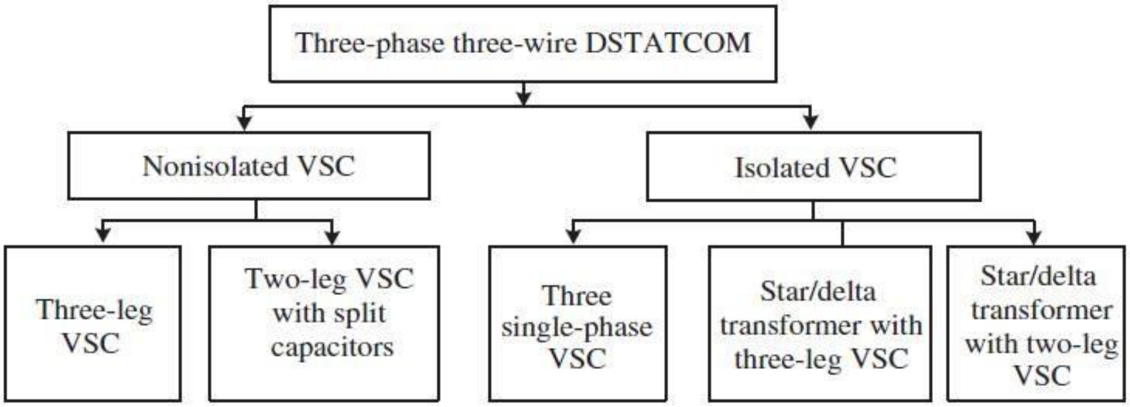


Fig. 6.9 Topology classification of three-phase three-wire DSTATCOMs

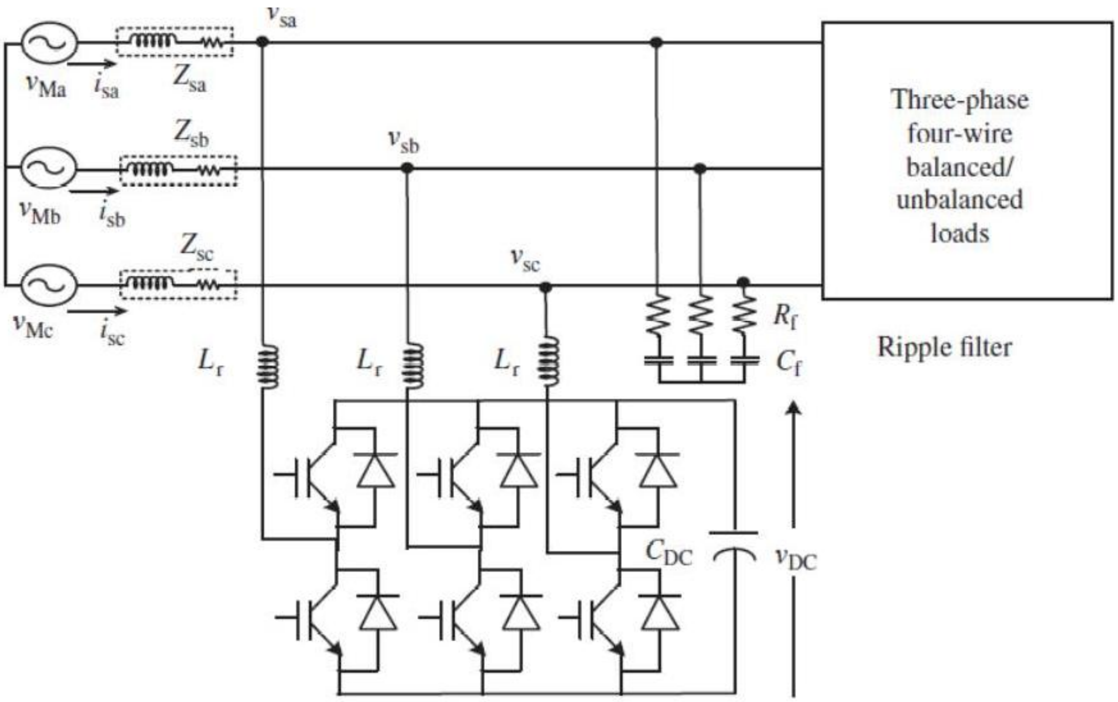


Fig. 6.10 A three-leg VSC-based three-phase three-wire DSTATCOM

The two-leg VSC-based DSTATCOM has the advantage that it requires only four switching devices, but there are two capacitors connected in series and the total DC capacitor voltage is twice the DC bus voltage of the three-leg VSC topology. The isolated configurations include three single-phase VSC-based DSTATCOMs, three-leg VSC-based DSTATCOMs, and two-leg VSC-based DSTATCOMs; these configurations are shown in figures 6.12–6.14, respectively. The advantage of the isolated VSC-based DSTATCOM topology is that the voltage rating of the VSC can be optimally designed as there is an interfacing transformer.

Three single-phase VSC-based DSTATCOMs require 12 semiconductor switches, whereas in three-leg VSC based DSTATCOMs there are only 6 switches. However, two-leg VSC-based DSTATCOMs require only four switches.

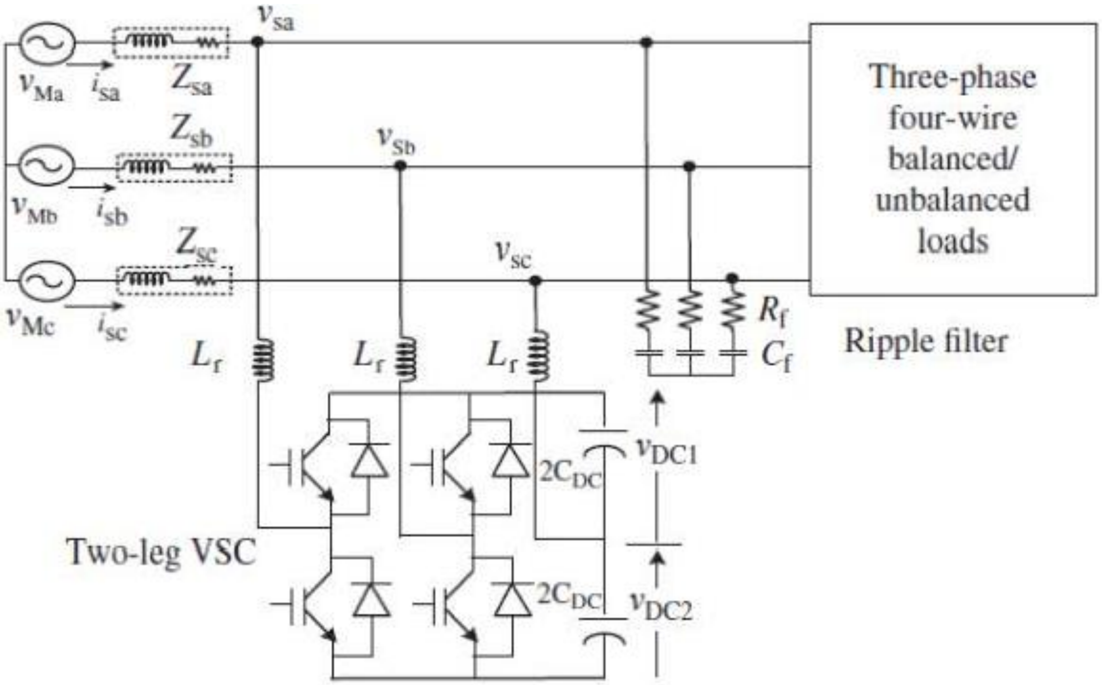


Fig. 6.11 An H-bridge VSC and midpoint capacitor-based three-phase three-wire DSTATCOM

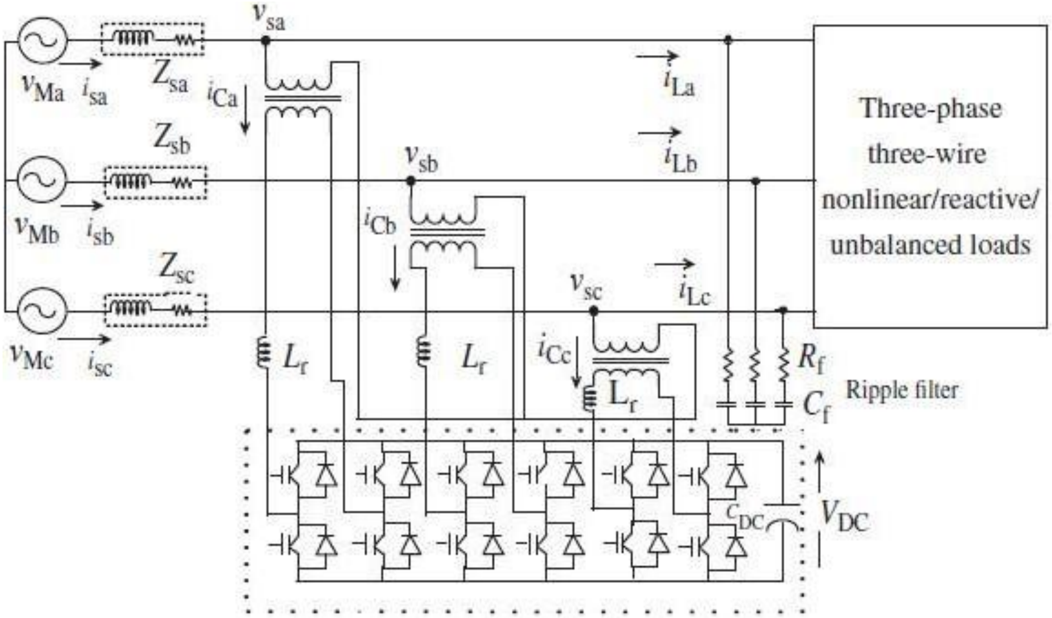


Fig. 6.12 A three single-phase VSC-based three-phase three-wire DSTATCOM

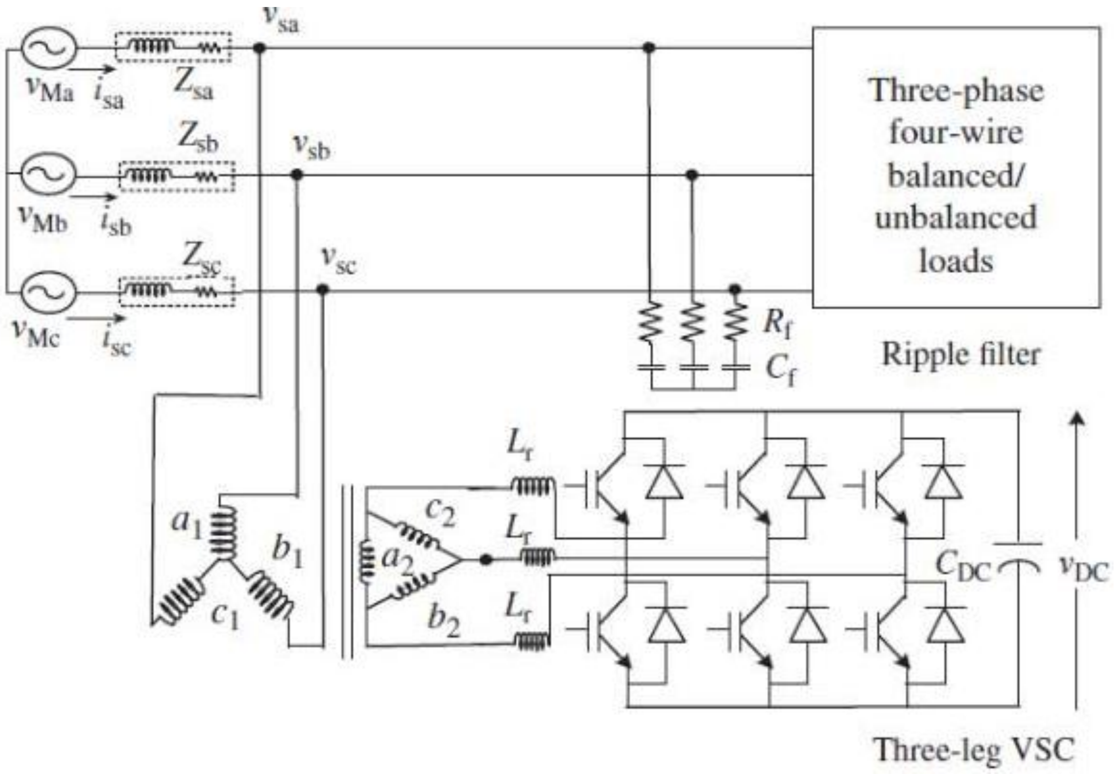


Fig. 6.13 An isolated three-leg VSC-based three-phase three-wire DSTATCOM

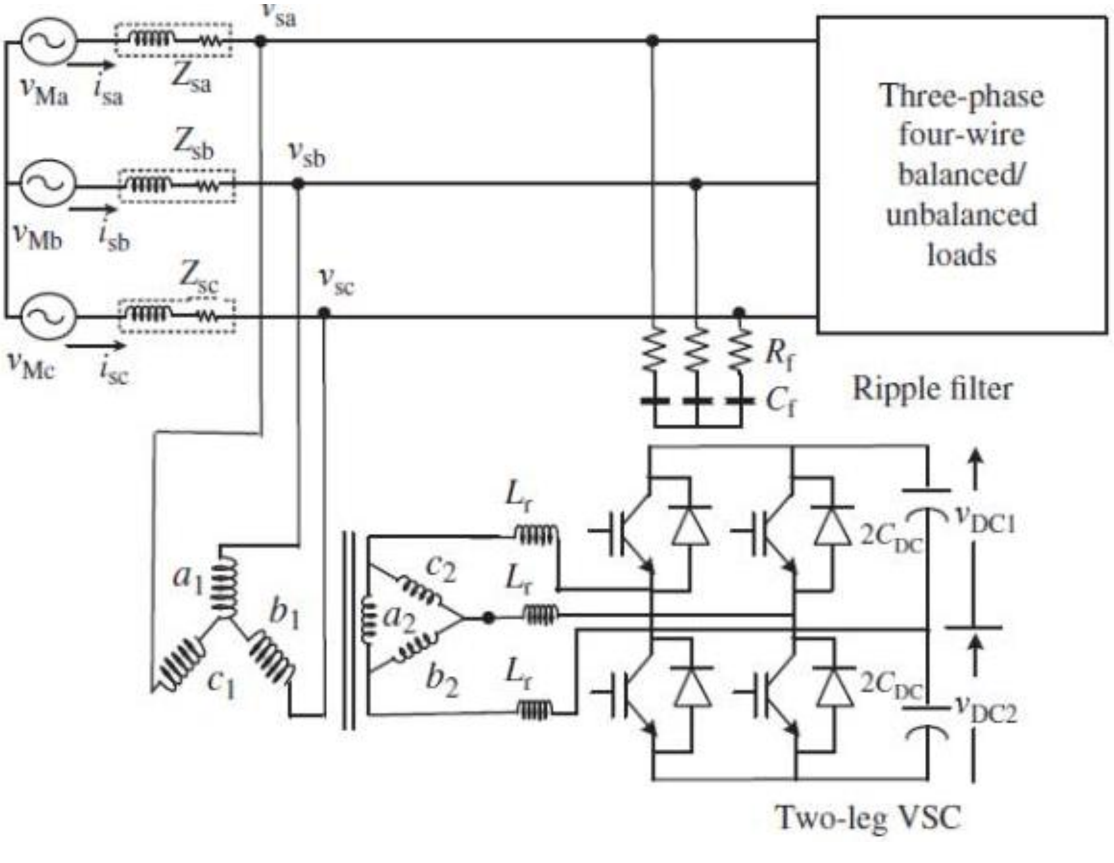


Fig. 6.14 An isolated H-bridge VSC and midpoint capacitor-based DSTATCOM

Four-Wire DSTATCOMs:

In a three-phase four-wire distribution system, there are three-phase loads and single-phase loads depending upon the consumers' demands. This results in severe burden of unbalanced currents along with the neutral current on the distribution feeder. To prevent the unbalanced currents from being drawn from the distribution bus, a shunt compensator, also called DSTATCOM, can be used. It ensures that the currents drawn from the distribution bus are balanced and sinusoidal and, moreover, the neutral current is compensated.

A DSTATCOM is a fast-response, solid-state power controller that provides power quality improvements at the point of connection to the utility distribution feeder. It is the most important controller for distribution networks. It has been widely used to precisely regulate the system voltage and/or for load compensation. It can exchange both active and reactive powers with the distribution system by varying the amplitude and phase angle of the voltage of the VSC with respect to the PCC voltage, if an energy storage system (ESS) is included into the DC bus. However, a capacitor-supported DSTATCOM is preferred for power quality improvement in the currents, such as reactive power compensation for unity power factor or voltage regulation at PCC, load balancing, and neutral current compensation.

The classification of three-phase four-wire DSTATCOM topologies is shown in Figure 6.15, based on the type of VSC used. They are mainly classified as non-isolated and isolated VSC-based DSTATCOMs. The non-isolated VSC-based DSTATCOMs consist of the following configurations: four-leg VSC, three leg VSC with split capacitors, three-leg VSC with three DC capacitors, three-leg VSC with transformers and two-leg VSC with transformers. The transformers used are a zigzag transformer, a star/delta transformer, a Scott transformer, a T-connected transformer, a star/hexagon transformer, and a star/polygon transformer.

The isolated VSC-based DSTATCOMs consist of the following configurations: three single-phase VSCs, three-leg VSC with transformers, and two-leg VSC with transformers. Various transformers used for isolation are a zigzag transformer, a star/delta transformer, a T-connected transformer, a Scott transformer, a star/hexagon transformer, and a star/polygon transformer.

The schematic diagram of a four-leg VSC-based three-phase four-wire DSTATCOM connected to a three-phase four-wire distribution system is shown in Figure 6.16. Figure 6.17 shows the schematic diagram of a three single-phase VSC-based three-phase four-wire DSTATCOM connected to a three phase four-wire distribution system. Figure 6.18 shows the schematic diagram of a three-leg VSC with split capacitor-based three-phase four-wire DSTATCOM connected to a three-phase four-wire distribution system.

Three-phase four-wire DSTATCOM configurations based on non-isolated three-leg VSCs with a zigzag transformer, a star/delta transformer, a T-connected transformer, a star/hexagon transformer, a star/polygon transformer, and a Scott transformer are shown in Figures 6.19–6.24 respectively. Similarly, three-phase four-wire DSTATCOM configurations based on non-isolated two-leg VSCs with a zigzag transformer, a star/delta transformer, a T-connected transformer, a star/hexagon transformer, a star/polygon transformer and a Scott transformer may be realized for load compensation.

Three-phase four-wire DSTATCOM configurations based on isolated three-leg VSCs with a zigzag transformer, a star/delta transformer, a T-connected transformer, a star/hexagon transformer, a star/polygon transformer, and a Scott transformer may be realized in a similar manner to the three-wire DSTATCOM configurations. Three-phase four-wire DSTATCOM configurations based on isolated two leg VSCs with a zigzag transformer, a star/delta transformer, a T-connected transformer, a star/hexagon transformer, a star/polygon transformer, and a Scott transformer may also be realized in a similar manner to non-isolated three-wire DSTATCOMs using neutral terminal of the transformers of the supply side.

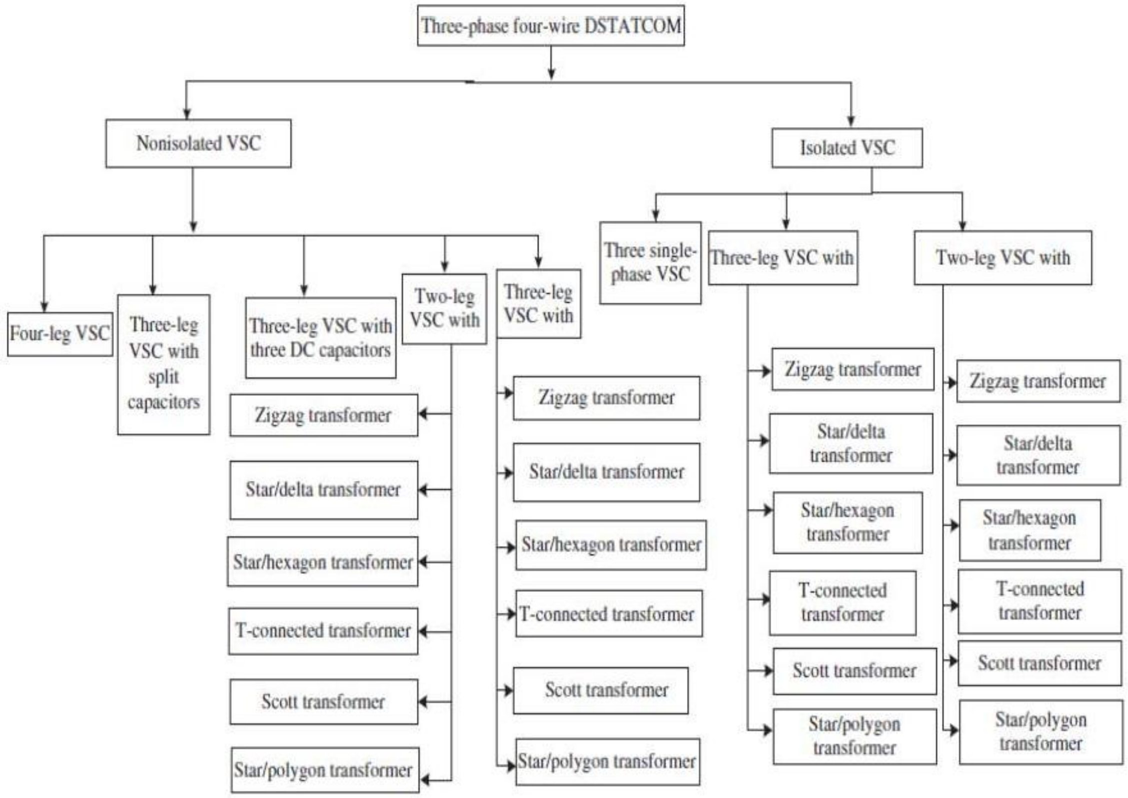


Fig. 6.15 Topology classification of three-phase four-wire DSTATCOMs

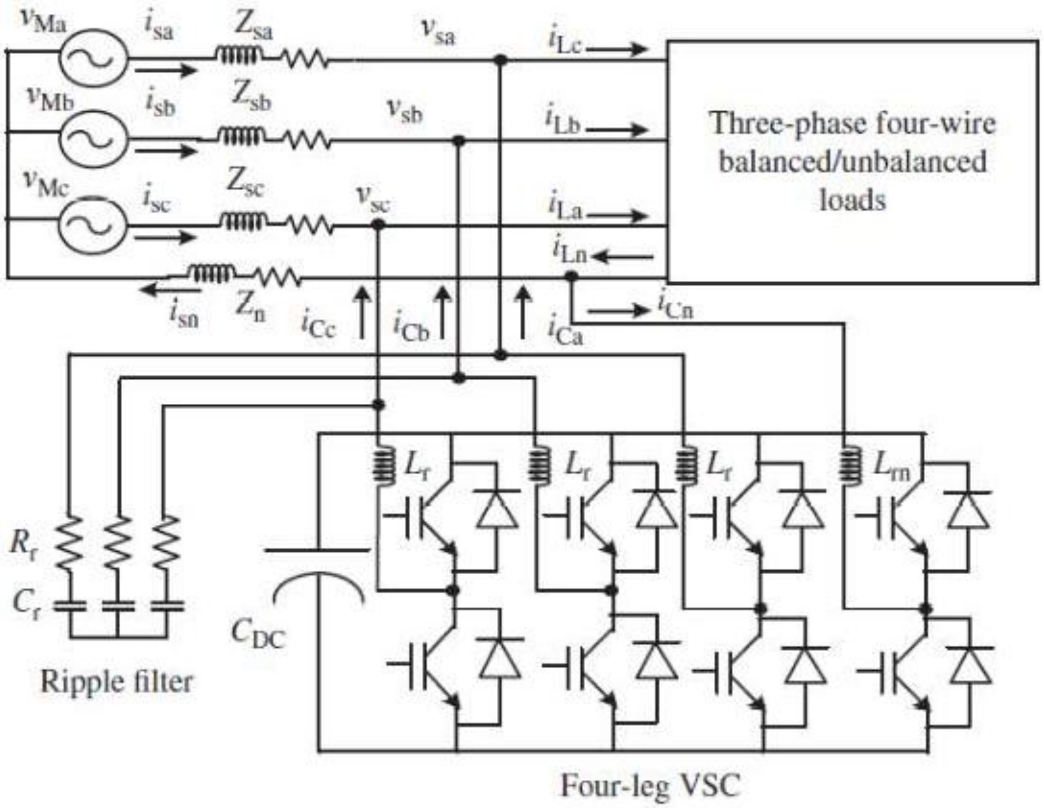


Fig. 6.16 A four-leg VSC-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

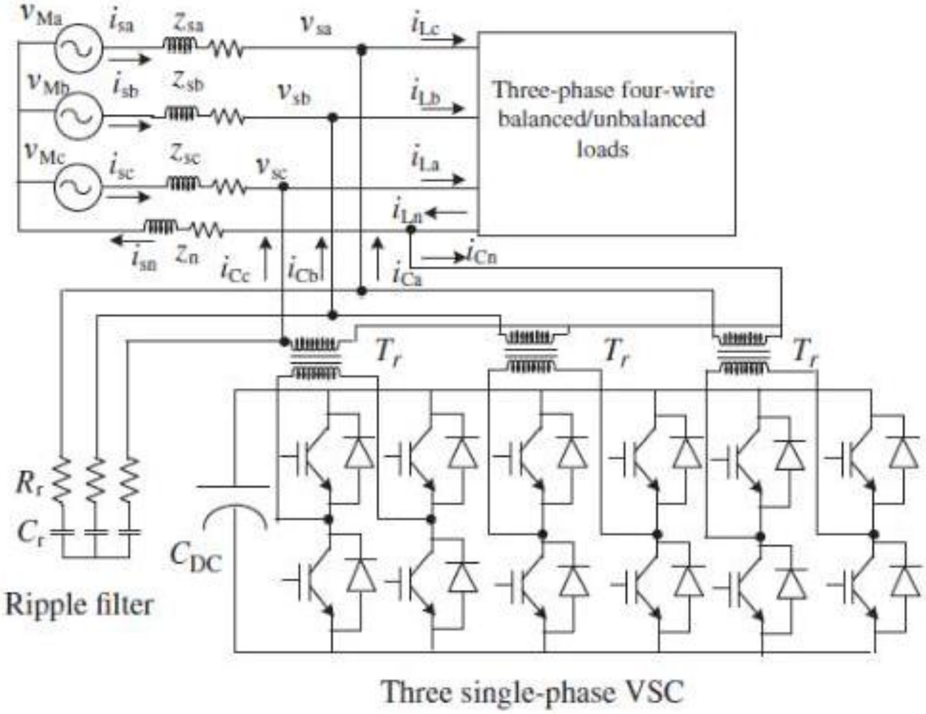


Fig. 6.17 A three single-phase VSC-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

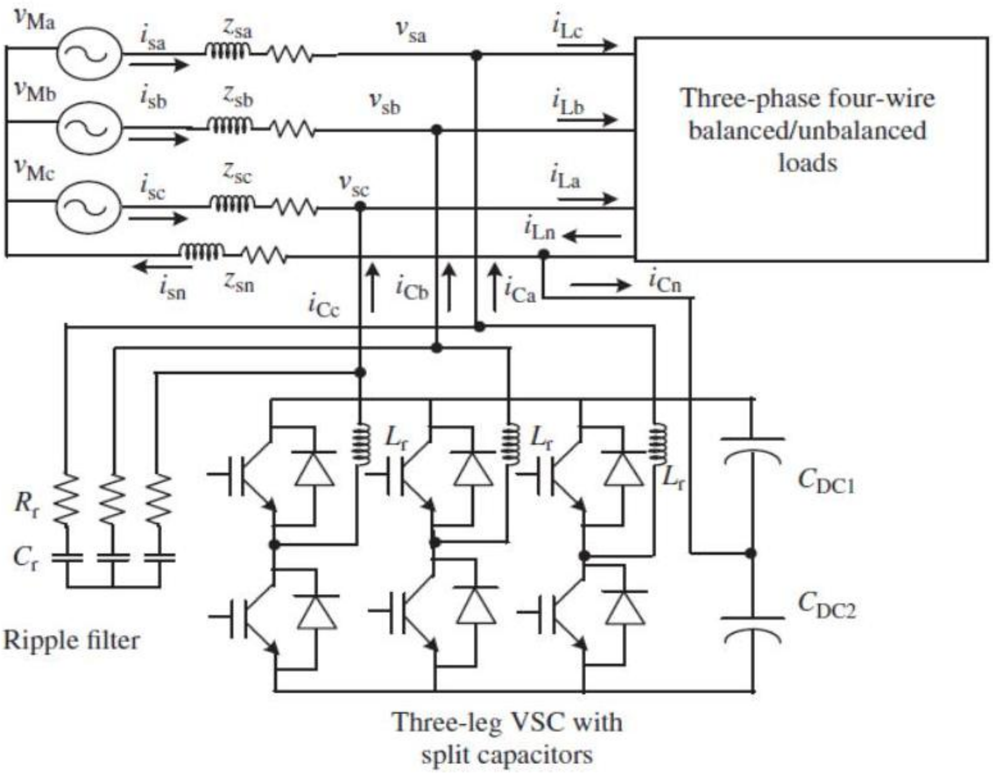


Fig. 6.18 A three-leg VSC and split capacitor-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

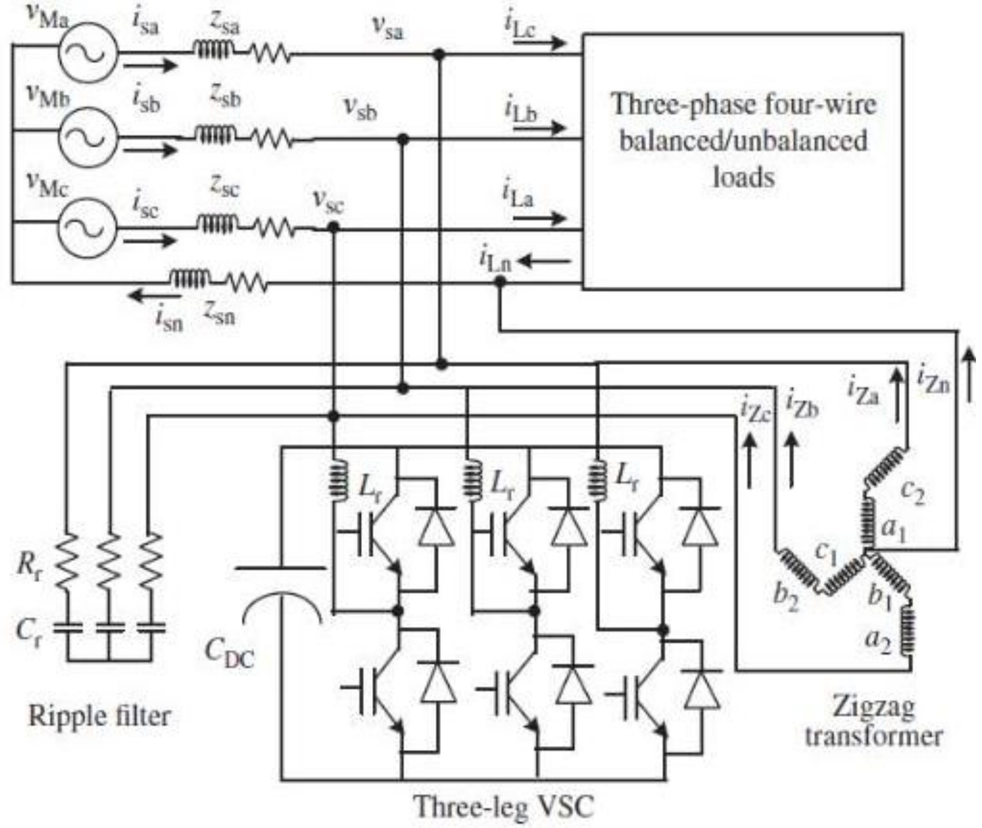


Fig. 6.19 A three-leg VSC and zigzag transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

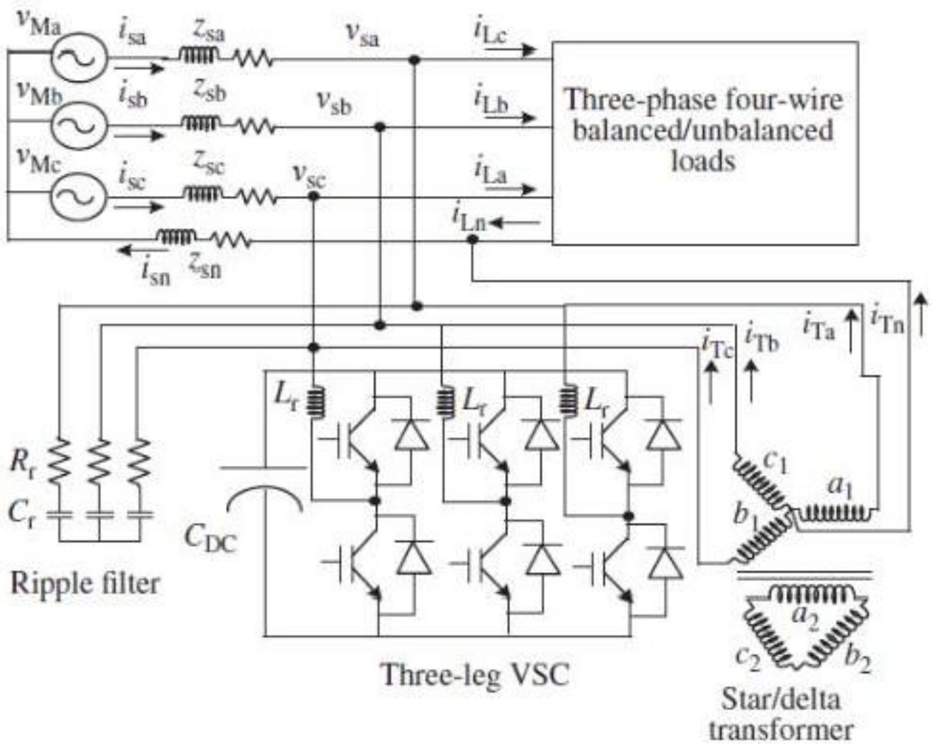


Fig. 6.20 A three-leg VSC and star/delta transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

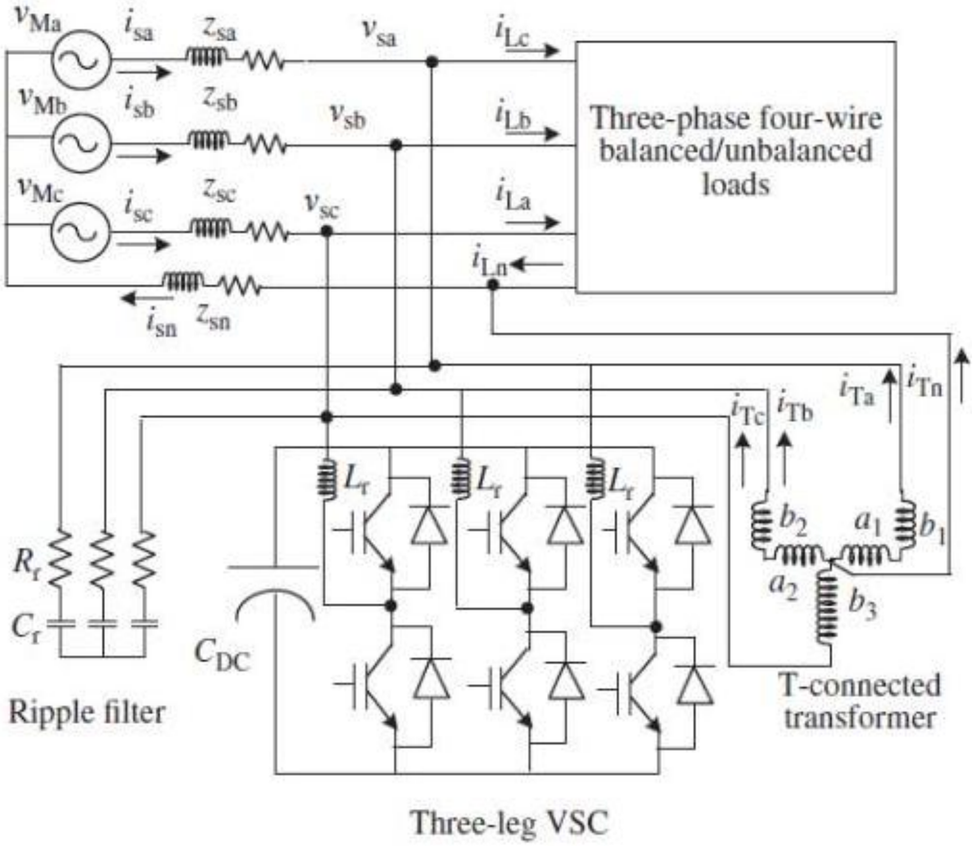


Fig. 6.21 A three-leg VSC and T-connected transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

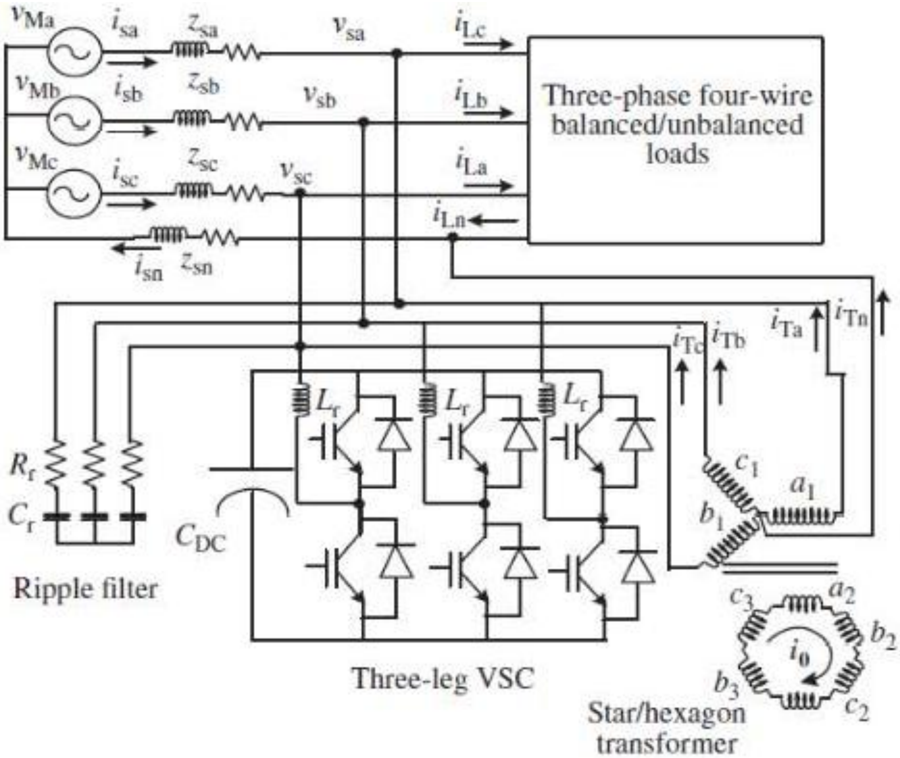


Fig. 6.22 A three-leg VSC and star/hexagon transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

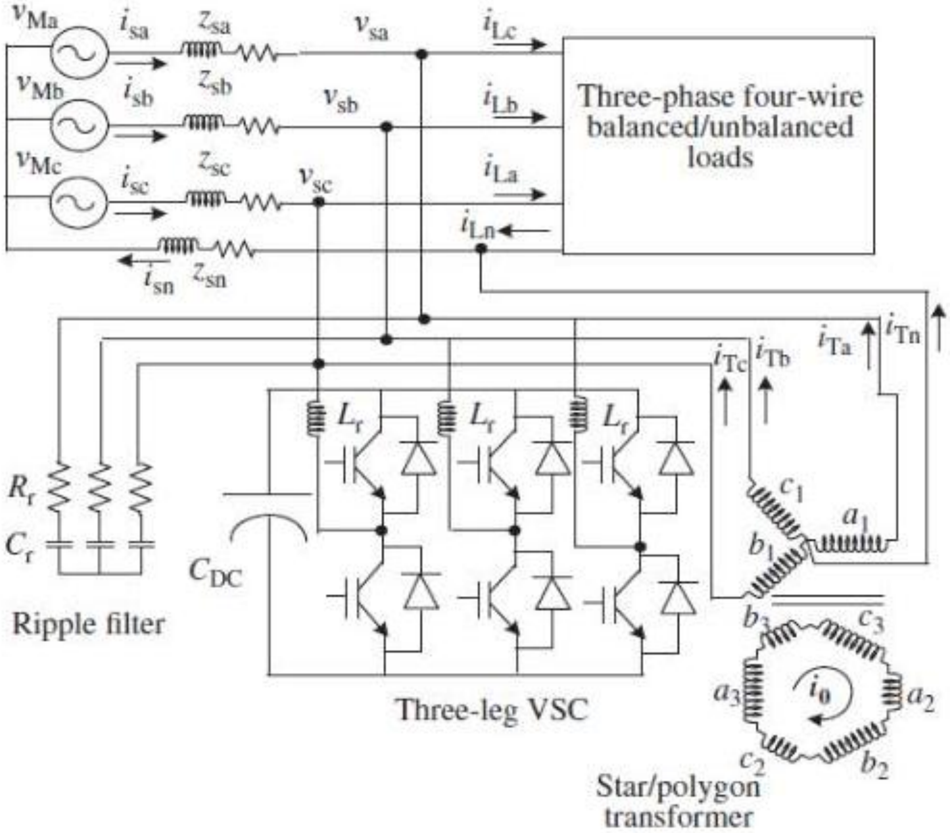


Fig. 6.23 A three-leg VSC and star/polygon transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

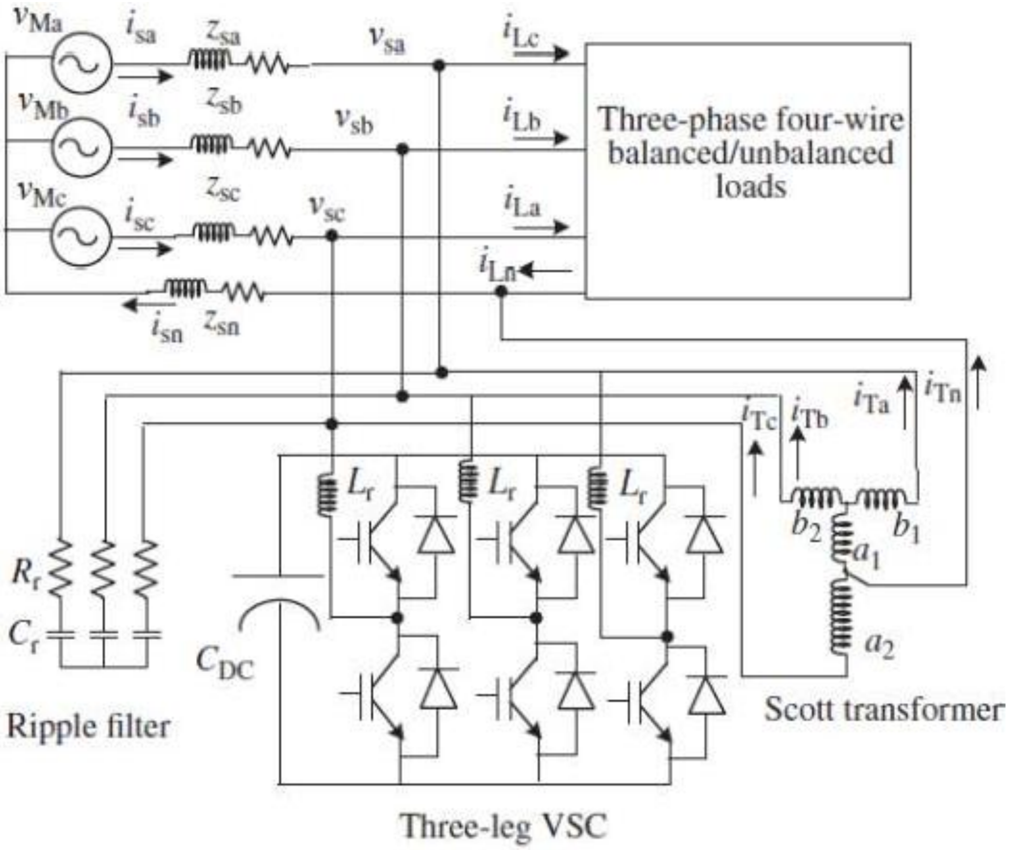


Fig. 6.24 A three-leg VSC and Scott transformer-based three-phase four-wire DSTATCOM connected to a three-phase four-wire system

6.3.3 Principle of Operation and Control of DSTATCOMs

The basic function of DSTATCOMs is to mitigate most of the current-based power quality problems such as reactive power, unbalanced currents, neutral current, harmonics and to provide sinusoidal balanced currents in the supply with the self-supporting DC bus of the VSC used as a DSTATCOM.

A fundamental circuit of the DSTATCOM for a three-phase three-wire AC system with balanced/unbalanced loads is shown in Figure 6.10. An IGBT-based current-controlled voltage source converter (CC-VSC) with a DC bus capacitor is used as the DSTATCOM. Using a control algorithm, the reference DSTATCOM currents are directly controlled by estimating the reference DSTATCOM currents.

However, in place of DSTATCOM currents, the reference supply currents may be estimated for an indirect current control of the VSC. The gating pulses to the DSTATCOM are generated by employing hysteresis (carrier less PWM (pulse-width modulation) or PWM (fixed frequency) current control over reference and sensed supply currents resulting in an indirect current control. Using the DSTATCOM, the reactive power compensation and unbalanced current compensation are achieved in all the control algorithms.

6.3.3.1 Principle of Operation of DSTATCOMs

The main objective of DSTATCOMs is to mitigate the current-based power quality problems in a distribution system. A DSTATCOM mitigates most of the current quality problems, such as reactive power, unbalance, neutral current, harmonics (if any) and fluctuations, present in the consumer loads or otherwise in the system and provides sinusoidal balanced currents in the supply with its DC bus voltage regulation.

In general, a DSTATCOM has a VSC connected to a DC bus and its AC sides are connected in shunt normally across the consumer loads or across the PCC as shown in Figures 6.10–6.12. The VSC uses PWM control; therefore, it requires small ripple filters to mitigate switching ripples. It requires Hall Effect voltage and current sensors for feedback signals and normally a DSP is used to implement the required control algorithm to generate gating signals for the solid-state devices of the VSC of the DSTATCOM. The VSC is normally controlled in PWM current control mode to inject appropriate currents in the system. The DSTATCOM also needs many passive elements such as a DC bus capacitor, AC interacting inductors, injection and isolation transformers and small passive filters.

6.3.3.2 Control of DSTATCOMs

The main objective of a control algorithm of DSTATCOMs is to estimate the reference currents using feedback signals. These reference currents along with corresponding sensed currents are used in PWM current controllers to derive PWM gating signals for switching devices (IGBTs) of the VSC used as a DSTATCOM. Reference currents for the control of DSTATCOMs have to be derived accordingly and these signals may be estimated using a number of control algorithms. There are many control algorithms reported in the literature for the control of DSTATCOMs, which are classified as time-domain and frequency-domain control algorithms. There are more than a dozen of time-domain control algorithms that are used for the control of DSTATCOMs. A few of these control algorithms are as follows,

- Unit template technique or PI controller-based theory
- Power balance theory (BPT)
- I cosΦ control algorithm
- Current synchronous detection (CSD) method

- Instantaneous reactive power theory (IRPT) also known as PQ theory or α–β theory
- Synchronous reference frame (SRF) theory also known as d–q theory
- Instantaneous symmetrical component theory (ISCT)
- Singe-phase PQ theory
- Singe-phase DQ theory
- Neural network theory (WIDROW'S LMS based ADALINE algorithm)
- Enhanced phase locked loop (EPLL) based control algorithm
- Conductance-based control algorithm
- Adaptive detecting control algorithm, also known as adaptive interference canceling theory

These control algorithms are time-domain control algorithms. Most of them have been used for the control of DSTATCOMs and other compensating devices. Similarly, there are around the same number of frequency-domain control algorithms. Some of them are as follows,

- Fourier series theory
- Discrete Fourier transform theory
- Fast Fourier transform theory
- Recursive discrete Fourier transform theory
- Kalman filter-based control algorithm
- Wavelet transformation theory
- Stock well transformation (S-transform) theory
- Empirical decomposition (EMD) transformation theory
- Hilbert–Huang transformation theory

These control algorithms are frequency-domain control algorithms. Most of them are used for power quality monitoring for a number of purposes in the power analyzers, PQ instruments, and so on. Some of these algorithms have been used for the control of DSTATCOMs. However, these algorithms are sluggish and slow, requiring heavy computation burden; therefore, these control methods are not too much preferred for real-time control of DSTATCOMs compared with time-domain control algorithms.

6.3.4 Analysis and Design of DSTATCOMs

The analysis and design of DSTATCOMs include the detailed analysis for deriving the design equations for calculating the values of different components used in their circuit configurations. There are a large number of topologies of DSTATCOMs. Therefore, it is not practically possible to include here the design of all circuit configurations due to space constraints. In view of these facts, the design of selected three topologies of DSTATCOMs, one for three-phase three wire DSTATCOMs and two for three-phase four-wire DSTATCOMs is given here through a step by step design procedure.

The design of a three-phase three-wire DSTATCOM includes the design of the VSC and its other passive components. The DSTATCOM includes a VSC, interfacing inductors, and a ripple filter. The design of the VSC includes the DC bus voltage level the DC capacitance, and the rating of IGBTs.

A three-phase three-wire DSTATCOM topology is considered for detailed analysis. Figure 6.10 shows a schematic diagram of one of the DSTATCOMs for a three-phase three-wire distribution system. It uses a three-leg VSC-based DSTATCOM. The design of the DSTATCOM is discussed in the following sections through the example of a 50 KVA, 415V DSTATCOM.

6.3.4.1 Design of a Three Phase Three-Wire DSTATCOM

The design of a DSTATCOM involves the estimation and selection of various components of the VSC of the DSTATCOM such as DC capacitor value, DC bus voltage, interfacing AC inductor and a ripple filter. A ripple filter is used to filter the switching ripples from the voltage at PCC. The design of the interfacing inductors and a ripple filter is carried out to limit the ripple in the currents and voltages. The design of a DC bus capacitor depends on the energy storage capacity needed during transient conditions. The rating of the DSTATCOM depends on the required reactive power compensation and degree of unbalance in the load. Hence, the current rating of the DSTATCOM is affected by the load power rating and its voltage rating depends on the DC bus voltage.

6.3.4.2 Design of a Three Phase Four-Wire DSTATCOM

A three-leg VSC is used as a distribution static compensator as shown in Figure 4.6 and this topology has six IGBTs, three AC inductors, and a DC capacitor. The required compensation to be provided by the DSTATCOM decides the rating of the VSC components.

The VSC is designed for compensating a reactive power of 50 KVA (with a safety factor of 0.1) in a 415 V, 50 Hz, three-phase distribution system.

6.3.5 Modeling, Simulation and Performance of DSTATCOMs

The MATLAB models of different topologies of DSTATCOMs are developed using SIMULINK and SIM Power Systems (SPS) toolboxes to simulate the performance of these DSTATCOMs in single-phase and three-phase distribution systems. A large number of cases of these topologies of DSTATCOMs are given in solved examples. Here, the performances of three topologies of three-phase DSTATCOMs with selected control algorithms are demonstrated for power factor correction and zero voltage regulation along with load balancing and neutral current compensation. The performance of DSTATCOMs is analyzed under balanced/unbalanced load conditions.

6.3.5.1 Performance of a SRF Based Three Leg VSC Based DSTATCOM

The performance of a SRF-based three-leg VSC-based three-phase three-wire DSTATCOM is demonstrated for PFC and ZVR modes along with load balancing. The performance of the DSTATCOM is analyzed under varying loads.

6.3.5.2 Performance of a Four-Leg VSC-Based Three Phase Four Wire DSTATCOM

The performance of a SRF-based four-leg VSC-based three-phase four-wire DSTATCOM is demonstrated for PFC and ZVR modes along with load balancing. The performance of the DSTATCOM is analyzed under varying loads.

6.3.5.3 Performance of a Three Single-Phase VSC-Based Three Phase Four Wire DSTATCOM

The performance of a SRF-based three single-phase VSC-based three-phase four-wire DSTATCOM is demonstrated for PFC and ZVR modes along with load balancing. The performance of the DSTATCOM is analyzed under varying loads.

6.4 Active Series Compensator

In modern distribution system, there are a number of voltage-based power quality (PQ) problems caused by substantial pollution and abnormal operating conditions. These power quality problems at point of common coupling (PCC) occur due to the voltage drop in feeders and transformers, various kinds of disturbances, faults, use of unbalanced lagging power factor consumer loads, and so on. Some of these voltage-related power quality problems are voltage spikes, surges, flickers, sags, swells, notches, fluctuations, voltage imbalance, waveform distortion and so on. The active series compensators are extensively used to both inject the voltage of required magnitude and frequency and restore the voltage across the loads to protect the sensitive loads from these voltage quality problems. These compensators are known as solid-state synchronous series compensators (SSCs) and dynamic voltage restorers (DVRs). They use insulated gate bipolar transistor (IGBT) based and metal oxide semiconductor field-effect transistor (MOSFET) based PWM (pulse-width modulated) voltage source converters (VSCs) and current source converters (CSCs) to inject the equal and opposite voltages of disturbances in series synchronism with AC mains to protect and provide the clean regulated voltage waveform across the critical loads.

The waveform of injected voltage is variable and it may consist of fundamental positive sequence, negative sequence, or even zero sequence, harmonic voltages and so on. For generation of such varying voltage waveforms, PWM power converters would require instantaneous exchange of reactive and active powers. These PWM converters can generate reactive power locally itself, but they need an exchange of active power through its DC bus. This exchange of instantaneous active power in a series compensator is made possible through energy storage elements such as a large capacitor at DC bus of the VSC or a large inductor in case of CSCs with a self-supporting DC bus for short durations in most of the applications.

The continuous and long duration exchange of the active power in these series compensators is achieved by installing a battery or another converter of similar nature or a simple rectifier with proper control. In many cases, a rectifier-supported well-regulated DC bus is used in these series compensators to both meet the need of exchange of the active power with suitable control to avoid the over and under voltages and reduce the cost of the system. Although the use of low-cost rectifier to support the DC bus of these series compensators can emulate the negative resistance in the series of line voltage to avoid the voltage drop, it may however cause current-based power quality problems.

In present-day distribution systems, the need for these types of custom power devices, namely, SSCs and DVRs, is increasing substantially so as to provide the required voltage waveforms for critical and sensitive loads. Accordingly, the analysis, design, and control of these series compensators for the compensation of voltage-based power quality problems have become one of the most important research areas.

6.4.1 State of the Art on Active Series Compensator

The custom power device technology is now mature enough for providing compensation for voltage based power quality problems in AC distribution systems. It has evolved in the last decade of development with varying configurations, control strategies, and solid-state devices. Active series compensators are used to eliminate voltage spikes, sags, swells, notches and harmonics, to regulate terminal voltage, to suppress voltage flicker, and to mitigate voltage unbalance in the three-phase systems. These wide range of objectives are achieved either individually or in combination depending upon the requirements, control strategy and configuration, which have to be selected appropriately.

One of the major factors in the advancement of SSC technology is the advent of fast, self-commutating solid-state devices. In the initial stages, BJTs and power MOSFETs were used for DVR development later, SITs and GTOs were employed to develop DVRs. With the introduction of IGBTs, the SSSC technology has got a real boost and at present it is considered an ideal solid-state device for SSCs. The improved sensor technology has also contributed to the enhanced performance of the SSC. The availability of Hall Effect sensors and isolation amplifiers at a reasonable cost and with adequate ratings has improved the SSC performance substantially.

Another breakthrough in the development of SSC has resulted from the microelectronics revolution. From the initial use of discrete analog and digital components, the SSSCs are now equipped with microprocessors, microcontrollers and DSPs. Now it is possible to implement complex algorithms online for the control of the SSC at a reasonable cost. This development has made it possible to use different control algorithms such as proportional–integral (PI) control, variable structure control, fuzzy logic control and neural nets-based control for improving the dynamic and steady-state performance of the SSC. With these improvements, the SSCs are capable of providing fast corrective action even under dynamically changing loads.

6.4.2 Classification of Active Series Compensator

Active series compensators can be classified based on the power converter type, topology and the number of phases. The type of power converter can be either CSC or VSC. The topology can be half-bridge VSC, full-bridge VSC and so on. The third classification is based on the number of phases such as single-phase two-wire and three-phase three- or four-wire systems.

6.4.2.1 Converter-Based Classification

Two types of power converters are used in the development of active series compensators. Figure 6.25 shows single-phase SSC (DVR) based on current source converter. In this CSC-based DVR, a diode is used in series with the self-commutating device (IGBT) for reverse-voltage blocking. However, GTO based DVR configurations do not need the series diode, but they have restricted switching frequency. Although CSCs are considered sufficiently reliable, they cause high losses and require high-voltage parallel AC power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings.

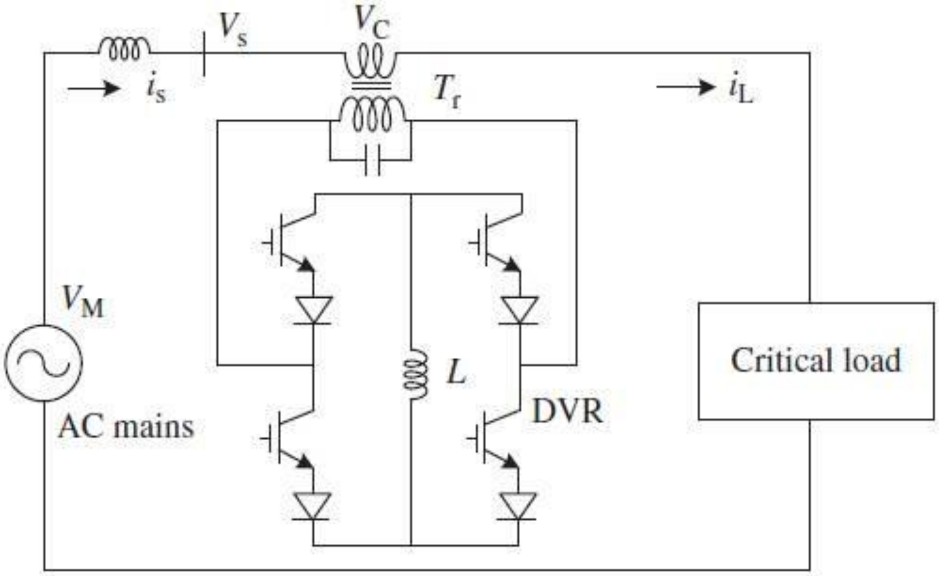


Fig. 6.25 CSC based single phase DVR

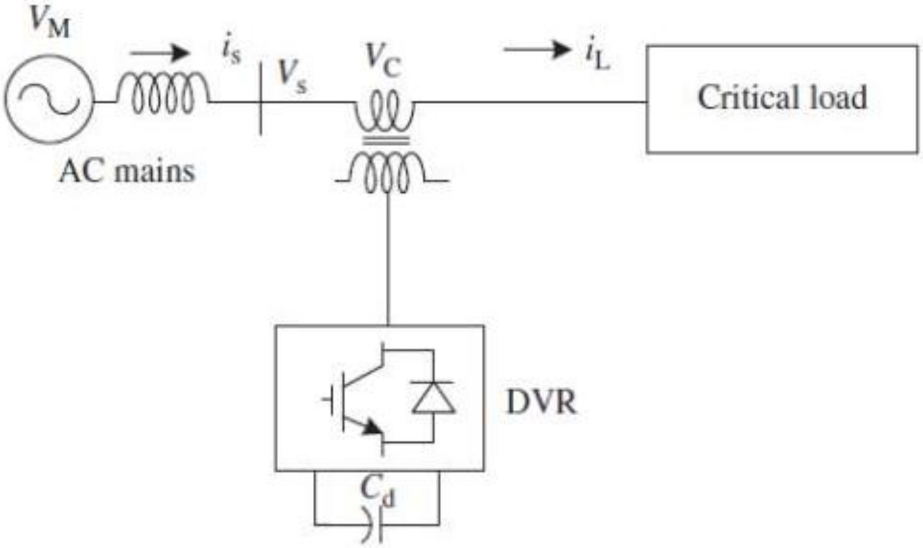


Fig. 6.26 VSC-based single-phase DVR

The other power converter used in SSC is a VSC as shown in figure 6.26. It has a self-supporting DC voltage bus with a large DC capacitor. It has become more dominant since it is lighter, cheaper, and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies. It is more popular in UPS based applications because in the presence of AC mains, the same power converter can be used as an active series compensator for series compensation of critical and sensitive loads.

6.4.2.2 Topology-Based Classification

Active series compensators can be classified based on the topology used as half-bridge, full-bridge and transformer less configurations. Figures 6.27–6.29 show the basic block of active series compensators. It is connected before the load in series with AC mains, using a matching transformer, to balance and regulate the terminal voltage of the load or line. It has been used to reduce negative sequence voltage and to regulate the voltage in three-phase systems. It can be installed by electric utilities to damp out harmonic propagation caused by resonance with line impedances and passive shunt compensators.

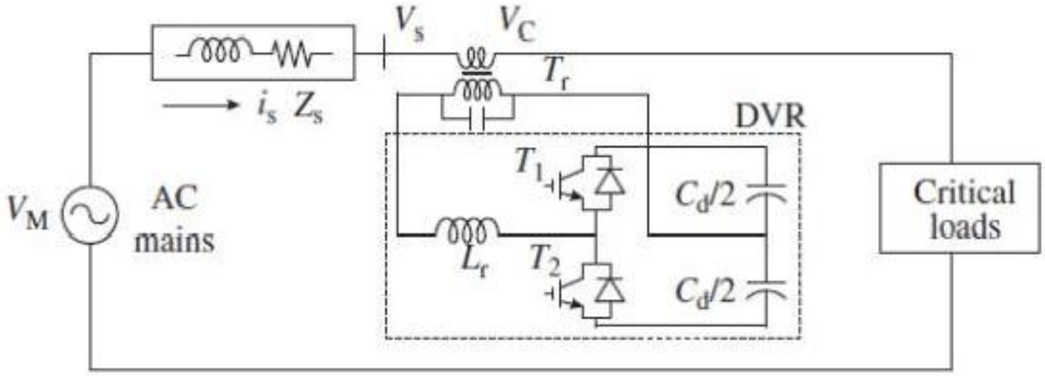


Fig. 6.27 Half-bridge topology of VSC-based single-phase DVR

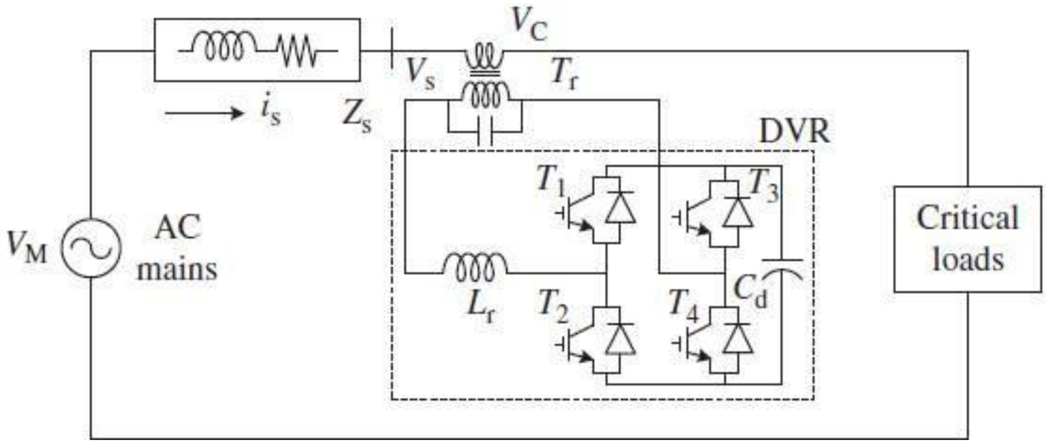


Fig. 6.28 Full-bridge topology of VSC-based single-phase DVR

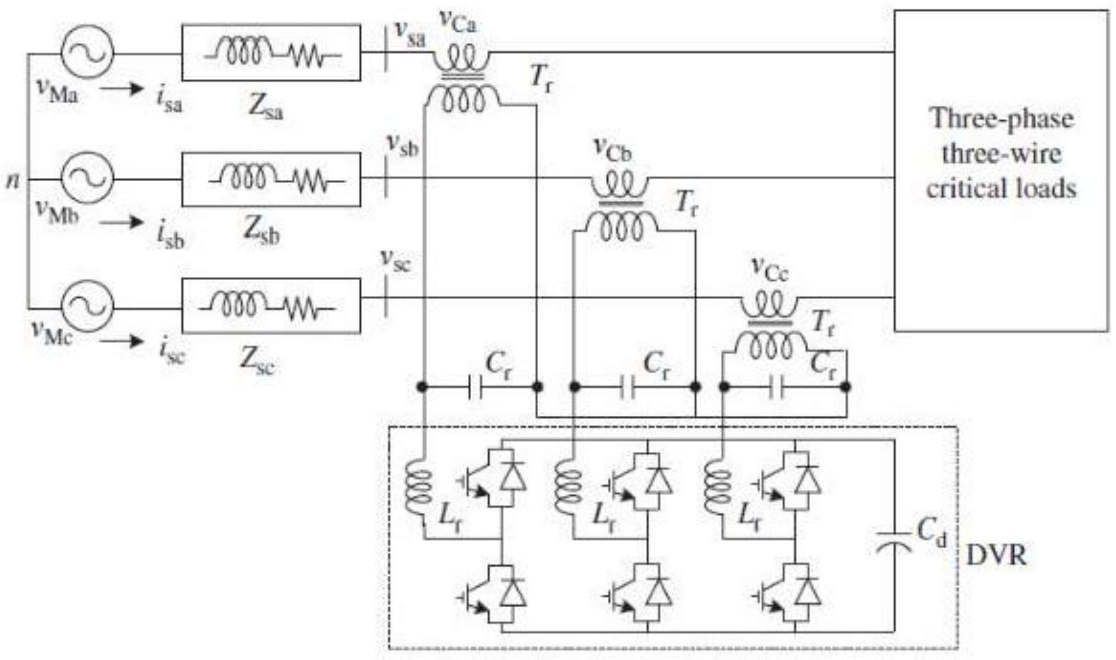


Fig. 6.29 Three-phase three-wire DVR

6.4.2.3 Supply System Based Classification

This classification of SSCs is based on the supply and/or the load system having single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many sensitive critical loads such as domestic appliances connected to single-phase supply systems. Some three-phase consumer loads are without neutral terminal, such as ASDs (adjustable speed drives), fed from three-wire supply systems. There are many single-phase loads distributed on four-wire, three-phase supply systems, such as computers, commercial lighting, and so on. Hence, SSCs may also be classified accordingly as two wire, three-wire, and four-wire configurations.

6.4.3 Principle of Operation and Control of Active Series Compensator

The fundamental circuit of the active series compensators for a three-phase, three-wire AC system is shown in figure 6.30. An IGBT-based VSC with a DC bus capacitor is used as the DVR. Using a control algorithm, the injected voltages are directly controlled by estimating the reference injected voltages. However, in place of injected voltages, the reference load voltages may be estimated for an indirect voltage control of its VSC. The gate pulses for the DVR are generated by employing hysteresis (carrier less PWM) or PWM (fixed frequency) voltage control over reference and sensed load voltages, which result in an indirect voltage control. Using the DVR with a proper control algorithm, the voltage spikes, surges, flickers, sags, swells, notches, fluctuations, waveform distortion, voltage imbalance, and harmonics compensation are achieved.

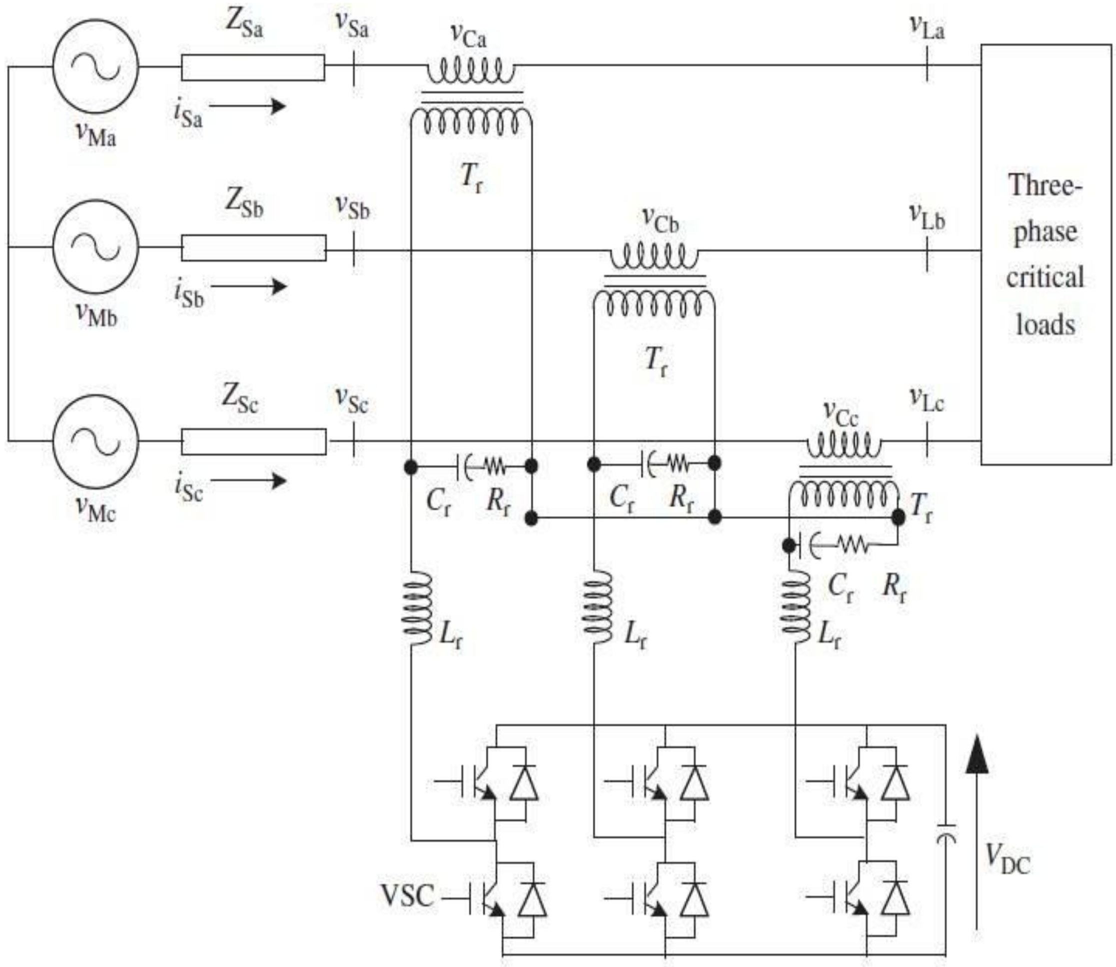


Fig. 6.30 Capacitor-supported DVR connected system

6.4.4 Analysis and Design of Active Series Compensator

Figure 6.30 shows a schematic diagram of a capacitor-supported DVR for power quality improvement in a distribution system. Three source voltages (v_{Ma}, v_{Mb}, v_{Mc}) represent a three-phase supply system and the series source impedance are shown as ZSa (Rs, Ls), ZSb (R_s, L_s) and Z_{Sc} (R_s, L_s). The PCC voltages (v_{Sa}, v_{Sb}, v_{Sc}) have power quality problems and the DVR uses injection transformers (T_r) to inject compensating voltages (v_{Ca}, v_{Cb}, v_{Cc}) to get undistorted load voltages (v_{La}, v_{Lb}, v_{Lc}). A VSC along with a DC capacitor (CDC) is used as a DVR. The switching ripple in the injected voltage is filtered using a series inductor (L_r) and a parallel capacitor (C_r).

6.4.5 Modeling, Simulation and Performance of Active Series Compensator

The performance of various topologies of three-phase DVR is simulated using MATLAB software using SIM Power Systems (SPS) toolboxes. However, because of space limitation and to give just basic understanding, only a BESS-supported DVR and a capacitor- supported DVR are considered for the compensation of sag, swell, harmonics, and an unbalance in the terminal voltage for various injection schemes using SRF theory control algorithm.

6.5 Unified Power Quality Compensator

The main objective of electric utilities is to supply their customers an uninterrupted sinusoidal voltage of constant magnitude and frequency with sinusoidal balanced currents at the AC mains. However, present day AC distribution systems are facing severe power quality (PQ) problems such as high reactive power burden, unbalanced loads, harmonic-rich load currents, and an excessive neutral current. In addition, these utilities are not able to avoid the voltage sag, swell, surges, notches, spikes, flicker, unbalance and harmonics in the supply voltages across the consumers load end. There are many critical and sensitive loads that require uninterrupted sinusoidal balanced voltages of constant magnitude and frequency, otherwise their protection systems operate due to power quality disturbances. Moreover, these critical loads use solid-state controllers and precision devices such as computers, processors, and other sensitive electronic components and they draw reactive power and harmonic currents that cause load unbalance and result in excessive neutral current. Some examples of these critical and sensitive loads are hospital equipment (life support systems, operation theaters, patient database, etc.), banking systems using computers with UPS (uninterruptable power supplies), semiconductor manufacturing industries, pharmaceutical industries, textile industries, food processing plants, and so on. Even small interruption in the operation of these sensitive and critical loads because of voltage disturbances may cause substantial loss of money due to loss of production, time, product quality, and services. A custom power device known as a unified power quality compensator (UPQC) is considered the right option for such critical and sensitive loads to compensate both voltage- and current-based power quality problems.

The UPQC, a combination of shunt and series compensators shown in figure 6.31 is recommended in the literature as a single solution for mitigating these multiple PQ problems of voltages and currents. The power circuit of a UPQC consists of two voltage source converters (VSCs) or current source converters (CSCs) joined back to back by a common DC link capacitor or an inductor at the DC bus respectively. The shunt device of the UPQC, also known as a DSTATCOM (distribution compensator) provides reactive power compensation, load balancing, neutral current compensation, and elimination of harmonics (if required) and it is connected in parallel to the consumer load or AC mains depending upon the configuration as a right shunt or left shunt UPQC respectively.

The series device of the UPQC, also known as a DVR (dynamic voltage restorer), keeps the consumer load end voltages insensitive to the supply voltage quality problems such as sag/swell, surges, spikes, notches, fluctuations, depression and unbalance. The DVR injects a compensating voltage between the supply and the consumer load and restores the load voltage to its reference value.

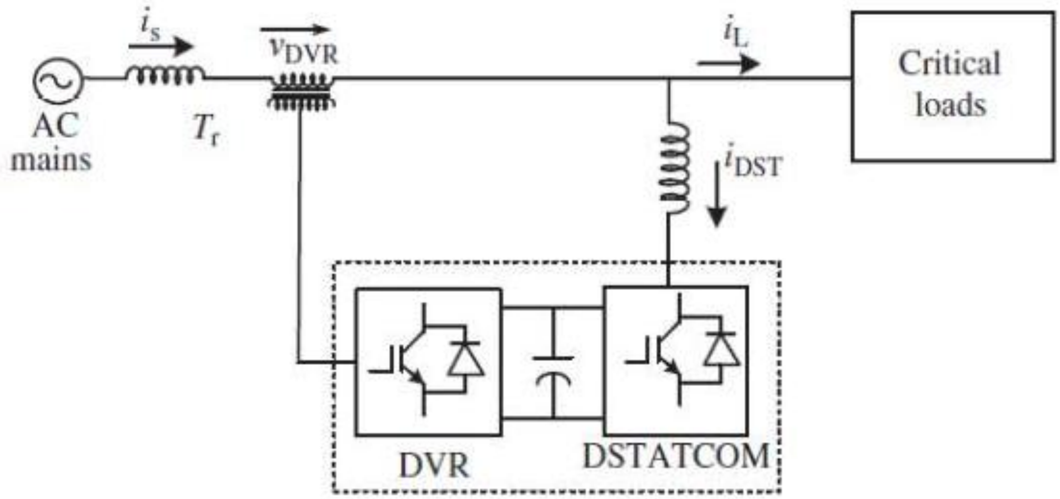


Fig. 6.31 A VSC-based unified power quality compensator

6.5.1 State of the Art on Unified Power Quality Compensator

A UPQC, which is a combination of shunt and series compensators, is proposed as a single solution for mitigating multiple PQ problems. The power circuit of a UPQC consists of two VSCs joined back to back by a common DC link. The shunt device known as the DSTATCOM provides reactive power compensation along with load balancing, neutral current compensation, and elimination of harmonics (if required) and is positioned parallel to the consumer load. The series device known as the DVR keeps the load end voltage insensitive to the supply voltage quality problems such as sag/swell, surges, spikes, notches, or unbalance. The DVR injects a compensating voltage between the supply and the consumer load and restores the load voltage to its reference value. The cost of PQ to manufacturing and emergency services together with the requirement of improved power quality in the current waveform justifies the cost and complex control required for UPQCs. There are many control techniques and topologies reported for the control of UPQCs.

6.5.2 Classification of Unified Power Quality Compensator

UPQCs may be classified based on the type of converter used, topology configuration, supply system and method of control, which affect their ratings. The converter can be either a CSC or a VSC. The topology depends on how the shunt device (DSTATCOM) and the series device (DVR) are connected to form a UPQC. For example, in a right shunt UPQC, the DSTATCOM is connected on the right-hand side of the DVR (connected across the consumer loads), and in a left shunt UPQC, the DSTATCOM is connected on the left-hand side of the DVR (connected across the PCC (point of common coupling)/AC mains). The topology of the UPQC may also differ depending on the internal configuration of the DSTATCOM and DVR. The third classification is based on the supply system, such as single-phase two-wire, three-phase three-wire or three-phase four-wire UPQC systems. The fourth classification is based on the method of control, such as UPQC-Q (a DVR is used for series voltage injection in quadrature with supply current with almost zero active power injection), UPQC-P (a DVR is used for series voltage injection in phase with supply current with only an active power injection), and UPQC-S (a DVR is used for series voltage injection at optimum phase angle with minimum KVA rating, S, or any other criterion).

6.5.2.1 Converter-Based Classification of UPQCs

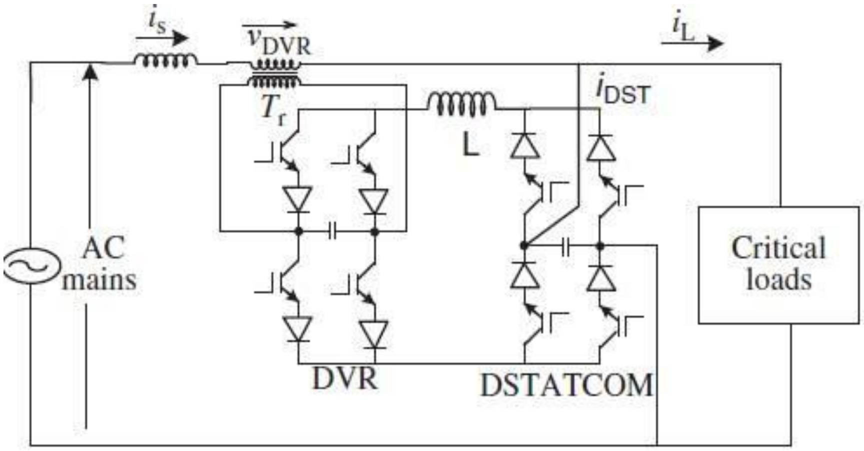


Fig. 6.32 A two-wire CSC-based unified power quality compensator

Two types of converters are used in the development of UPQCs. Figure 6.31 shows a UPQC using VSCs. VSC-based UPQCs have many advantages over CSC-based UPQCs.

Figure 6.32 shows a UPQC using CSCs. A diode is used in series with the self-commutating device (IGBT: insulated gate bipolar transistor) for reverse voltage blocking. However, GTO (gate turn-off thyristor) based CSC configurations of UPQCs do not need the series diode, but they have restricted frequency of switching. They are considered sufficiently reliable, but have higher losses and require higher values of parallel AC power capacitors or inductive energy storage at the DC bus, which is bulky, noisy, and costly and has high level of losses. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings. Because of these reasons, VSC-based UPQCs have taken a lead in most of the applications.

6.5.2.2 Topology-Based Classification of UPQCs

UPQCs can also be classified based on the topology used, such as right shunt UPQCs and left shunt UPQCs. Figure 6.33 shows the basic configuration of a right shunt UPQC. Its DVR is connected before the load in series with the AC mains, using a matching transformer, to mitigate sag, swell, spikes, and notches to balance and regulate the terminal voltage across the consumer loads, and to eliminate voltage harmonics. It has been used to eliminate negative-sequence voltage and to regulate the load voltage in three-phase systems. It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and passive shunt compensators. It is considered a superior configuration as it has reduced ratings of both converters and requires simple control. Figure 6.34 shows a left shunt UPQC.

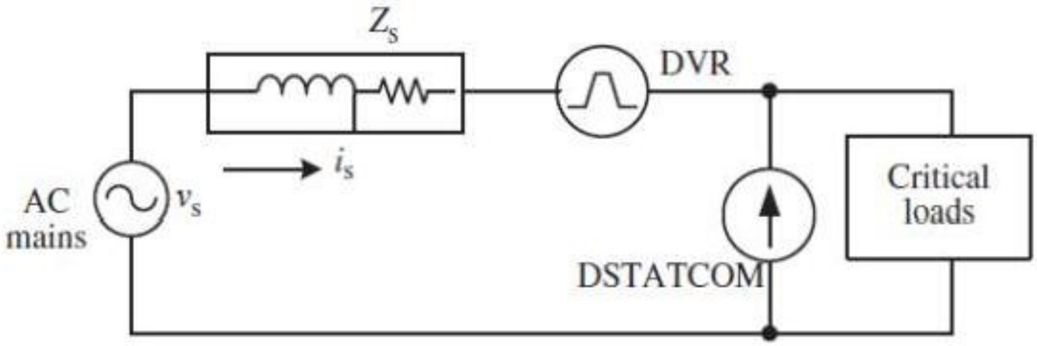


Fig. 6.33 A right shunt UPQC as a combination of DSTATCOM and DVR

The DC link storage element (either an inductor or a DC bus capacitor) is shared between two CSCs or VSCs operating as the DVR and DSTATCOM. It is considered an ideal compensator that mitigates voltage- and current-based power quality problems and is capable of giving clean power to critical and sensitive loads such as computers and medical equipment. It can balance and regulate the terminal voltage and eliminate negative-sequence currents. Its main drawbacks are high cost and control complexity. Therefore, a right shunt UPQC is considered a better option and dealt with in more detail.

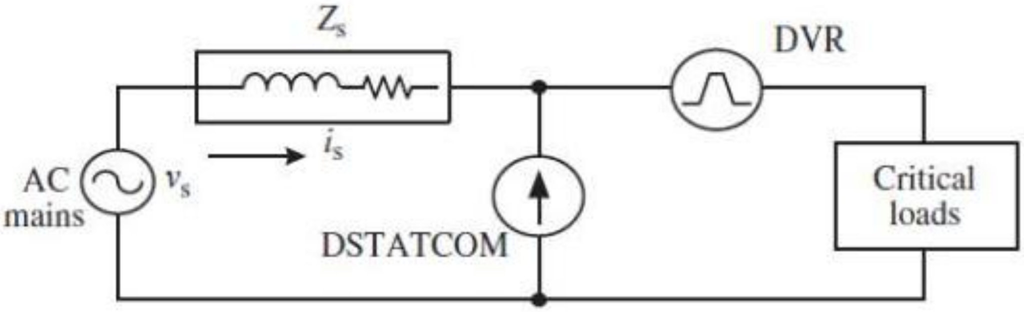


Fig. 6.34 A left shunt UPQC as a combination of DSTATCOM and DVR

6.5.2.3 Supply System-Based Classification of UPQCs

There are many consumer loads such as domestic appliances connected to single-phase supply systems. Some three-phase consumer loads are without neutral terminal, such as ASDs (adjustable speed drives) fed from three-wire supply systems. There are many single-phase consumer loads distributed on three phase four wire supply systems, such as computers and commercial lighting. Hence, UPQCs may also be classified according to supply systems as single-phase two-wire UPQCs, three-phase three-wire UPQCs and three-phase four-wire UPQCs.

This classification of UPQCs is based on the supply and/or the load system having single-phase (two wire) and three-phase (three-wire or four wire) systems. A number of configurations of single-phase two wire, three phase three wire, and three-phase four-wire UPQCs are given for enhancement of power quality in the currents as well as in the voltages. In three-phase four-wire UPQCs, various transformers may also be used for either isolating or deriving the fourth leg for neutral current compensation in the shunt connected VSC of the DSTATCOM, which may be a zigzag transformer, a T-connected transformer, a star/delta transformer, a star/hexagon transformer and so on.

6.5.3 Principle of Operation and Control of Unified Power Quality Compensator

A CSC based UPQC shown in Figure 6.32 and a VSC-based UPQC shown in Figures 6.35–6.38. Out of these two, VSC based UPQCs are preferred due to a number of benefits of VSCs such as low passive filter requirements, low losses, and high switching frequency. Similarly, out of right shunt UPQCs and left shunt UPQCs, the former are preferred due to a number of benefits such as low losses, less circulation of power, easy and simple control, and better performance.

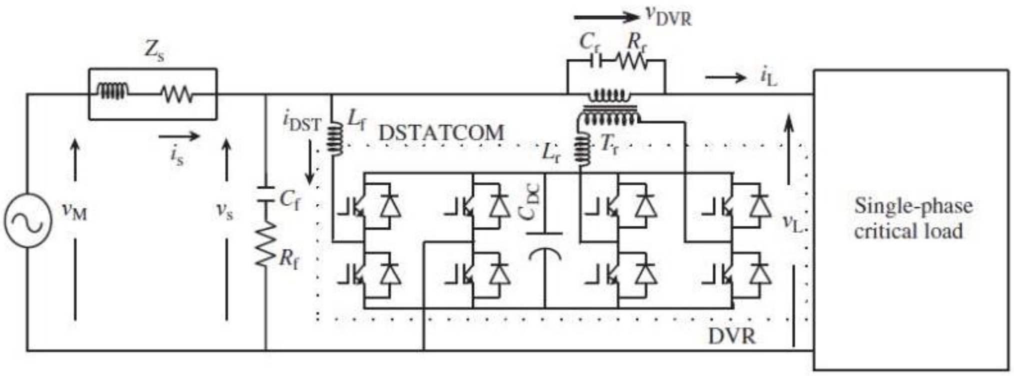


Fig. 6.35 A single-phase left shunt UPQC

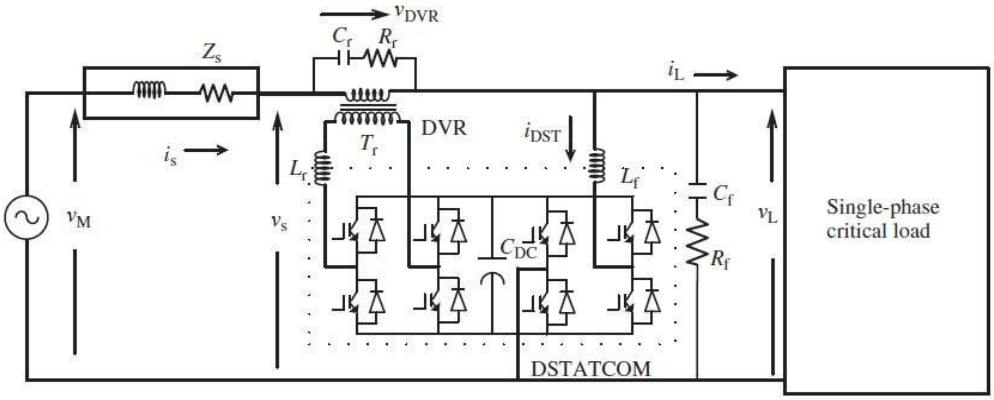


Fig. 6.36 A single phase right shunt UPQC

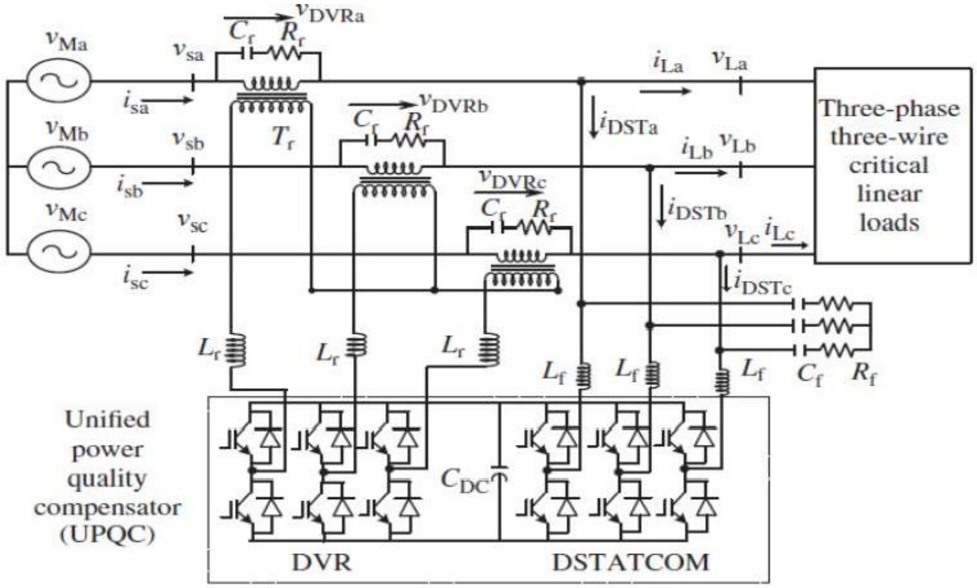


Fig. 6.37 Three-phase three-wire right shunt UPQC topology with a three-leg VSC-based DSTATCOM and DVR

Therefore, the principle of operation and control of UPQCs will be limited to VSC-based right shunt UPQCs, shown in Figures 6.6–6.8 for single-phase two-wire, three phase three-wire, and three-phase four-wire configurations of UPQCs. Here, most of the concepts are given for three-phase UPQCs, which can also be applied to single-phase UPQCs.

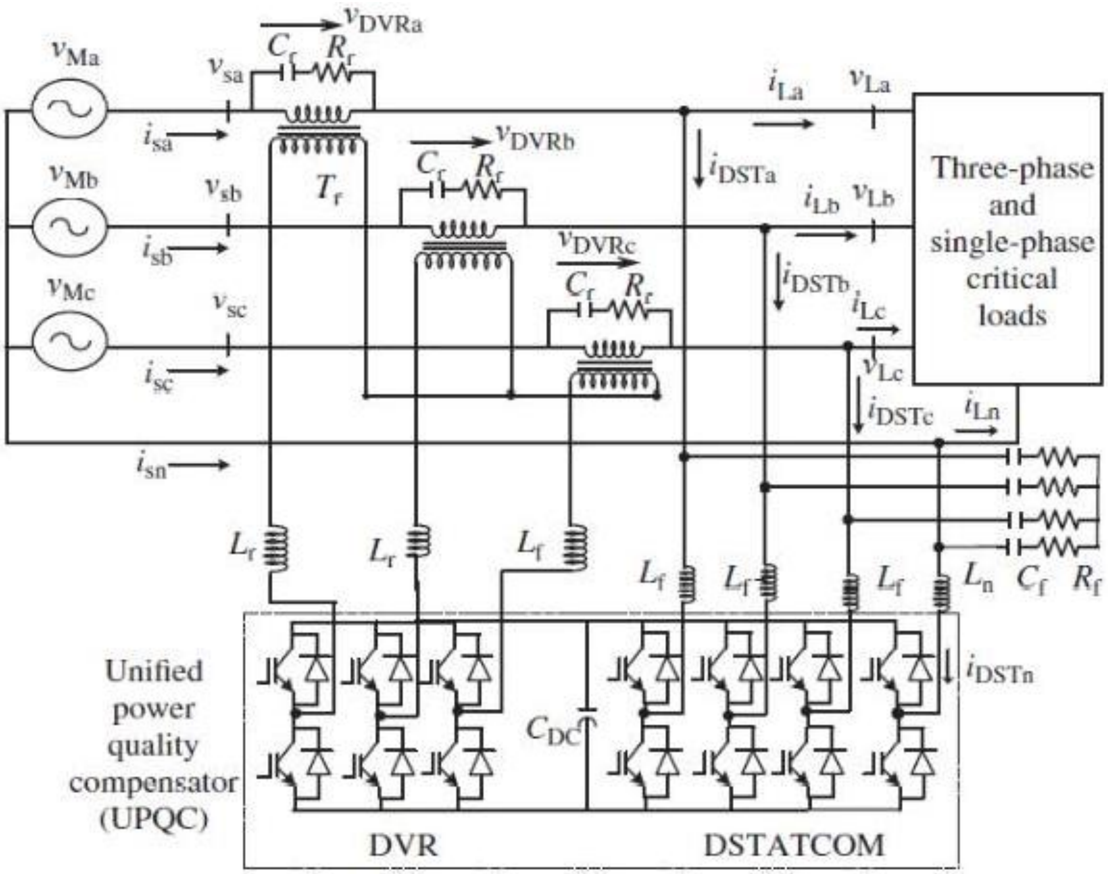


Fig. 6.38 Three-phase four-wire right shunt UPQC topology with a four-leg VSC-based DSTATCOM and DVR

6.5.3.1 Principle of Operation of UPQCs

The main objective of UPQCs is to mitigate multiple power quality problems in a distribution system. A UPQC mitigates most of the voltage quality problems such as sag, swell, surges, noise, spikes, notches, flicker, unbalance, fluctuations, regulation, and harmonics present in the supply/PCC system and a series compensator, DVR, provides clean, ideal, sinusoidal balanced voltages of constant magnitude at the consumer load end for satisfactory operation of the consumer equipment. At the same time, the shunt compensator of the UPQC, DSTATCOM, mitigates most of the current quality problems such as reactive power, unbalanced currents, neutral current, harmonics, and fluctuations present in the consumer loads or otherwise in the system and provides sinusoidal balanced currents in the supply, with its DC bus voltage regulation in proper coordination with the DVR.

In general, a UPQC has two VSCs connected to a common DC bus, one VSC is connected in series (known as the DVR or series compensator) of AC lines through an injection transformer and another VSC is connected in shunt (known as the DSTATCOM or shunt compensator) normally connected across the consumer loads or across the PCC as shown in figures 6.36–6.38. Both the VSCs use PWM control; therefore, they require small ripple filters to mitigate switching ripples. They require Hall Effect voltage and current sensors for feedback signals and normally a digital signal processor (DSP) is used to implement the required control algorithm to generate gating signals for the solid-state devices of both VSCs of the UPQC. The series VSC used as the DVR is normally controlled in PWM voltage control mode to inject appropriate voltages in series with the AC mains and the shunt VSC used as the DSTATCOM is normally controlled in PWM current control mode to inject appropriate currents in parallel with the load in the system. The UPQC also needs many passive elements such as a DC bus capacitor, AC interacting inductors, injection and isolation transformers, and small passive filters.

6.5.3.2 Control of UPQCs

The criteria for the control of UPQCs are divided into three categories: UPQC-Q, UPQC-P, or UPQC-S. Reference signals for the control of both components of the UPQC, namely, DSTATCOM and DVR, have to be derived accordingly using a number of control algorithms normally used for the control of the DSTATCOM and DVR. There are more than a dozen of control algorithms that are used for the control of the DSTATCOM and DVR. A few of these control algorithms are as follows,

- Synchronous reference frame theory, also known as d–q theory
- Instantaneous reactive power theory, also known as PQ theory or α–β theory
- Instantaneous symmetrical component theory
- Power balance theory (BPT)
- Neural network theory (Widrow’s LMS-based Adaline algorithm)
- PI controller-based algorithm
- Current synchronous detection (CSD) method
- I cosΦ algorithm
- Single-phase PQ theory
- Enhanced phase locked loop (EPLL)-based control algorithm
- Conductance-based control algorithm

- Adaptive detecting algorithm, also known as adaptive interference canceling theory

These control algorithms are time-domain control algorithms. Most of them have been used for the control of the DSTATCOM and DVR. Similarly, there are around the same number of frequency-domain control algorithms. Some of them are as follows,

- Fourier series theory
- Discrete Fourier transform theory
- Fast Fourier transform theory
- Recursive discrete Fourier transform theory
- Kalman filter-based control algorithm
- Wavelet transformation theory
- Stock well transformation (S-transform) theory
- Empirical decomposition (EMD) transformation theory
- Hilbert–Huang transformation theory

6.5.4 Analysis and Design of Unified Power Quality Compensator

The design of a three-phase four-wire UPQC includes the design of the DSTATCOM and DVR. The DSTATCOM includes a VSC, interfacing inductors and a ripple filter. The design of the VSC includes the DC bus voltage level, the DC capacitance, and the rating of IGBTs used in VSCs. Similarly, the design of DVR includes design of the VSC, interfacing inductors, ripple filters and injection transformers. A three-phase four-wire UPQC topology is considered for detailed analysis. Figure 6.38 shows the schematic diagram of one of the UPQCs for a three-phase four-wire distribution system. It uses a four-leg VSC-based DSTATCOM.

6.5.5 Modeling, Simulation and Performance of Unified Power Quality Compensator

The UPQCs are modeled in MATLAB platform for different configurations and operating conditions. Performance simulation is carried out in detail for a large number of cases, which are given in numerical examples.

UNIT – VII

LOAD THAT CAUSES POWER QUALITY PROBLEMS

TOPICS COVERED: **Introduction – State of the Art on Nonlinear Loads – Classification of Nonlinear Loads – Power Quality Problems caused by Nonlinear Loads – Analysis of Nonlinear Loads – Modeling, Simulation and Performance of Nonlinear Loads.**

7.1 Introduction

In true sense, most of the electrical loads have nonlinear behavior at the AC mains. As they draw harmonic currents of various types such as characteristic harmonics, non characteristic harmonics, inter harmonics, sub harmonics, reactive power component of current, fluctuating current, unbalanced currents from the AC mains these loads are known as nonlinear loads. Majority of rotating electric machines and magnetic devices such as transformers, reactors, chokes, magnetic ballasts, and so on behave as nonlinear loads due to saturation in their magnetic circuits, geometry such as presence of teeth and slots, winding distribution, air gap asymmetry, and so on. Many fluctuating loads such as furnaces, electric hammers and frequently switching devices exhibit highly nonlinear behavior as electrical loads. Even non saturating electrical loads such as power capacitors behave as nonlinear loads at the AC mains and they create a number of power quality problems due to switching and resonance with magnetic components in the system and are overloaded due to harmonic currents caused by the presence of harmonic voltages in the supply system.

Moreover, the solid-state control of AC power using diodes, thyristors and other semiconductor switches is widely used to feed controlled power to electrical loads such as lighting devices with electronic ballasts, controlled heating elements, magnet power supplies, battery chargers, fans, computers, copiers, TVs, switched mode power supplies (SMPS) in computers and other equipments, furnaces, electroplating, electrochemical processes, adjustable speed drives (ASDs) in electric traction, air-conditioning systems, pumps, wastewater treatment plants, elevators, conveyers, cranes, and so on. These AC loads consisting of solid-state converters draw non sinusoidal currents from the AC mains and behave in a nonlinear manner and therefore they are also known as nonlinear loads. These nonlinear loads consisting of solid-state converters draw harmonic currents and reactive power component of current from the AC mains. In three-phase systems, they could also cause unbalance and sometimes draw excessive neutral current, especially the distributed single-phase nonlinear loads on three-phase four-wire supply system. These solid-state converters may be AC–DC converters, AC voltage controllers, cycloconverters and so on. The injected harmonic currents, reactive power burden, unbalanced currents, and excessive neutral current caused by these nonlinear loads result in low system efficiency, poor power factor (PF), mal-operation of protection systems, AC capacitors overloading and nuisance tripping, noise and vibration in electrical machines, heating of the rotor bars due to negative sequence currents, de-rating of components of distribution system, user equipment, and so on. They also cause distortion in the supply voltage, disturbance to protective devices and other consumers, and interference in nearby communication networks and digital and analog control systems.

These nonlinear loads exhibit different behavior thereby causing different power quality problems, and they are therefore often classified according to their performance. Accordingly, the power quality improvement techniques for mitigating the power quality problems caused by nonlinear loads are also different to reduce the rating and cost of devices used for these purposes. One of the major and broad classifications of these nonlinear loads is based on their behavior either as current fed type or as voltage fed type or a combination of both. The current fed type of nonlinear loads with AC–DC converters having constant DC current used for field winding excitation, magnet power supplies, thyristor converter feeding DC motor drives, converter feeding current source inverter-fed AC motor drives, magnetic devices with saturation, and so on draw the prespecified kind of current pattern. Normally devices used for power quality improvements of such current fed type nonlinear loads are connected in shunt with the loads to supply locally all their current components other than the fundamental active power component of load current. On the contrary, the voltage fed type of nonlinear loads having AC–DC converters feeding almost constant DC voltage loads such as battery chargers, AC–DC converters with large DC filter capacitor as front-end converters in SMPS, AC–DC converters in voltage source inverter feeding AC motor drives, and so on draw highly nonlinear and unpredictable current waveform rich in harmonics with high crest factor (CF). In general, devices used for power quality improvements of such voltage fed type nonlinear loads are connected in series with these loads to block all their harmonic currents with much reduced rating and they do not have reactive power requirement. The mixed nonlinear loads consist of either several current fed type and voltage type of nonlinear loads or typically AC–DC converters with LC DC bus filter. The devices used for power quality improvements of such mixed nonlinear loads are connected in shunt with these loads or consist of hybrid of shunt and reduced rating series devices.

Despite causing power quality problems, the use of nonlinear loads, especially those employing solid-state controllers, is increasing day by day owing to benefits of the low cost and small size, remarkable energy conservation, simplicity in control, reduced wear and tear, and low maintenance requirements in the new and automated electric appliances leading to high productivity. Although these electronically automated energy-efficient electrical loads are most sensitive to power quality problems, they themselves cause additional power quality problems to the supply system. Hence, it is very important to classify and analyze their behavior to identify the proper power quality improvement devices for mitigating the power quality problems or to modify their structure for reducing or eliminating the power quality pollution at the AC mains.

7.2 State of the Art on Nonlinear Loads

Since the inception of AC power, majority of electrical equipment are developed based on the principle of energy storage, which are used in the process of energy conversion and especially in the magnetic energy storage system. They behave as inductive loads causing burden on the AC mains of the lagging reactive power and thereby poor power factor in the AC network that results in increased losses and poor utilization of components of distribution system such as transformers, feeders, and switchgear due to increased current for a given active power. AC power capacitors and synchronous condensers have been used to supply the reactive power locally and to reduce the burden of reactive power on the AC mains. In addition, because of a number of single-phase loads in the distribution system, especially domestic, residential, and commercial in small power ratings and traction, transportation, rural distribution systems, and so on in medium power ratings, there have been additional problems of load unbalancing and excessive neutral current causing increased losses, voltage imbalance and derating of the distribution system. Moreover, switching in many electrical loads causes switching transients and inrush currents resulting in various voltage-based power quality problems such as surges, spikes, sags, voltage fluctuations, voltage imbalance, and so on. These power quality problems affect other loads and system components such as protection systems, telecommunication systems, and so on. These power quality problems of voltage imbalance and fluctuations even affect good linear loads such as AC motors, especially induction motors, with negative sequence currents and subsequent rotor heating and increased losses and thus resulting in derating of these motors. Some additional power quality problems are created because of several physical phenomena in electric equipment such as saturation especially in single-phase induction motors, magnetic ballasts, transformers, voltage regulators based on ferroresonant and tap changers, and air gap asymmetry in rotating electric motors. They result in the generation of harmonics and increased neutral current. These harmonics and neutral current result in voltage distortion at the neutral terminal, increased losses, and harmonic voltage at the point of common coupling (PCC).

With the subsequent advancement, the modern automated controlled electrical loads use solid-state converters because of a number of benefits, namely, energy conservation, reduced size, reduced overall cost and so on. However, even with sinusoidal applied voltage, they draw non-sinusoidal and increased current from the AC mains in addition to the fundamental active power component of current. Some of these nonlinear loads are as follows,

- Fluorescent lighting and other vapor lamps with electronic ballasts
- Switched mode power supplies
- Computers, copiers, and television sets
- Printer, scanners, and fax machines
- High-frequency welding machines
- Fans with electronic regulators
- Microwave ovens and induction heating devices
- Xerox machines and medical equipment
- Variable frequency-based HVAC (heating ventilation and air-conditioning) systems
- Battery chargers and fuel cells
- Electric traction
- Arc furnaces
- Cycloconverters
- Adjustable speed drives
- Static slip energy recovery schemes of wound rotor induction motors
- Wind and solar power generation
- Static VAR compensators (SVCs)
- HVDC transmission systems
- Magnet power supplies
- Plasma power supplies

- Static field excitation systems

These types of nonlinear loads draw harmonic currents and reactive power component of the current from the single-phase AC mains. Some of them have harmonic currents, reactive power component of the current, and unbalanced currents in the three-phase three-wire supply system. The single-phase distributed nonlinear loads also consist of harmonic currents, reactive power component of the current, and unbalanced currents and excessive neutral current in three-phase four-wire system. These increased currents in addition to the fundamental active power component of current cause increased losses, poor power factor, disturbances to other consumers, communication systems, protection systems, and many other electronics appliances, voltage distortion, voltage spikes, voltage notches, surges, dip, sag, swell in voltages, and so on. Owing to the ever-increasing use of such nonlinear loads in present-day distribution system for obvious reasons, the exhaustive study of these nonlinear loads becomes very relevant to find the proper remedy for mitigation of power quality problems caused by them in the supply system.

7.3 Classification of Nonlinear Loads

The nonlinear loads can be classified based on

i. The use of non-solid-state or solid-state devices, for example, the presence or absence of power electronics converter in the circuits of nonlinear loads
ii. The use of converter types such as AC–DC converter type, AC voltage controller type, and cycloconverter type
iii. Their nature as stiff current fed type or stiff voltage fed type or a combination of both
iv. The number of phases such as two-wire single-phase, three-phase three-wire, and four-wire three-phase systems.

*7.3.1 Non-Solid-State and Solid-State Device Types of Nonlinear Load*s

The nonlinear loads may be classified based on whether they consist of solid-state devices or any other power converters or not. There are a number of electrical loads that are nonlinear in nature, but they do not involve any power converters. Similarly, there are only some nonlinear loads that consist of solid-state converters.

7.3.1.1 Non-Solid-State Device Type Nonlinear Loads

There are many electrical loads in nature that do not consist of any solid-state device or power electronics converter. However, they behave as nonlinear loads when they are connected to AC mains. Most of the electrical machines fall in this category of nonlinear loads. A number of physical phenomena in these electrical machines cause their behavior as nonlinear loads. Typically, the saturation in magnetic material of these machines and electromagnetic devices, skin and proximity effects in conductors, non-uniform air gap in rotating machines, effect of teeth and slotting, and so on result in harmonic currents under steady-state and transient conditions in the AC mains when they are connected to the AC supply system. Some practical examples of these types of nonlinear loads are various types of transformers operating at no load or light load conditions, magnetic ballasts of fluorescent lamps, and single-phase induction motors as they are usually designed with high level of no load current (due to high level of saturation) to reduce the cost and size of these motors. They draw harmonic currents and reactive power component of the current, and also cause excessive neutral current in the three-phase four-wire supply system due to such distributed single-phase nonlinear loads.

7.3.1.2 Solid-State Device Type Nonlinear Loads

Many types of electrical equipment consist of different circuits of solid-state devices to process the AC power to suit specific application. They draw non-sinusoidal current from the AC mains and they behave as nonlinear loads. This non-sinusoidal current consists of harmonic currents and the reactive power component of the current along with the fundamental active power component of current. They use various AC–DC converters, AC voltage controllers, cycloconverters or a combination of all in their front-end converter. In the single-phase configuration, they draw harmonic currents and reactive power from the AC mains. Examples of single-phase nonlinear loads include both domestic and commercial equipment among the home appliances are microwave oven, induction heaters, television sets, electronic ballasts-based lighting systems, domestic inverter, adjustable speed drive-based air conditioners and AC voltage regulator-based fans, whereas the commercial and industrial equipment are computers, copiers, fax machines, xerox machines, scanner, printers, small welding sets, and so on. In the three-phase, three-wire supply system, they may also draw unbalanced three-phase currents in addition to harmonic currents and reactive power. Some practical loads are three-phase adjustable speed drives, consisting of converter-fed DC motor drives, synchronous motor drives, induction motor drives, and other electric motors used in HVAC systems, wastewater treatment plants, large industrial fans, pumps, compressors, cranes, elevators, electrochemical process such as electroplating and electro mining, and so on. In the three-phase four-wire supply system, there are many single-phase nonlinear loads connected to AC mains causing excessive neutral current. Distributed single-phase loads on all three phases such as electronic ballasts-based lighting systems, computer loads in high storied buildings, and all other single-phase loads cause burden on the AC mains of harmonic currents, reactive power component of currents, unbalanced currents, and excessive neutral current.

7.3.2 Converter-Based Nonlinear Loads

There are various types of converters used in electrical equipments that behave as nonlinear loads. These nonlinear loads mainly consist of AC–DC converters, AC voltage controllers, cycloconverters, or a combination of all. These are classified on the basis of these converters, but are not confined to them. Figure 7.1 shows some of these types of current fed loads.

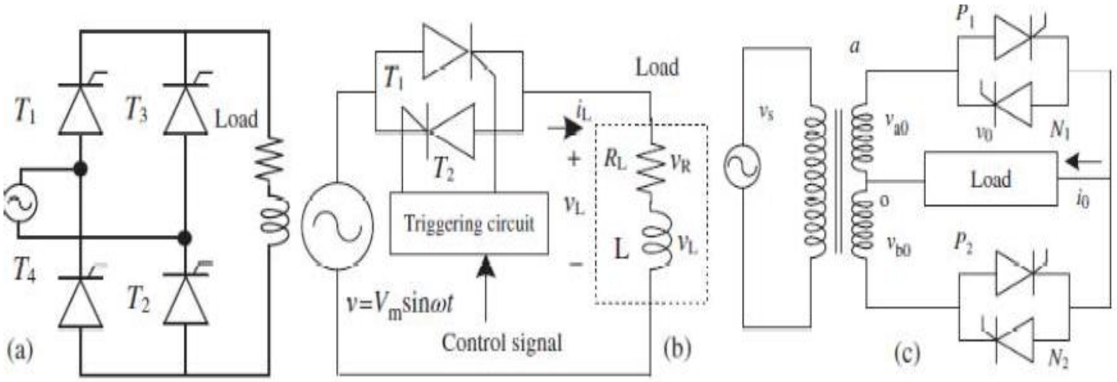


Fig. 7.1 Various types of current fed nonlinear loads

7.3.2.1 AC–DC Converter-Based Nonlinear Loads

A large number of loads use AC–DC converters as front-end converters ranging from few watts to megawatt rating. These converters are developed in many circuit configurations such as single-phase and three-phase, uncontrolled, semi controlled and fully controlled, and half-wave, full-wave, and bridge converter circuits to suit the requirements of specific application. Depending upon the types of filters used for filtering the rectified DC, their behaviors vary in a number of ways at the AC mains. Some of the examples of such nonlinear loads include microwave ovens, SMPS, computers, fax machines, battery chargers, HVDC transmission systems, electric traction, adjustable speed drives and so on. In some cases they draw current with excessive harmonic contents with high crest factor. However, in many cases they draw current with moderate harmonic contents and reactive power with low crest factor, even less than the sine wave. They exhibit poor power factor at the AC mains generally due to harmonics only, but with reactive power as well.

7.3.2.2 AC Controllers-Based Nonlinear Loads

Some nonlinear loads use AC voltage controllers for the control of AC rms voltage across the electrical loads to control the physical process. They draw the harmonic currents along with the reactive power and cause poor power factor. In single-phase distributed loads on three-phase supply systems, they also cause excessive harmonic currents. Some of the examples of such nonlinear loads include AC voltage regulator in fans, lighting controllers, heating controllers, soft starters, speed controllers, and energy saving controllers of three-phase induction motors operating under light load conditions in a number of applications such as hack saw, electric hammers, wood-cutting machines, and so on. They are also used in static VAR compensators (SVCs) in TCRs (thyristor controlled reactors) and so on.

7.3.2.2.1 Cycloconverter Based Nonlinear Loads

In many applications, cycloconverters are used to convert AC voltage of a fixed frequency to variable voltage at a variable frequency or vice versa. These cycloconverters based nonlinear loads draw harmonic currents not only at higher order harmonics but also at sub harmonics and reactive power and exhibit a very poor power factor at the AC mains. Some of the examples of such nonlinear loads include cycloconverter fed large-rating synchronous motor drives in cement mills, ore crushing plants, large-rating squirrel cage induction motors, slip energy recovery scheme of wound rotor induction motor drives, VSCF (variable speed constant frequency) generating systems, and so on.

7.3.3 Nature Based Classification

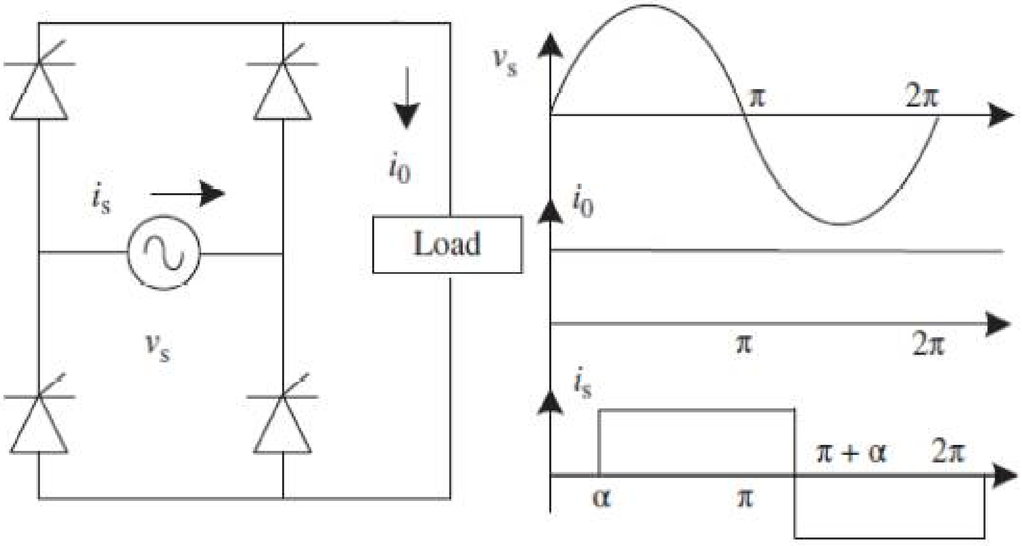


Fig. 7.2 A single-phase controlled converter-based current fed type of nonlinear load

Most of the nonlinear loads behave as either stiff current fed type or as stiff voltage fed type or a combination of both. The stiff current fed loads normally consist of AC–DC converters with constant DC current load and a predetermined harmonic pattern in the AC mains with reactive power burden.

The voltage stiff loads consist of generally AC–DC converters with a large DC capacitor at the DC bus to provide ideal DC voltage source for the remaining process of solid-state conversion and draw peaky current from the AC mains with high crest factor. Since the analysis of the behavior and remedy for mitigation of power quality problems of these types of loads depend reasonably on this classification, it becomes relevant and important to select a proper compensator.

7.3.3.1 Current Fed Type of Nonlinear Loads

The stiff current fed types of nonlinear loads generally have predetermined pattern of harmonics and sometimes they have reactive power burden on the AC mains. They have flat current waveform drawn from the AC mains with a low value of crest factor. They typically consist of AC–DC converters feeding DC motor drives, magnet power supplies, field excitation system of the alternators, controlled AC–DC converters used to derive DC current source for feeding current source inverter supplying large-rating AC motor drives, HVDC transmission systems, and so on. Figure 7.2 shows such current fed type of nonlinear load.

7.3.3.2 Voltage Fed Type of Nonlinear Loads

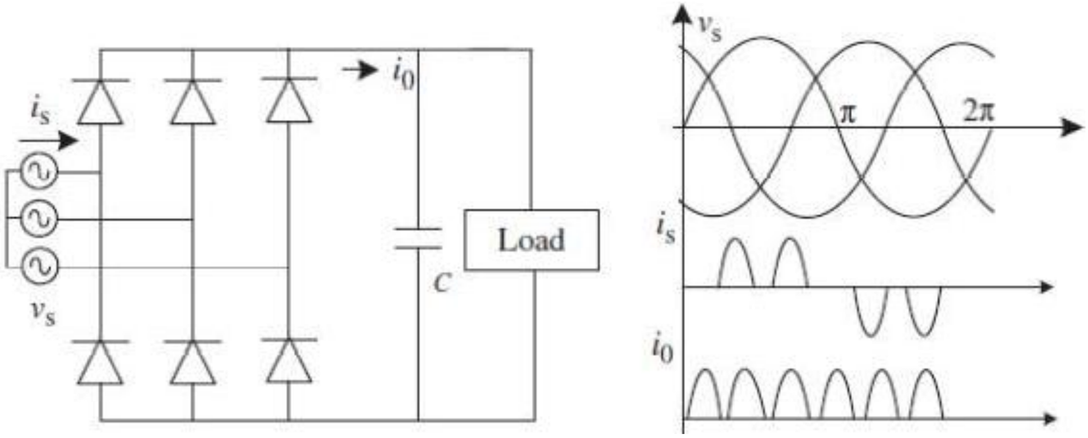


Fig. 7.3 A three-phase converter-based voltage fed type of nonlinear load

The stiff voltage types of nonlinear loads behave as sink of harmonic currents. Typical example of such load is an AC–DC converter with a large DC capacitor at its DC bus to provide an ideal DC voltage source for the remaining process of solid-state conversion and it draws peaky current from the AC mains with high crest factor as shown in figure 7.3. They generally do not have reactive power requirement, but they have much greater amount of harmonic currents drawn from the AC mains. Examples of such loads include SMPS, battery chargers, front-end converters of voltage source inverter fed AC motor drives, electronic ballasts and most of the electronic appliances.

7.3.3.3 Mix of Current Fed and Voltage Fed Types of Nonlinear Loads

The mixed nonlinear loads are combination of current fed and voltage fed types of loads. A group of nonlinear loads and a combination of linear and nonlinear loads fall under this category. Most of the electrical loads consisting of solid-state converters behave as these types of nonlinear loads.

7.3.4 Supply System-Based Classification

This classification of nonlinear loads is based on the supply system having single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads such as domestic appliances that are fed from single-phase supply systems. Some three-phase nonlinear loads are without neutral conductor, such as ASDs (Adjustable Speed Drives), fed from a three-wire supply system. There are many nonlinear single-phase loads distributed on a four-wire, three-phase supply system, such as computers, commercial lighting and so on.

7.3.4.1 Two-Wire Nonlinear Loads

There are a very large number of single-phase nonlinear loads supplied by the two-wire single-phase AC mains. All these loads consisting of single-phase diode rectifiers, semi converters and thyristor converters behave as nonlinear loads. They draw harmonic currents and sometimes also the reactive power from the AC mains. Typical examples of such loads are power supplies, electronic fan regulators, electronic ballasts, computers, television sets, and traction. Figure 7.4 shows such voltage fed type nonlinear load.

7.3.4.2 Three-Wire Nonlinear Loads

Three-phase, three-wire nonlinear loads inject harmonic currents and sometimes they draw reactive power from the AC mains and sometimes they also have unbalanced currents. These nonlinear loads are in large numbers and consume major amount of electric power. Typical examples are ASDs using DC and AC motors, HVDC transmission systems, and wind power conversion. Figure 7.5 shows such current fed type nonlinear load.

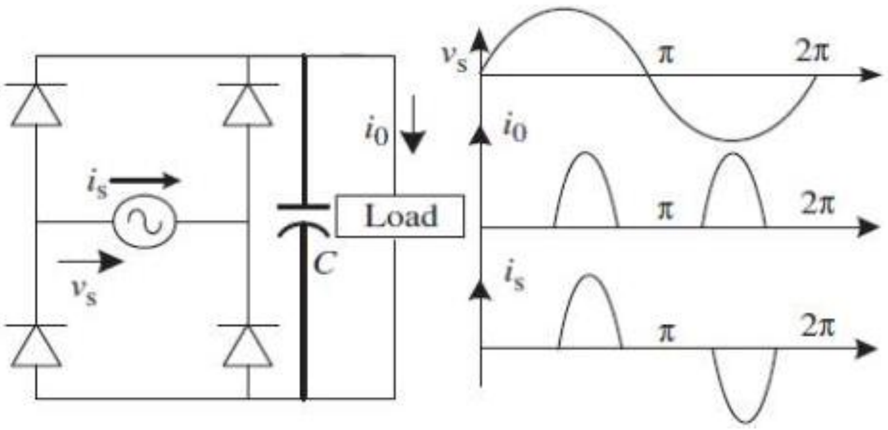


Fig. 7.4 A single-phase converter-based voltage fed type of nonlinear load

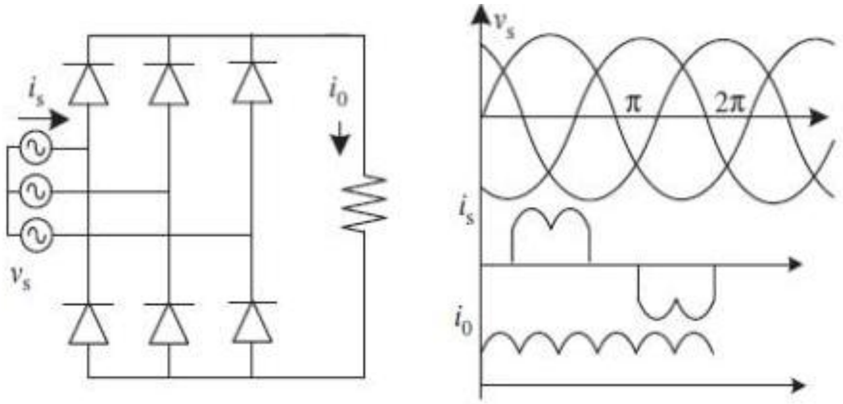


Fig. 7.5 A three-phase converter-based current fed type of nonlinear load

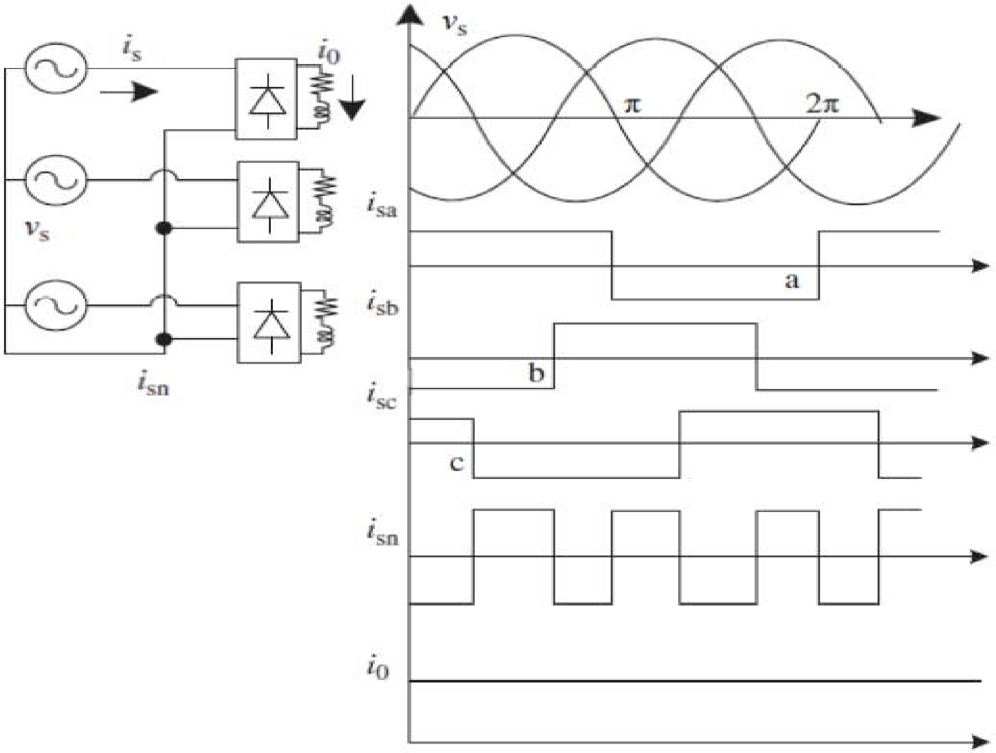


Fig. 7.6 Three-phase four wire converter-based current fed type of nonlinear loads

7.3.4.3 Four-Wire Nonlinear Loads

A large number of single-phase nonlinear loads may be supplied from the three-phase AC mains with the neutral conductor. Apart from harmonic currents, reactive power, and unbalanced currents, they also cause excessive neutral current due to harmonic currents and unbalancing of these loads on three phases. Typical examples are computer loads and electronic ballasts-based vapor lighting systems. Besides, they cause voltage distortion and voltage imbalance at the PCC and some potential at the neutral terminal. Figure 7.6 shows such current fed type nonlinear load.

7.4 Power Quality Problems Caused by Nonlinear Loads

The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the RMS value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows,

- Increased RMS value of the supply current
- Increased losses
- Poor power factor
- Poor utilization of distribution system
- Heating of components of distribution system
- Derating of the distribution system
- Distortion in voltage waveform at the point of common coupling, which indirectly affects many types of equipment
- Disturbance to the nearby consumers
- Interference in communication system
- Mal-operation of protection systems such as relays
- Interference in controllers of many other types of equipment
- Capacitorbankfailureduetooverload,resonance,harmonicamplification,andnuisancefuseoperation
- Excessive neutral current
- Harmonic voltage at the neutral point

Some of these nonlinear loads, in addition to harmonics, require reactive power and create unbalancing, which not only increases these verity of the above-mentioned problems but also causes additional problems.

- Voltage regulation and voltage fluctuations
- Imbalance in three-phase voltages
- Derating of cables and feeders

The voltage imbalance creates substantial problems to electrical machines due to negative sequence currents, noise, vibration, torque pulsation, rotor heating, and so on and of course their de-rating.

7.5 Analysis of Nonlinear Loads

There are varieties of nonlinear loads in the AC network that create power quality problems. Therefore, it has become important and relevant to analyze these loads and thereby select a right technique for power quality improvements. Majority of these nonlinear loads can be analyzed using the measured data at the site and then the power quality problems are identified to select a right technique for their mitigation. However, this technique becomes quite cumbersome, expansive, and sometimes practically difficult as it requires a large manpower, costly measuring equipment, and analytical tools. The other method for analyzing these nonlinear loads is an identification of its input stage with its output requirements and set the circuit parameters for the required performance for particular application reported in the literature. Once the equivalent circuit of the nonlinear load is properly analyzed, it can be used to design, model, and simulate the mitigation technique for power quality improvements.

7.6 Modeling, Simulation and Performance of Nonlinear Loads

As the quantification and identification of the majority of nonlinear loads may be carried out by using their equivalent circuit and by properly tuning their parameters to match their behavior with practical applications, the modeling of these nonlinear loads is very much essential for this purpose. Moreover, once the model of these nonlinear loads is developed, it can be used for the simulation of its performance. Apart from it, once the performance and identification of the load are done properly, this developed model can be used to select the right mitigation technique for power quality improvements.

7.7 Summary

Majority of power quality problems are mainly caused by the use of nonlinear loads. The nonlinear loads draw non-sinusoidal current from AC mains, which consists of various harmonic currents such as characteristic harmonics, non characteristic harmonics, inter harmonics, sub harmonics, reactive power component of current, fluctuating current, unbalanced currents, and so on. These nonlinear loads are classified into different categories considering the severity of the created problems. A number of practical examples of these nonlinear loads are given to have a proper exposure of power quality problems. An analytical study of various performance indices of these nonlinear loads is made in detail with several numerical examples to study the level of power quality they may cause in the system. Since these nonlinear loads cannot be dispensed due to many economic advantages, energy conservation, and increase in production; therefore, it is quite important to study the behavior of these nonlinear loads to find out proper mitigation techniques for power quality improvements to reduce the pollution of the supply system.

7.8 Review Questions

Short Answer Questions

1. What are voltage-fed nonlinear loads? Give two examples.
2. What are current-fed nonlinear loads? Give two examples.
3. What are the reasons for which nonlinear loads draw harmonic currents from AC mains?
4. What is the value of THD of the input current of a single-phase diode rectifier with constant DC current?
5. What is the value of THD of the input current of a three-phase diode rectifier with constant DC current?
6. What is the value of CF of the input current of a single-phase diode rectifier with constant DC current?
7. What is the value of CF of the input current of a three-phase diode rectifier with constant DC current?
8. What is the value of DF of the input current of a single-phase diode rectifier with constant DC current?
9. What is the value of DF of the input current of a three-phase diode rectifier with constant DC current?

10. What is the value of PF of the input current of a single-phase diode rectifier with constant DC current?
11. What is the value of PF of the input current of a three-phase diode rectifier with constant DC current?
12. What is the value of PF of a single-phase thyristor bridge converter with constant DC current at a firing angle of 60°?
13. What is the value of PF of a three-phase thyristor bridge converter with constant DC current at a firing angle of 30°?
14. What are the reasons that nonlinear loads cause excessive neutral current?
15. Which nonlinear loads cause excessive neutral current? Give two examples.
16. Which nonlinear loads do not consist of solid-state control and they have the harmonic currents?
17. Which nonlinear loads draw harmonic currents but do not need reactive power? Give two examples.
18. What are the power quality problems due to harmonic currents drawn by nonlinear loads?
19. What are the power quality problems due to reactive power component of currents drawn by nonlinear loads?
20. What is the classification of nonlinear loads based on solid-state converter used in them?
21. What are the reasons that these nonlinear loads are to be used in many types of equipment?
22. What are the reasons that load unbalancing is observed in three-phase supply system?
23. Which solid-state converter used in nonlinear loads has maximum power quality problems and why?
24. What are the reasons that the solid-state controllers are needed in some nonlinear loads?
25. Why magnetic ballasts have harmonic currents in fluorescent lighting system?