ST.ANNE'S
COLLEGE OF ENGINEERING AND TECHNOLOGY

(Approved by AICTE, New Delhi & Affiliated to Anna University)

Anguchettypalayam, panruti-607 106

III YEAR-V SEMESTER

EE3006/ POWER QUALITY

(REGULATION 2021)

ELECTRICAL & ELECTRONICS ENGINEERING

EE3006 **POWER QUALITY** **L T P C 3 0 0 3**

COURSE OBJECTIVES:

- To learn the basic definitions in Power Quality.
- To study the power quality issues in Single Phase and Three Phase Systems.
- To understand the principles of Power System Harmonics.
- To know the way to use DSTATCOM for Harmonic Mitigation.
- To learn the concepts related with Series Compensation.

UNIT I INTRODUCTION

Introduction – Characterization of Electric Power Quality: Transients, short duration and long duration voltage variations, Voltage imbalance, waveform distortion, Voltage fluctuations, Power frequency variation, Power acceptability curves – power quality problems: poor load power factor, Non-linear and unbalanced loads, DC offset in loads, Notching in load voltage, Disturbance in supply voltage – Power quality standards.

UNIT II ANALYSIS OF SINGLE PHASE AND THREE PHASE SYSTEM

Single phase linear and non-linear loads – single phase sinusoidal, non-sinusoidal source – supplying linear and nonlinear loads – three phase balanced system – three phase unbalanced system – three phase unbalanced and distorted source supplying non-linear loads – concept of power factor – three phase- three wire – three phase - four wire system.

UNIT III MITIGATION OF POWER SYSTEM HARMONICS

Introduction - Principle of Harmonic Filters – Series-Tuned Filters – Double Band-Pass Filters – damped Filters – Detuned Filters – Active Filters – Power Converters – Harmonic Filter Design – Tuned Filter – Second-Order Damped Filter – Impedance Plots for Filter Banks – Impedance Plotsfor a Three-Branch 33 kV Filter.

UNIT IV LOAD COMPENSATION USING DSTATCOM

Compensating single – phase loads – Ideal three phase shunt compensator structure – generating reference currents using instantaneous PQ theory – Instantaneous symmetrical components theory – Generating reference currents when the source is unbalanced –Realization and control of DSTATCOM – DSTATCOM in Voltage control mode.

UNIT V SERIES COMPENSATION OF POWER DISTRIBUTION SYSTEM

Rectifier supported DVR – DC Capacitor supported DVR – DVR Structure – Voltage Restoration – Series Active Filter – Unified Power Quality Conditioner.

TOTAL : 45 PERIODS

EE3006-POWER QUALITY

UNIT – 1 INTRODUCTION

Introduction – Characterization of Electric Power Quality: Transients, short duration and Long duration voltage variations, Voltage imbalance, waveform distortion, Voltage Fluctuations, Power frequency variation, Power acceptability curves – power quality Problems: poor load power factor, Non linear and unbalanced loads, DC offset in loads, Notching in load voltage, Disturbance in supply voltage – Power quality standards.

Part – A

1. **Define Power Quality (Nov/Dec 11,Apr/May 11,Nov/Dec 10)**
   Power quality means supply of the power within the permitted variation of the voltage and frequency and without any deviation of sinusoidal waveform in balanced condition. Power quality is any deviation of the voltage or current waveform from its normal sinusoidal wave shape. These disturbances include, but are not limited to sag, overvoltage, interruption, swell and any other distortions to the sinusoidal waveform

2. **List the major electric power quality issues. [May/June 2004]**

   Harmonics
   Voltage sag
   Voltage
   swellFlicker
   Noise
   Under
   voltageOver
   voltage.

3. **Define sag.[Nov/Dec 2013]**

   Voltage sag is an event in which the RMS voltage decreases between 0.1 and 0.9 p.u atthe power frequency. It lasts for durations of 0.5 cycles to 1 minute.

4. **Find the total harmonic distortion of a voltage waveform with the following harmonic frequency make up: fundamental=114v, 3^{rd} harmonic=4v, 5^{th} harmonic=2v, 7^{th} harmonics=1.5v and 9^{th} harmonic=1v .[Nov/Dec 2003]**

$$\frac{\sqrt{V_3^2+V_5^2+V_7^2+V_9^2}}{V1}=(4.8218/114)=4.23\%$$

6. Define voltage imbalance.[May/June 2013]

Voltage unbalance is a steady state quantity defined as the maximum deviation from the average o the three phase voltages or currents, divided by the average of the three phase voltages or currents expressed in percent.

7.What is the need for power quality standards?[May/June 2013]

- These standards clarify our responsibilities and those of our electric customers in maintaining high-quality electric service.
- It also helps to determine what voltage range is required to operate equipment effectively, which is essential to the efficient and reliable operation of sensitive electronic loads.
  Provides guidelines, recommendations and assure compatibility between end use equipment and system.
- Installation and mitigation guidelines are also given in standards.

8.List any four primary types of waveform distortion.[Nov/Dec 2012]

- DC offset
- Harmonics
- Flicker
- Inter harmonics

9. Distinguish between swell and over voltage.[Nov/Dec 2012]

S.no	Voltage Swell	Over voltage
1	Voltage increases between 1.1 and 1.8 per unit.	RMS voltage increases between 1.1 and 1.2P.U
2	Occurs for durations of 0.5 cyclesto 1 minute.	Occurs for more than one minute

10.Define Total Demand Distortion.[Nov/Dec 2006]

The total demand distortion is defined as the square root of the sum of the squares of the RMS value of the currents from 2nd to the highest harmonic (say 25thmaximum in power system) divided by the peak demand load current and is expressed as a percent.

11. What is the most common power quality problem.

Voltage sags are considered the most common power quality problem.. These can be caused by the utility or by customer loads. When sourced from the utility , they are most commonly caused by faults on the distribution system. These sags will be from 3 to 30 cycles and can be single or three phase. Depending on the design of the distribution system, a ground fault on 1 phase can cause a simultaneous swell on another phase.

12. What is the second most common power quality problem.

Power quality problems are related to grounding, ground bonds and neutral to ground voltages, ground loops, ground current or ground associated issues.

13. What type of equipment is affected by power quality issues.

All electrically operated or connected equipment is affected by power quality.

14. What are the types of power quality solutions available on the market today.

There are hundreds of manufacturers making thousands of different power quality solutions today.

The categories of these solutions are :

Utility based solutions for the substation level.
User based solution for whole facility protection.
User load level solutions for specific loads

15. How can power quality problems be detected.

A piece of equipment misoperates at the same time of day.
Circuit breakers trip without being overloaded.
Equipment fails during a thunderstorm.
Automated systems stop for no apparent reason.

16.What are harmonics.

Harmonics are distortions in the AC waveform. These distortions are caused by loads on the electrical system that use the electrical power at a different frequency than the fundamental 50 or 60 Hz.

17. How do harmonics affect the electrical system.

In general harmonics cause magnetic portions of the electrical system to overheat. Such as transformers, line reactors, magnetic relays and power factor capacitors.

18. How do harmonics affect the load.

The affect of harmonics on loads varies a great deal and is dependent on the load itself. Most loads are not affected by moderate levels of harmonics . Exceptions to this are loads that perform electrical measurements in the frequency domain of the harmonics.

19. How do you measure power quality?

It requires power quality measurement equipment to measure , record and diagnosis harmonic problems. Power quality instruments offer a service of characterizing all aspects of power quality and determining if it is acceptable to the load.

20. Why is power conditioning needed?

Effective power conditioning will prevent the erosion of your equipment and by filtering out these harmful properties will substantially enhance its reliability.

21. What types of equipment are affected by power line noise?

Any equipment based on semiconductor technology can be affected which includes all computers , telecommunications PBXs and key systems, automated manufacturing and design systems, computerized medical equipment and point of sale terminals.

22. Why are these transients or noise on the power line causing problems now?

Advances in digital logic technology have produced smaller and more sophisticated devices. This new generation of micro-circuitry is extremely dense and substantially more susceptible and transient damage.

23. What represent quality of power?

This term covers technical aspects as well as non-technical aspects like the interaction between the customer and the network operator. Eg. The speed with which the network operator reacts to complaints, etc.

24. What are the power quality issues?

Power frequency disturbances, power system transients, grounding and bonding, electromagnetic interference , power system harmonics, electrostatic discharge, power factor.

25. Classify power quality events in short duration events.

Sag
Swell
Interruption.

26.Define transient over voltages.

A transient over voltage can be defined as the response of an electrical network to a sudden change in network conditions, either intended or accidental, (e.g. a switching operation or a fault) or network stimuli (e.g. lightning strike).

27. What are the' types of transient over voltages?

1) Impulsive 2) Oscillatory

28. Define impulsive transients. Give example for impulsive transient over Voltages.

An impulsive transient is a sudden, non-power frequency change in the steady state condition of the voltage and/or current waveforms that is essentially in one direction, either positive or negative,with respect to those waveforms.
The most common cause of this type of transient is lightning.

29. Give examples for oscillatory transient over voltages.

Switching operations within the distribution network are a major cause of oscillatory transient over voltages. Such operations include

(a) Switching of utility capacitor banks,
(b) Switching of circuit breakers to clear network faults, and
(c) Switching of distribution feeders to rearrange the network for maintenance or construction

30. What is the effect of capacitor switching transients on network?

Transients of this magnitude and duration are usually not a problem on the utility system, but they can produce problems at a user facility. Severe over voltages can appear on user facility capacitors through a phenomenon known as voltage magnification.

31. Differentiate between linear loads and non-linear loads.

Linear load: Any load that draws current at supply fundamental frequency only is a linear load. The current drawn does not contain any harmonics (multiples of the supply frequency). Motors,resistors, inductors and capacitors are all linear loads.

Non Linear load: Any load that draws harmonic currents from the supply is a nonlinear load. The current waveform of such non-linear loads, is discontinuous and non sinusoidal because of the presence of harmonics.

32. What is voltage and current distortion?

Voltage distortion is any deviation from the nominal sine waveform of the AC line voltage .

Current distortion is any deviation from the nominal sine waveform of the AC line current.

33. What are voltage fluctuations?

A voltage fluctuation is a regular change in voltage that happen when devices or equipment requiring a higher load are used. The effects of a voltage fluctuation are similar to the effects of an undervoltage. It causes lights to flicker or glow brighter.

34. Define power frequency variations?

Power frequency variations are defined as the deviation of the power system fundamental frequency from it specified nominal value (50 or 60 Hz).

35. Mention power quality standards.

Phenomena	Standards
Classification of power quality	IEC 61000-2-5: 1995 [2], IEC 61000-2-1: 1990 [3] IEEE 1159: 1995 [4]
Transients	IEC 61000-2-1: 1990 [3], IEEE c62.41: (1991) [5] IEEE 1159: 1995 [4], IEC 816: 1984 [6]
Voltage sag/swell and interruptions	IEC 61009-2-1: 1990 [3], IEEE 1159: 1995 [4]
Harmonics	IEC 61000-2-1: 1990 [3], IEEE 519: 1992 [7] IEC 61000-4-7: 1991 [8]
Voltage flicker	IEC 61000-4-15: 1997 [9]

PART - B

1. Explain the type of power quality problem and causes.

The impact of long duration voltage variations is greater than those of short duration variations. A sustained overvoltage lasting for few hours can cause damage to household appliances without their owner knowing it, until it is too late. The undervoltage has the same effect as that of a voltage sag. In the case of a sag the termination of process is sudden. But normal operation can be resumed after the normal voltage is restored. However in the case of a sustained undervoltage, the process cannot even be started or resumed. A sustained interruption is usually caused by faults. Since the loss to customers due to any sustained interruption can be in the order of millions of dollars, it

is necessary for the utility to have a good preventive maintenance schedule and to have agreements or regulations to encourage high supply reliability.

Voltage imbalance can cause temperature rise in motors and can even cause a large motor to trip. Harmonics, dc offset and notching cause waveform distortions. Harmonics can be integer multiples of fundamental frequency, fractions of the fundamental frequency (subharmonics) and at frequencies that are not integer multiples of the fundamental frequency (interharmonics). Unwanted harmonic currents flowing through the distribution network can causes needless losses. Harmonics also can cause malfunction of ripple control or traffic control systems, losses and heating in transformers, electromagnetic interference (EMI) and interference with the communication systems. Ripple control refers to the use of a 300Hz to 2500Hz signal added to distribution lines to control switching of loads such as hot water heaters or street lighting. Interharmonic voltages can upset the operation of fluorescent lamps and television receivers. They can also produce acoustic noise in power equipment. DC offsets can cause saturation in the power transformer magnetic circuits. A notch is a periodic transient that rides on the supply voltage. It can damage capacitive components connected in shunt due to high rate of voltage rise at the notches.

Power quality is the interaction of electronic equipment within the electrical environment. This consists of generators, Transformers, breakers, wiring and grounding.

Good power quality would be a reliable supply of sinusoidal, 60Hz waveforms resulting in few operational anomalies.Power quality is defined as the electric power consisting of Specific range of voltage, current, frequency that result in normal operation of customer equipment. A perfect power supply would be one that is always available, always within voltage and frequency tolerances and has a pure noise-free sinusoidal wave shape.Power quality is an increasingly important issue for all electrical consumer . Problems with powering and grounding can cause data and processing errors that affect production and service quality. Each time production is interrupted electrical consumer, your loses the margin on the product that is not manufactured and sold .

Table 1.1. Power quality problems and their causes

Broad Categories	Specific Categories	Methods of Characterization	Typical Causes
Transients	Impulsive	Peak magnitude, rise time and duration	Lightning strike, transformer energization, capacitor switching
	Oscillatory	Peak magnitude, frequency components	Line or capacitor or load switching.
Short duration voltage variation	Sag	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Swell	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Interruption	Duration	Temporary (self-clearing) faults
Long duration voltage variation	Undervoltage	Magnitude, duration	Switching on loads, capacitor deenergization
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization
	Sustained interruptions	Duration	Faults
Voltage imbalance		Symmetrical components	Single-phase loads, single-phasing condition
	Harmonics	THD, Harmonic spectrum	Adjustable speed drives and other nonlinear loads
Waveform distortion	Notching	THD, Harmonic spectrum	Power electronic converters
	DC offset	Volts, Amps	Geo-magnetic disturbance, half-wave rectification
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

Voltage flickers are caused by arc discharge lamps, arc furnaces, starting of large motors, arc welding machines etc. Voltage flickers are frequent variations in voltage that can cause the light intensity from incandescent lamps to vary. This variation is perceived as disturbing by human observers, particularly in the range of 3 to 15 times per second. The voltage flicker can have adverse effects on human health as the high frequency flickering of light bulbs, fluorescent tubes or television screen can cause strain on the eyes resulting in headaches or migraines. The voltage flicker can also reduce the life span of electronic equipment, lamps etc.

2.Write short notes on various Power Quality issues . (OR)

What is the impact of transients on power quality? Classify the transients that occur in a power system. (OR)

Explain Voltage imbalance , short and long duration variations.(OR)

Disturbances in supply voltage - discuss

The ultimate reason that we are interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment.

- Long Duration Voltage Variation
  - i) Over voltage
  - ii) Under voltage
- Short duration voltage Variation
  - i) Voltage sag
  - ii) Voltage Swell
- Power Frequency Variation
- Interruption
- Voltage Imbalance
- Flicker

CHARACTERIZATION OF ELECTRIC POWER QUALITY
Transients

The term *transients* has long been used in the analysis of power system Variations to denote an event that is undesirable and momentary in Nature.

Transients can be classified into two categories,

Impulsive and Oscillatory.

These terms reflect the waveshape of a current or voltage transient

Impulsive Transient

An *impulsive transient* is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity (primarily either positive or negative).

Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. For example, a 1.2 _ 50-_s 2000-volt (V) impulsive transient nominally rises from zero to its peak value of 2000 V in 1.2 _s and then decays to half its peak value in 50 _s. The most common cause of impulsive transients is lightning.

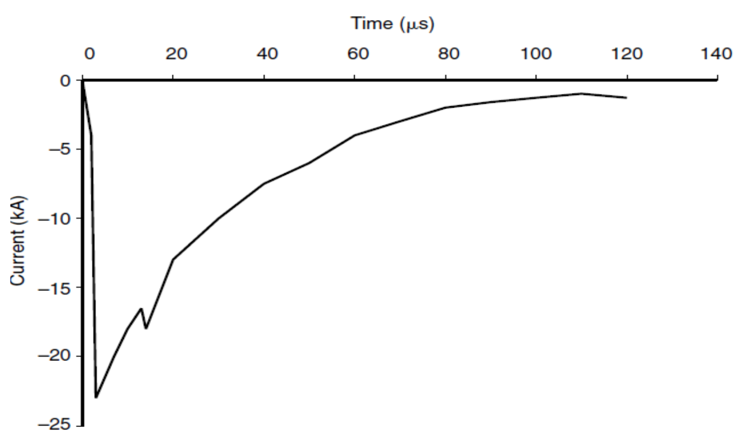
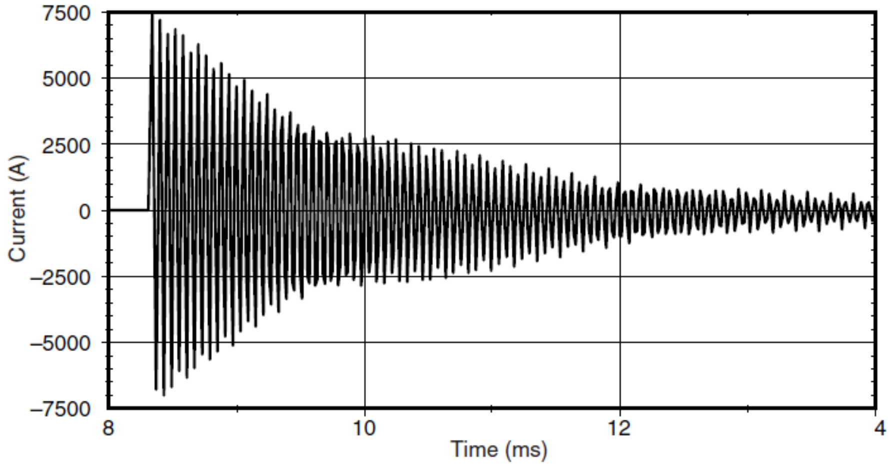


Figure 2.1 Lightning stroke current impulsive transient.

Oscillatory Transient

An oscillatory transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values.

An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominate frequency), duration, and magnitude



Oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds (or several cycles of the principal frequency) are considered ***high-frequency transients***.

A transient with a primary frequency component between 5 and 500 KHz with duration measured in the tens of microseconds (or several cycles of the principal frequency) is termed a ***medium-frequency transient.***

A transient with a primary frequency component less than 5 kHz, and a duration from 0.3 to 50 ms, is considered a ***low-frequency transient*** short duration and long duration voltage variations

Long-Duration Voltage Variations

Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min.

Long-duration variations can be either *overvoltages* or *under voltages*. Over voltages and under voltages generally are not the result of system faults, but are caused by load variations on the system and system switching operations. Such variations are typically displayed as plots of rms voltage versus time.

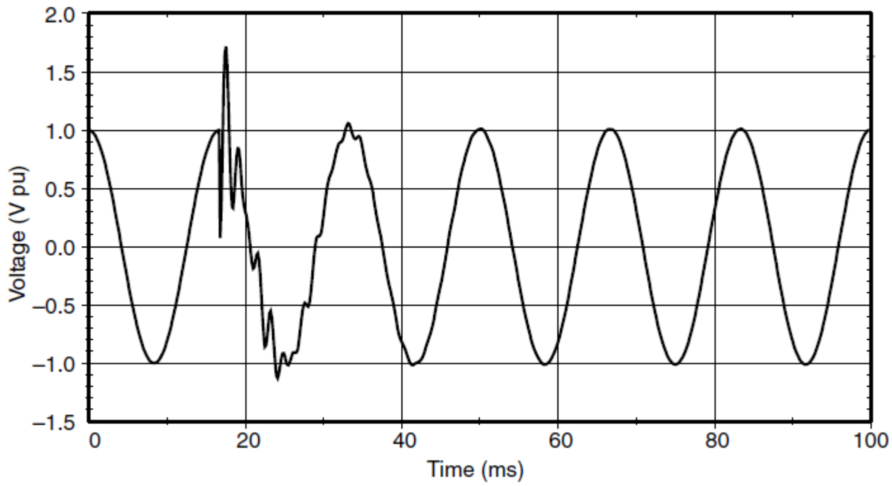


Figure 2.3 Low-frequency oscillatory transient caused by capacitor bank energization. 34.5-kV bus voltage.

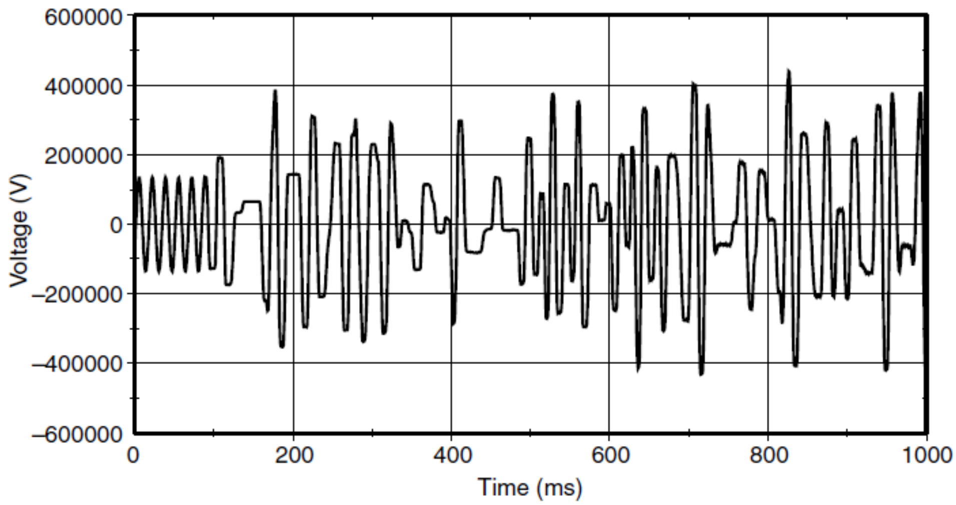


Figure 2.4 Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer.

Over voltage

An *over voltage* is an increase in the rms ac voltage greater than 110 percent at the power frequency for a duration longer than 1 min. Over voltages are usually the result of load switching (e.g., switching off a large load or energizing a capacitor bank). The over voltages result because either the system is too weak for the desired voltage regulation or voltage controls are inadequate. Incorrect tap settings on transformers can also result in system overvoltages.

Under voltage

An *undervoltage* is a decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 min. Under voltages are the result of switching events that are the opposite of the events that cause overvoltages.

A load switching on or a capacitor bank switching off can cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances. Overloaded circuits can result in under voltages also.The term *brownout* is often used to describe sustained periods of under voltage initiated as a specific utility dispatch strategy to reduce power demand. Because there is no formal definition for brownout and it is not as clear as the term undervoltage when trying to characterize a disturbance, the term brownout should be avoided.

Sustained interruptions

When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a *sustained interruption.* Voltage interruptions longer than 1 min are often permanent and require human intervention to repair the system for restoration. The term sustained interruption refers to specific power system phenomena and, in general, has no relation to the usage of the term *outage*

Outage

Outage, as defined in IEEE Standard 100,8 does not refer to a specific phenomenon, but rather to the state of a component in a system that has failed to function as expected ***interruption.***The term *interruption* in the context of power quality monitoring has no relation to reliability or other continuity of service statistics. Thus, this term has been defined to be more specific regarding the absence of voltage for long period

Interruption

An *interruption* occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min. Interruptions can be the result of power system faults, equipment failures, and control malfunctions. The interruptions are measured by their duration since the voltage magnitude is always less than 10 percent of nominal. The duration of an interruption due to a fault on the utility system is determined by the operating time of utility protective devices. Instantaneous reclosing generally will limit the interruption Caused by a nonpermanent fault to less than 30 cycles.

Delayed reclosing of the protective device may cause a momentary or temporary interruption. The duration of an interruption due to equipment malfunctions or loose connections can be irregular. Some interruptions may be preceded by a voltage sag when these interruptions are due to faults on the source system. The voltage sag occurs between the time a fault initiates and the protective device operates Figure shows such a momentary interruption during which voltage on one phase sags to about 20 percent for about 3 cycles and then drops to zero for about 1.8 s until the recloser closes back in.

Short-Duration Voltage Variations

This category encompasses the IEC category of *voltage dips and short interruptions*. Each type of variation can be designated as *instantaneous, momentary,* or *temporary,* depending on its duration.

Short-duration voltage variations are caused by fault conditions, the energization of large loads which require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage drops (*sags*), voltage rises (*swells*), or a complete loss of voltage (*interruptions*). The fault condition can be close to or remote from the point of interest. In either case, the impact on the voltage during the actual fault condition is of the short-duration variation until protective devices operate to clear the fault.

Sags (dips)

A *sag* is a decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.

Voltage sags are usually associated with system faults but can also be caused by energization of heavy loads or starting of large motors.

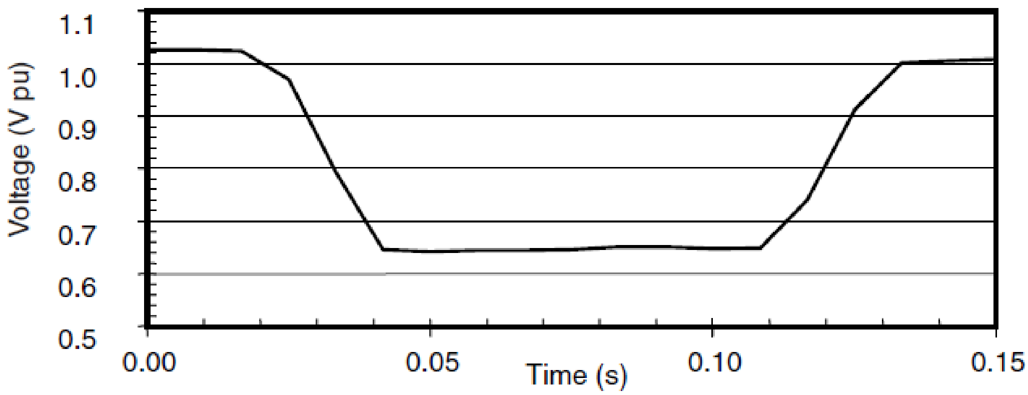
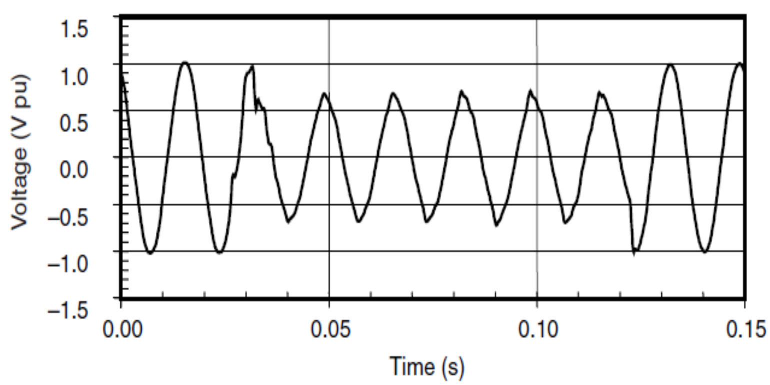


Figure 2.6 shows a typical voltage sag that can be associated with a single-line-to-ground (SLG) fault on another feeder from the same substation. An 80 percent sag exists for about 3 cycles until the substation breaker is able to interrupt the fault current. Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of overcurrent protection.

(a)



(b)

Figure 2.6 Voltage sag caused by an SLG fault. (*a*) RMS waveform for voltage

Figure 2.7 illustrates the effect of a large motor starting. An induction motor will draw 6 to 10 times its full load current during start-up. If the current magnitude is large relative to the available fault current in the system at that point, the resulting voltage sag can be significant. In this case, the voltage sags immediately to 80 percent and then grad-

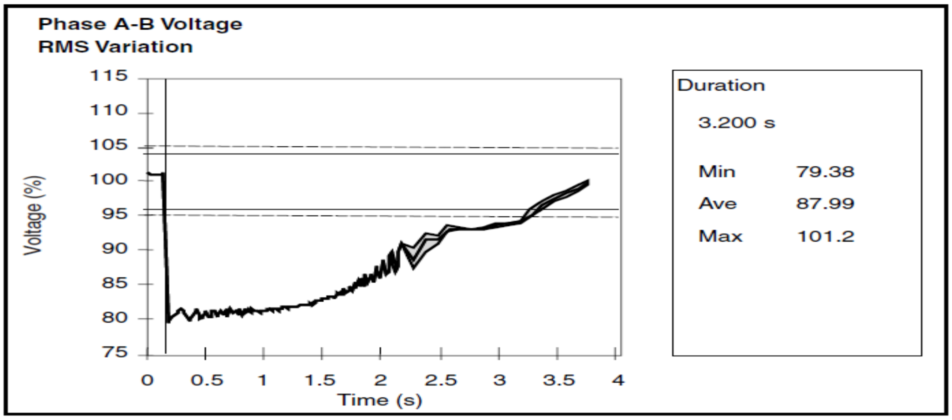


Figure 2.7 Temporary voltage sag caused by motor starting.

Voltage sags are usually associated with system faults but can also be caused by energization of heavy loads or starting of large motors.

Swell

A *swell* is defined as an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.
Sags, Swells are usually associated with system fault conditions, but they are not as common as voltage sags. One way that a swell can occur is from the temporary voltage rise on the unfaulted phases during an SLG fault voltage swell caused by an SLG fault. Swells can also be caused by switching off a large load or energizing a large capacitor bank.

Swells are characterized by their magnitude (rms value) and duration. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. On an ungrounded system, with an infinite zero-sequence impedance, the line-to-ground voltages on the ungrounded phases will be 1.73 pu during an SLG fault condition. Close to the substation on a grounded system, there will be little or no voltage rise on the unfaulted phases because the substation transformer is usually connected delta-wye, providing a low-impedance zero-sequence path for the fault current. Faults at different points along four-wire, multigrounded feeders will have varying degrees of voltage swells on the unfaulted phases.

The term *momentary overvoltage* is used by many writers as a synonym for the term *swell*.

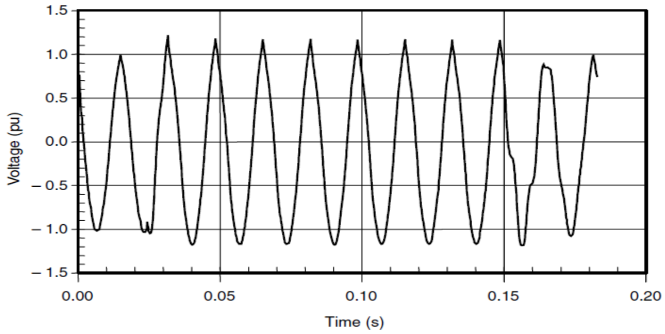


Figure 2.8 Instantaneous voltage swell caused by an SLG fault.

VOLTAGE IMBALANCE

3.Illustrate the principle of Voltage Imbalance.

Voltage imbalance

Voltage imbalance (also called *voltage unbalance*) is sometimes defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent.

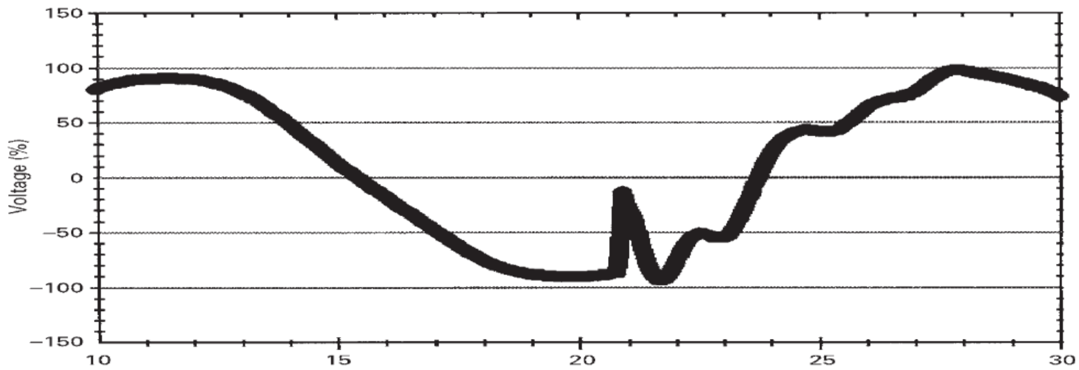
Imbalance is more rigorously defined in the standards[6,8,11,12] using symmetrical components. The ratio of either the negative- or zero-sequence component to the positive-sequence component can be used to specify the percent unbalance. The most recent standards[11] specify that the negative-sequence method be used. Figure 2.9 shows an example of these two ratios for a 1-week trend of imbalance on a residential feeder.

The primary source of voltage unbalances of less than 2 percent is single-phase loads on a three-phase circuit. Voltage unbalance can also be the result of blown fuses in one phase of a three-phase capacitor bank. Severe voltage unbalance (greater than 5 percent) can result from single-phasing conditions.

$$\text{Voltage unbalance} = 100 \times \frac{\text{max. deviation from average voltage}}{\text{average voltage}}$$

Voltage unbalance

Voltage unbalance or imbalance is the deviation of each phase from the average voltage of all three phases. It can be calculated by the formula:



Most equipment, especially motors, can tolerate a voltage unbalance of 2 percent. A voltage unbalance greater than 2 percent will cause motors and transformers to overheat. This is because a current unbalance in an induction device, like a motor or transformer, varies as the cube of the voltage unbalance applied to the terminals. Potential causes of voltage unbalance include capacitor banks not operating properly, single phasing of equipment, and connecting more single-phase loads on one phase than another. Installing monitors to measure the voltage unbalance provides the necessary data to analyze and eliminate the cause of the unbalance.

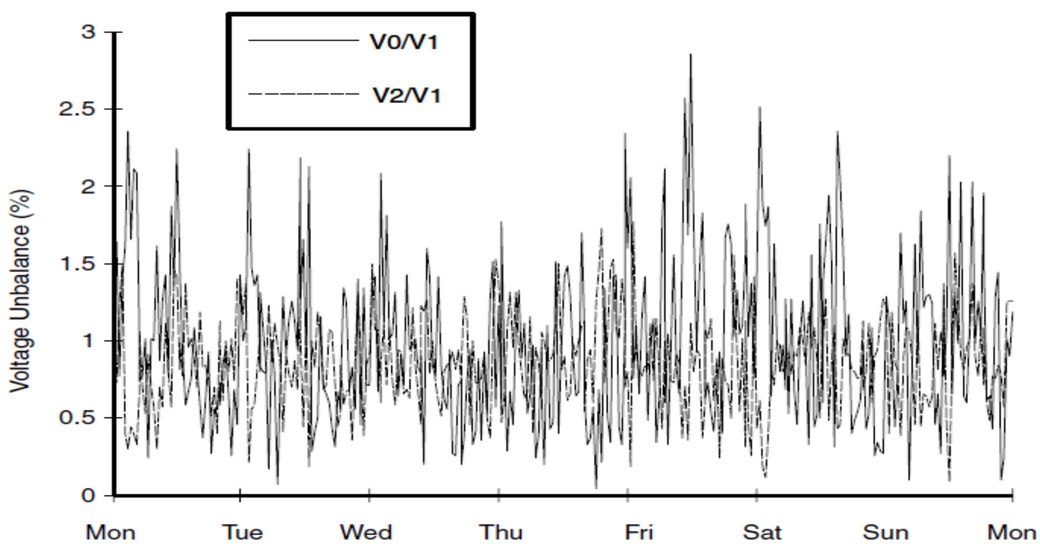


Figure 2.9 Voltage unbalance trend for a residential feeder.

WAVEFORM DISTORTION

4.Discuss the categories of waveform distortion in detail.

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
- Interharmonics
- Notching
- Noise

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.

HARMONICS

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the sup- ply system is designed to operate (termed the *fundamental* frequency; usually 50 or 60 Hz).6 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.

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the *total harmonic distortion* .

Harmonic spectrum for a typical adjustable-speed-drive (ASD) input current. Current distortion levels can be characterized by a THD value, as previously described, but this can often be misleading 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 distortion is high.

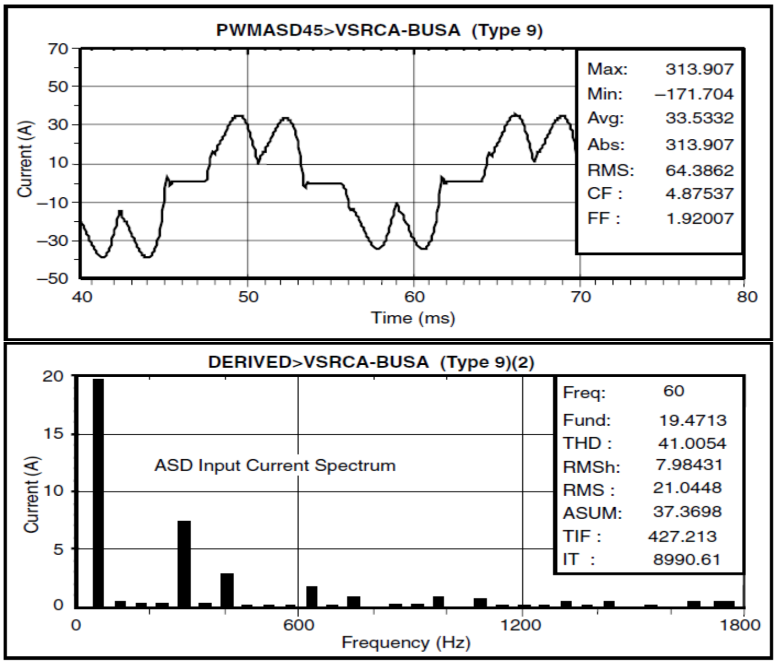


Figure 2.10 Current waveform and harmonic spectrum for an ASD input current.

Interharmonics. 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 *interharmonics*. They can appear as discrete frequencies or as a wideband spectrum.

Notching. *Notching* is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another.

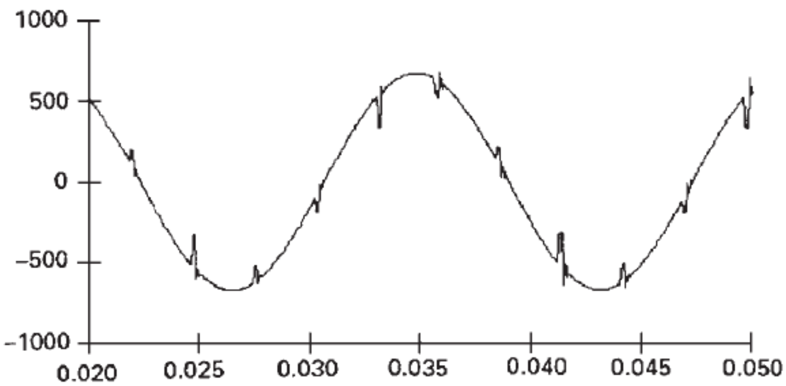


Figure 2.11 Example of voltage notching caused by a three-phase converter.

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.

VOLTAGE FLUCTUATIONS

5.Enumerate the effects of power frequency variations and voltage fluctuations.

2.8 Voltage Fluctuation

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by ANSI C84.1 of 0.9 to 1.1 pu.

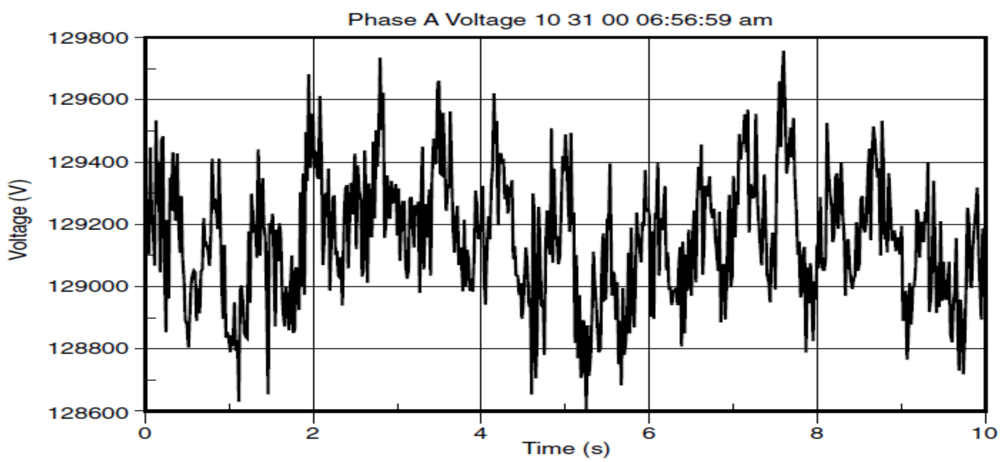


Figure 2.12 Example of voltage fluctuations caused by arc furnace operation.

POWER FREQUENCY VARIATIONS

2.9 Power Frequency Variations

Power frequency variations are defined as the deviation of the power system fundamental frequency from it specified nominal value (e.g., 50 or 60 Hz).

The power system frequency is directly related to the rotational speed of the generators supplying the system. There are slight variations in frequency as the dynamic balance between load and generation changes. The size of the frequency shift and its duration depend on the load characteristics and the response of the generation control system to load changes. Figure 2.14 illustrates frequency variations for a 24-h period on a typical 13-kV substation bus.

Frequency variations that go outside of accepted limits for normal steady-state operation of the power system can be caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line.

On modern interconnected power systems, significant frequency variations are rare. Frequency variations of consequence are much more likely to occur for loads that are supplied by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency-sensitive equipment.

Sources of Power Quality Problems

Power quality experts find it a challenge to analyze any power quality problem and determine the source of the problem. They usually measure the effect of the problem and draw on their experience to identify the type of disturbance from the measurement. Even experienced power quality experts often find it is difficult to determine the source of the power quality problem. They know they need to understand the basic reasons why different devices and phenomena cause power quality problems. One common characteristic of sources of power quality problems is the interruption of the current or voltage sine wave. This interruption results in one of the disturbances discussed at the beginning of this chapter.

The major sources of power quality problems can be divided into two categories, depending on the location of the source in relationship to the power meter. One category is on the utility side of the meter and includes switching operations, power system faults, and lightning. The other category is on the end-user side of the meter and includes nonlinear loads, poor grounding, electromagnetic interference, and static electricity. So let's first examine the characteristics of utility-caused power quality problems.

POWER ACCEPTABILITY CURVES

6.DescribePower acceptability curves.

ITI curve A set of curves published by the Information Technology Industry Council (ITI) representing the withstand capabilities of computers connected to 120-V power systems in terms of the magnitude and duration of the voltage disturbance.[10] The ITI curve replaces the curves originally developed by the ITI's predecessor organization, the Computer Business Equipment Manufacturers Association (CBEMA).[9] See *CBEMA curve.*

2.12 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 446[9] that we typically use in our analysis of power quality monitoring results is shown in Fig. 2.15. 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 overexcitation. 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 cycle and higher due to limitations in power qual-

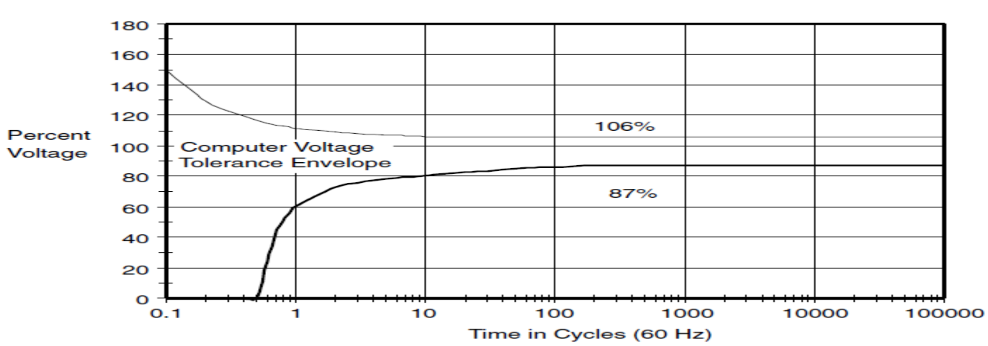


Figure 2.15 A portion of the CBEMA curve commonly used as a design target for equipment and a format for reporting power quality variation data.

ity monitoring instruments and differences in opinion over defining the magnitude values in the subcycle time frame.

The CBEMA organization has been replaced by ITI,[10] and a modified curve has been developed that specifically applies to common 120-V computer equipment (see Fig. 2.16). The concept is similar to the CBEMA curve. Although developed for 120-V computer equipment, the curve has been applied to general power quality evaluation like its predecessor curve.

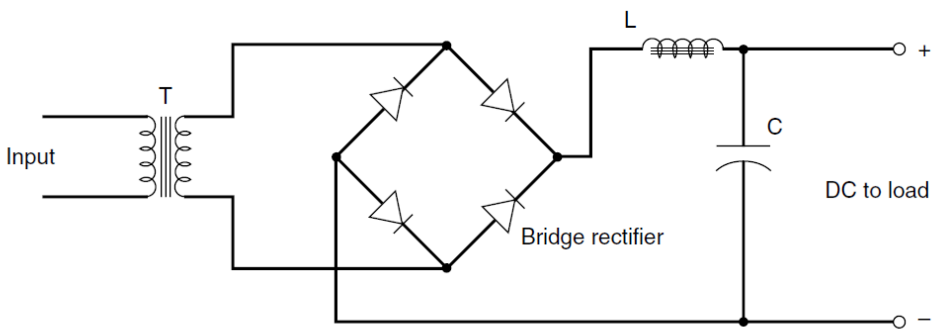
Both curves are used as a reference in this book to define the withstand capability of various loads and devices for protection from power quality variations. For display of large quantities of power quality monitoring data, we frequently add a third axis to the plot to denote the number of events within a certain predefined cell of magnitude and duration. If restricted to just the two-dimensional views shown in Fig. 2.16, the plot tends to turn into a solid mass of points over time, which is not useful.

NONLINEAR AND UNBALANCED LOADS

7.Write short notes on nonlinear and unbalanced loads.

Nonlinear loads. There are today many types of nonlinear loads. They include all types of electronic equipment that use switched-mode power supplies, adjustable-speed drives, rectifiers converting ac to dc, inverters converting dc to ac, arc welders and arc furnaces, electronic and magnetic ballast in fluorescent lighting, and medical equipment like MRI (magnetic radiation imaging) and x-ray machines. Other devices that convert ac to dc and generate harmonics include battery chargers, UPSs, electron beam furnaces, and induction furnaces, to name just a few. All these devices change a smooth sinusoidal wave into irregular distorted wave shapes. The distorted wave shapes produce harmonics.

Most electronic devices use switched-mode power supplies that produce harmonics. Manufacturers of electronic equipment have found that they can eliminate a filter and eliminate the power supply transformer (shown in Figure 2.22) by the use of a switched-mode power supply (shown in Figure 2.23). What is a switched-mode power supply? How does it produce harmonics? The switched-mode process converts ac to dc using a rectifier bridge, converts dc back to ac at a high frequency using a switcher, steps the ac voltage down to 5 V using a small transformer, and finally converts the ac to dc using another rectifier. Electronic equipment requires 5 V dc to operate. Go inside a switched-mode power supply and you'll find a switching circuit that takes stored energy from a capacitor in short pulses and delivers voltage at a frequency of 20 to 100 kHz to a transformer in the form of a square wave. The high-frequency switching requires a small and light transformer. However, the pulsed square wave distorts the sine wave and produces harmonics.



These devices use the latest electronic controls to control the speed of motors to match the requirements of the load. However, they have been a source of trouble. They trip off inadvertently. They cause nearby transformers to overheat and trip off. What is causing this to happen? The adjustable-speed drives produce nonlinear loads. Nonlinear loads, such as adjustable-speed drives, electronic ballasts for fluorescent lamps, and power supplies for welding machines, as shown in is defined as "a load where the waveshape of the steady state current does not follow the waveshape of the applied voltage." This usually occurs when the load is not a pure resistance, capacitance, or inductance, but instead contains electronic components to control the function of the equipment to meet the requirements of the load. Often the nonlinearity of the load results in the generation of harmonics that cause overheating of electrical equipment. Figure 1.12 shows how har-

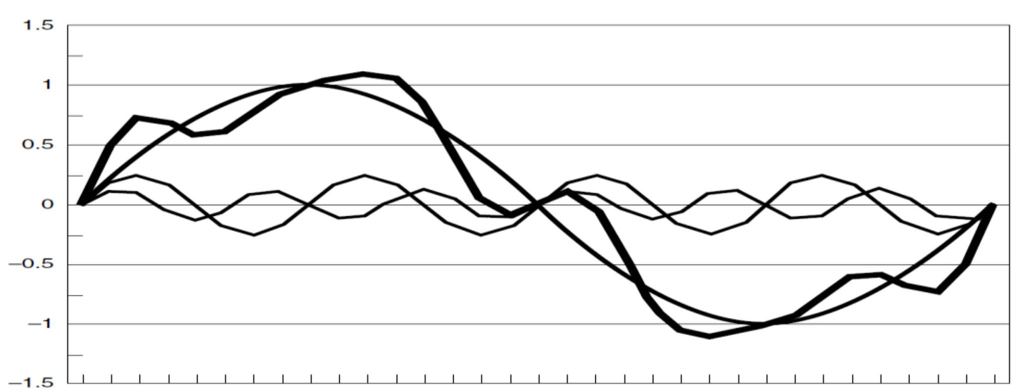


Figure 1.12 Harmonics effect.

Sensitive loads

Computers and microprocessors have invaded our homes, offices, hospitals, banks, airports, and factories. It is hard to imagine any industry today that is not impacted by computers and microprocessors. Microprocessors have even become a part of today's toys and consumer appliances. Figure 1.6 shows examples of microprocessor-controlled equipment that can be affected by poor power quality.

Why do computers cause loads to be more sensitive? The brains of all computers are integrated circuit (IC) chips. They are the source of this sensitivity, which has increased over the last 25 years as more transistors have been placed on a micro chip. The number of transistors on a chip has increased significantly from the two transistors on the first microchip invented in 1958 to 7.5 million on Intel's Pentium II microchip in 1995, as illustrated in Figure 1.7 (mips refers to millions of instructions per second). In fact, the computer industry has observed that each new chip contains roughly twice as much capacity as its predecessor and each chip is released within 18 to 24 months of the previous chip. This principle has become known as Moore's law and was named after an Intel founder, Gordon Moore, who made this observation in a 1965 speech.

As computer chip manufacturers seek to increase the density of electrical components on a chip, the chips become even more sensitive to changes in the electrical power supply. The density of these components in a very small package causes computers to have a low tolerance for voltage deviations. They are prone to current flowing from one conductor to another if the insulation is damaged. As more components are jammed in a small area, they will tend to generate more insulation-damaging heat. Figure 1.8 shows the density of the electrical components in an IC.

In addition, computers use the on and off voltages and the timing provided by the power supply to store and manipulate data in the microprocessor. Any deviations from the voltage that is specified can cause the data to be corrupted or erased. This is what often causes your computer to "freeze up." These disturbances affect not only your personal computer, but also any industrial or commercial office process that uses microprocessors. These include electronically controlled devices, such as adjustable-speed drives, scanners, cash registers in grocery stores, fax and copy machines in offices, telecommunication equipment, and medical equipment.

Power quality has probably not deteriorated over time, but instead the equipment requirements for higher power quality have increased in the 1990s. In the past, most equipment could tolerate a voltage disturbances of ±5 percent of nominal voltage. For example, nonelectronic equipment, like motors, incandescent lights, and resistance heaters, could tolerate decreases and increases in voltage of 6 V on a 120-V receptacle. Table 1.1 from the American National Standards Institute (ANSI) 84l1 shows the voltage tolerances in the secondary system, i.e., 120 V in a residence and 480 V in a factory, of the end user.

POWER QUALITY PROBLEMS & POOR LOAD POWER FACTOR

8.Summarize the effects of power quality problems and poor power factor loads.

Poor power factor loads

As a general rule, an electrical system using motors exhibits a low power factor. Low power factors result in overall low power system efficiency, including increased conductor and transformer losses and low voltage. Low power factor also reduces line and transformer capacity. Utilities must supply both the active and reactive power and compensate for these losses. For this reason, most utilities charge their customers a penalty for low power factor. Many utilities increase the demand charge for every percent the power factor drops below a set value, say 95 percent. However, more and more utilities are charging for kVAR-hours just like they charge for kW-hours. These charges provide utility customers an incentive to increase their power factor by the use of power factor improvement capacitors. Otherwise, the utility has to install power factor improvement capacitors on its own power system. But how do capacitors improve power factor?

It is generally more energy-efficient and cost-effective to improve the power factor of the electrical system at an industrial plant than to require generators to provide the necessary reactive requirements of the plant's loads. Improving power factor can be accomplished through the addition of shunt capacitors.

Effects of Power Quality Problems

The effects of power quality problems are many and varied. Often a utility customer calls the utility in an attempt to determine the cause of a power quality problem. This chapter has discussed the various types of power quality problems. However, most power quality problems manifest themselves as some effect on an end-user's electrical equipment. These symptoms include motors overheating, adjustable-speed drives tripping off, computers shutting down, flickering lights, and stopped production. The effects of power quality problems can be best be understood by looking at the various types of loads that are affected by power quality problems, including computers, consumer products, lighting, meters, ferromagnetic equipment, telephones, manufacturing processes, and capacitors.

Computers and computer-controlled equipment are most subject to power quality problems. They freeze up and lose data. Most power quality problems on computers are caused by voltage variations.

Consumer products include digital clocks, microwave ovens, television sets, video cassette recorders, and stereo equipment. Most consumer products are affected by voltage sags and outages causing the electronic timer to shut down. This problem manifests itself by the blinking clock.

Lighting includes incandescent, high-intensity discharge, and fluorescent lights. Incandescent lights often dim during a voltage sag. All lighting will flicker when arc furnaces and arc welders cause the voltage to fluctuate.

Meters will give erroneous readings in the presence of harmonics.

Ferromagnetic equipment include transformers and motors. They overheat and lose life when harmonic currents increase the loading on them.

Telephones will experience noise induced by adjacent electrical equipment.

Adjustable-speed drives not only cause harmonics but are affected by them. The frequent shutdown of an adjustable-speed drive is usually an indication of excessive harmonics.

Many manufacturing processes experience frequent shutdowns due to voltage sags.

Capacitors can amplify as well as draw harmonic currents to themselves. This often causes the capacitors to fail or be tripped off-line.

9.Define various power quality terms.

Council (ITI), and a new curve has been developed that is commonly referred to as the ITI curve. See *ITI curve.*

common mode voltage The noise voltage that appears equally from current-carrying conductor to ground.[2]

coupling A circuit element, or elements, or a network that may be considered common to the input mesh and the output mesh and through which energy may be transferred from one to another.[8]

crest factor A value reported by many power quality monitoring instruments representing the ratio of the crest value of the measured waveform to the root mean square of the fundamental. For example, the crest factor of a sinusoidal wave is 1.414.

critical load Devices and equipment whose failure to operate satisfactorily jeopardizes the health or safety of personnel, and/or results in loss of function, financial loss, or damage to property deemed critical by the user.

current distortion Distortion in the ac line current. See *distortion.*

differential mode voltage The voltage between any two of a specified set of active conductors.

dip See *sag.*

distortion Any deviation from the normal sine wave for an ac quantity.

distributed generation (DG) Generation dispersed throughout the power system as opposed to large, central station power plants. In the context used in this book, DG typically refers to units less than 10 megawatts (MW) in size that are interconnected with the distribution system rather than the transmission system.

dropout A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

dropout voltage The voltage at which a device will release to its deenergized position (for this document, the voltage at which a device fails to operate).

electromagnetic compatibility The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.[2,3]

equipment grounding conductor The conductor used to connect the non–current carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer). See National Fire Protection Association (NFPA) 70-1993, Section 100.[7]

ground window The area through which all grounding conductors, including metallic raceways, enter a specific area. It is often used in communications systems through which the building grounding system is connected to an area that would otherwise have no grounding connection.

harmonic (component) A component of order greater than 1 of the Fourier series of a periodic quantity.[2]

harmonic content The quantity obtained by subtracting the fundamental component from an alternating quantity.

harmonic distortion Periodic distortion of the sine wave. See *distortion* and *total harmonic distortion* (THD).

harmonic filter On power systems, a device for filtering one or more harmonics from the power system. Most are passive combinations of inductance, capacitance, and resistance. Newer technologies include active filters that can also address reactive power needs.

harmonic number The integral number given by the ratio of the frequency of a harmonic to the fundamental frequency.[2]

harmonic resonance A condition in which the power system is resonating near one of the major harmonics being produced by nonlinear elements in the system, thus exacerbating the harmonic distortion.

impulse A pulse that, for a given application, approximates a unit pulse or a Dirac function.[2] When used in relation to monitoring power quality, it is preferable to use the term impulsive transient in place of impulse.

impulsive transient A sudden, nonpower frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative).

instantaneous When used to quantify the duration of a short-duration variation as a modifier, this term refers to a time range from one-half cycle to 30 cycles of the power frequency.

instantaneous reclosing A term commonly applied to reclosing of a utility breaker as quickly as possible after an interrupting fault current. Typical times are 18 to 30 cycles.

interharmonic (component) A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz).

interruption, momentary (electrical power systems) An interruption of a duration limited to the period required to restore service by automatic or supervisory-controlled switching operations or by manual switching at locations where an operator is immediately available. Note: Such switching operations must be completed in a specified time not to exceed 5 min.

interruption, momentary (power quality monitoring) A type of short-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 30 cycles and 3 s.

interruption, sustained (electrical power systems) Any interruption not classified as a momentary interruption.

interruption, sustained (power quality) A type of long-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time greater than 1 min.

interruption, temporary A type of short-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 3 s and 1 min.

inverter A power electronic device that converts direct current to alternating current of either power frequency or a frequency required by an industrial process. Common inverters today employ pulse-width modulation to create the desired frequency with minimal harmonic distortion.

islanding Refers to a condition in which distributed generation is isolated on a portion of the load served by the utility power system. It is usually an undesirable situation, although there are situations where controlled islands can improve the system reliability.

isolated ground An insulated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor is insulated from the metallic raceway and all ground points throughout its length. It originates at an isolated ground-type receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source. See NFPA 70-1993, Section 250-74, Exception #4 and Section 250-75, Exception.[7]

isolation Separation of one section of a system from undesired influences of other sections.

ITI curve A set of curves published by the Information Technology Industry Council (ITI) representing the withstand capabilities of computers connected to 120-V power systems in terms of the magnitude and duration of the voltage disturbance.[10] The ITI curve replaces the curves originally developed by the ITI's predecessor organization, the Computer Business Equipment Manufacturers Association (CBEMA).[9] See *CBEMA curve.*

linear load An electrical load device that, in steady-state operation, presents an essentially constant load impedance to the power source throughout the cycle of applied voltage.

long-duration variation A variation of the rms value of the voltage from nominal voltage for a time greater than 1 min. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g., undervoltage, overvoltage, or voltage interruption).

low-side surges A term coined by distribution transformer designers to describe the current surge that appears to be injected into the transformer secondary terminals during a lightning strike to grounded conductors in the vicinity.

momentary When used to quantify the duration of a short-duration variation as a modifier, refers to a time range at the power frequency from 30 cycles to 3 s.

noise Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.[8] (For this document, "control systems" is intended to include sensitive electronic equipment in total or in part.)

nominal voltage (Vn) A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 208/120, 480/277, 600).[6]

nonlinear load Electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

normal mode voltage A voltage that appears between or among active circuit conductors.

notch A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half-cycle, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half-cycle.

oscillatory transient A sudden, nonpower frequency change in the steady-state condition of voltage or current that includes both positive- or negative-polarity value.

overvoltage When used to describe a specific type of long-duration variation, refers to a voltage having a value of at least 10 percent above the nominal voltage for a period of time greater than 1 min.

passive filter A combination of inductors, capacitors, and resistors designed to eliminate one or more harmonics. The most common variety is simply an inductor in series with a shunt capacitor, which short-circuits the major distorting harmonic component from the system.

phase shift The displacement in time of one voltage waveform relative to other voltage waveform(s).

power factor, displacement The power factor of the fundamental frequency components of the voltage and current waveforms.

power factor (true) The ratio of active power (watts) to apparent power (voltamperes).

Plt The long-term flicker severity level as defined by IEC 61000-4-15, based on an observation period of 2 h.

Pst The short-term flicker severity level as defined by IEC 61000-4-15, based on an observation period of 10 min. A Pst value greater than 1.0 corresponds to the level of irritability for 50 percent of the persons subjected to the measured flicker.

pulse An abrupt variation of short duration of a physical quantity followed by a rapid return to the initial value.

pulse-width modulation (PWM) A common technique used in inverters to create an ac waveform by controlling the electronic switch to produce varying-width pulses. Minimizes power frequency harmonic distortion in some applications, but care must be taken to properly filter out the switching frequencies, which are commonly 3 to 6 kHz.

reclosing The common utility practice used on overhead lines of closing the breaker within a short time after clearing a fault, taking advantage of the fact that most faults are transient, or temporary.

recovery time The time interval needed for the output voltage or current to return to a value within the regulation specification after a step load or line change.[8] Also may indicate the time interval required to bring a system back to its operating condition after an interruption or dropout.

recovery voltage The voltage that occurs across the terminals of a pole of a circuit-interrupting device upon interruption of the current.[8]

rectifier A power electronic device for converting alternating current to direct current.

resonance A condition in which the natural frequencies of the inductances and capacitances in the power system are excited and sustained by disturbing phenomena. This can result in excessive voltages and currents. Waveform distortion, whether harmonic or nonharmonic, is probably the most frequent excitation source. Also, various short-circuit and open-circuit faults can result in resonant conditions.

safety ground See *equipment grounding conductor*.

sag A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min.

shield As normally applied to instrumentation cables, refers to a conductive sheath (usually metallic) applied, over the insulation of a conductor or conductors, for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors that may be susceptible to, or which may be generating, unwanted electrostatic or electromagnetic fields (noise).

shielding Shielding is the use of a conducting and/or ferromagnetic barrier between a potentially disturbing noise source and sensitive circuitry. Shields are used to protect cables (data and power) and electronic circuits. They may be in the form of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

shielding (of utility lines) The construction of a grounded conductor or tower over the lines to intercept lightning strokes in an attempt to keep the lightning currents out of the power system.

short-duration variation A variation of the rms value of the voltage from nominal voltage for a time greater than one-half cycle of the power frequency but less than or equal to 1 min. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, or interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, or temporary).

signal reference grid (or plane) A system of conductive paths among interconnected equipment, which reduces noise-induced voltages to levels that minimize improper operation. Common configurations include grids and planes.

sustained When used to quantify the duration of a voltage interruption, refers to the time frame associated with a long-duration variation (i.e., greater than 1 min).

swell A temporary increase in the rms value of the voltage of more than 10 percent of the nominal voltage, at the power frequency, for durations from 0.5 cycle to 1 min.

sympathetic tripping When a circuit breaker on an unfaulted feeder section trips unnecessarily due to backfeed into a fault elsewhere. Most commonly occurs when sensitive ground fault relaying is employed.

synchronous closing Generally used in reference to closing all three poles of a capacitor switch in synchronism with the power system to minimize transients.

temporary When used to quantify the duration of a short-duration variation as a modifier, refers to a time range from 3 s to 1 min.

total demand distortion (TDD) The ratio of the root mean square of the harmonic current to the rms value of the rated or maximum demand fundamental current, expressed as a percent.

total disturbance level The level of a given electromagnetic disturbance caused by the superposition of the emission of all pieces of equipment in a given system.[2]

total harmonic distortion (THD) The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental.[8]

transient Pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.[2]

triplen harmonics A term frequently used to refer to the odd multiples of the third harmonic, which deserve special attention because of their natural tendency to be zero sequence.

undervoltage When used to describe a specific type of long-duration variation, refers to a measured voltage having a value at least 10 percent below the nominal voltage for a period of time greater than 1 min. In other contexts, such as distributed generation protection, the time frame of interest would be measured in cycles or seconds.

voltage change A variation of the root mean square or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.[6]

voltage dip See *sag*.

voltage distortion Distortion of the ac line voltage. See *distortion*.

voltage fluctuation A series of voltage changes or a cyclical variation of the voltage envelope.[6]

voltage imbalance (unbalance) A condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120 degree phase relationship or both. Frequently expressed as the ratio of the negative-sequence or zero-sequence voltage to the positive-sequence voltage, in percent.

voltage interruption Disappearance of the supply voltage on one or more phases. Usually qualified by an additional term indicating the duration of the interruption (e.g., momentary, temporary, or sustained).

voltage regulation The degree of control or stability of the rms voltage at the load. Often specified in relation to other parameters, such as input-voltage changes, load changes, or temperature changes.

voltage magnification The magnification of capacitor switching oscillatory transient voltage on the primary side by capacitors on the secondary side of a transformer.

waveform distortion A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

POWER QUALITY STANDARDS

11.Illustrate various power quality standards

TABLE 1.2 United States Power Quality Standards Synopsis

Title/Subject	Standards
Industrial Electric Power Systems (*Red Book*)	ANSI/IEEE 141
Industrial & Commercial (I&C) Power System Ground (*Green Book*)	ANSI/IEEE 142
Commercial Electric Power Systems (*Gray Book*)	ANSI/IEEE 241
I&C Power System Protection (*Buff Book*)	ANSI/IEEE 242
I&C Power System Analysis (*Brown Book*)	ANSI/IEEE 399
I&C Power System Emergency Power (*Orange Book*)	ANSI/IEEE 446
I&C Power System Reliability (*Gold Book*)	ANSI/IEEE 493
Control of Noise in Electronic Controls	ANSI/IEEE 518
Harmonics in Power Systems	ANSI/IEEE 519
Electric Systems in Healthcare Facilities (*White Book*)	ANSI/IEEE 602
Energy Management in I&C Facilities (*Bronze Book*)	ANSI/IEEE 795
Interconnection Practices for Photovoltaic Systems	ANSI/IEEE 929
Interfacing Dispersed Storage and Generation	ANSI/IEEE 1001
Test Procedures for Interconnecting Static Power Converters	ANSI/IEEE 1035
Grounding of Power Station Instrumentation and Control	ANSI/IEEE 1050
Guides and Standards on Surge Protection	ANSI C62
Voltage Ratings for Power Systems and Equipment	ANSI C84.1
Guides and Standards for Relay and Overcurrent Protection	ANSI C37
Transformer Derating for Supplying Nonlinear Loads	ANSI C57.110
Electromagnetic Compatibility	ANSI C63.18
Wire Line Communication Protection in Power Stations	IEEE P487
Power and Ground Sensitive Electronic Equip. (*Emerald Book*)	IEEE 1100
Monitoring and Definition of Electric Power Quality	IEEE 1159
Guide on Equipment Sensitive to Momentary Voltage Disturbances	IEEE 1250
Guide on Compatibility for ASDs and Process Controllers	IEEE P1346
Uninterruptible Power Supply Specification	NEMA UPS
National Electric Code	NFFA 70
Protection of Electronic Computer Data Processing Equipment	NFFA 75
Lightning Protection Code for Buildings	NFFA 78
Electric Power for ADP Installations	NIST 94
Overview of Power Quality and Sensitive Electrical Equipment	NIST SP678
Standard for Safety of Transient Voltage Surge Suppressors	UL 1449

Grounding	IEEE 446, 141, 142, 1100; ANSI/NFPA 70
Powering	ANSI C84.1; IEEE 141, 446, 1100, 1250
Surge protection	IEEE C62, 141, 142; NFPA 778; UL 1449
Harmonics	IEEE C57.110, 519, P519a, 929, 1001
Disturbances	ANSI C62.41; IEEE 1100, 1159, 1250
Life/fire safety	FIPS Pub. 94; ANSI/NFPA 70; NFPA 75; UL 1478, 1950
Mitigation equipment	IEEE 446, 1035, 1100; 1250; NEMA-UPS
Telecommunication equipment	FIPS Pub. 94; IEEE 487, 1100
Noise control	FIPS Pub. 94; IEEE 518, 1050
Utility interface	IEEE 446, 929, 1001, 1035
Monitoring	IEEE 1100, 1159
Load immunity	IEEE 141, 446, 1100, 1159, P1346
System reliability	IEEE 493

IEEE vs IEC

Harmonic environment	None	IEC 1000-2-1/2
Compatibility limits	IEEE 519	IEC 1000-3-2/4 (555)
Harmonic measurement	None	IEC 1000-4-7/13/15
Harmonic practices	IEEE 519A	IEC 1000-5-5
Component heating	ANSI/IEEE C57.110	IEC 1000-3-6
Under-Sag-environment	IEEE 1250	IEC 38, 1000-2-4
Compatibility limits	IEEE P1346	IEC 1000-3-3/5 (555)
Sag measurement	None	IEC 1000-4-1/11
Sag mitigation	IEEE 446, 1100, 1159	IEC 1000-5-X
Fuse blowing/upsets	ANSI C84.1	IEC 1000-2-5
Oversurge environment	ANSI/IEEE C62.41	IEC-1000-3-7
Compatibility levels	None	IEC 3000-3-X
Surge measurement	ANSI/IEEE C62.45	IEC 1000-4-1/2/4/5/12
Surge protection	C62 series, 1100	IEC 1000-5-X
Insulation breakdown	By product	IEC 664

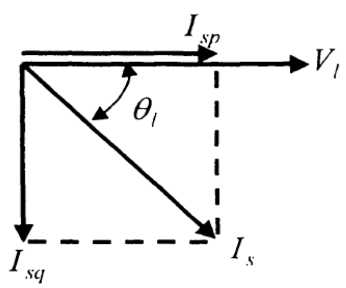
Table 1.2. Some power quality standards of IEC and IEEE

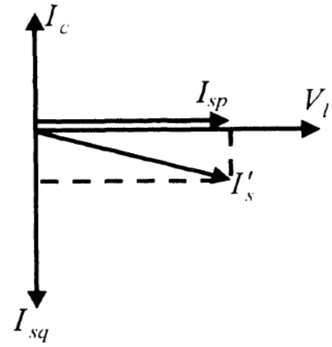
Phenomena	Standards
Classification of power quality	IEC 61000-2-5: 1995 [2], IEC 61000-2-1: 1990 [3] IEEE 1159: 1995 [4]
Transients	IEC 61000-2-1: 1990 [3], IEEE c62.41: (1991) [5] IEEE 1159: 1995 [4], IEC 816: 1984 [6]
Voltage sag/swell and interruptions	IEC 61009-2-1: 1990 [3], IEEE 1159: 1995 [4]
Harmonics	IEC 61000-2-1: 1990 [3], IEEE 519: 1992 [7] IEC 61000-4-7: 1991 [8]
Voltage flicker	IEC 61000-4-15: 1997 [9]

12.List out the major concern of consumer and utility in power quality problem.

POOR LOAD POWER FACTOR

Consider a distribution system in which a source is supplying an inductive load through a feeder. The feeder has a resistance of R_s and a reactance of X_s. The feeder current is denoted by I_s and the load voltage is denoted by V_l. The load power factor is lagging and the power factor angle is denoted by θ_l. The system phasor diagram is shown in Figure 2.13 (a). In this diagram the load current is resolved into a real part $I_{sp} = |I_s|\cos\theta_l$ and a reactive part $I_{sq} = |I_s|\sin\theta_l$. Of these two components, the work done depends only on the real power.





Poor p.f **p.f correction by shunt capacitors**

Now suppose the load power factor is poor, i.e., the load has a large X/R ratio. Then the power factor angle θ_l will be large. This implies that the reactive component of the current is large and hence the magnitude of the load current $|I_s|$ is also large. This will not only cause a significant drop in the feeder voltage but there will also be a large amount of $|I_s|^2R_s$ loss. This loss is associated with high heat dissipation in the feeder. Excessive heat may reduce the life span of the feeder.

To correct the large feeder drop, let us assume that as a remedial action we connect a capacitor in parallel with the load. This capacitor draws a current I_c that is in phase opposition to I_{sq}. The resulting current drawn by the capacitor-load combination is denoted by I'_s. This is shown in Figure 2.13 (b). It can be seen that even though the real component of the current remains the same, the magnitude of the current drawn from the source has reduced considerably. This is because the reactive component of the current drawn has reduced considerably and, as a consequence, the power factor

LOADS CONTAINING HARMONICS

Power Electronics loads are the major source of harmonics in power systems.

It is well known that any nonsinusoidal but periodic signal can be decomposed into a fundamental component (50 or 60 Hz for power systems) and its integer multiples called the harmonic components. The harmonic number usually specifies a harmonic component, which is the ratio of its frequency to the fundamental frequency. For example when the fundamental frequency is 50 Hz, a harmonic with a number of 3 (3^{rd} harmonics) will have a frequency of 150 Hz. The harmonic components that are integer multiples of the 3^{rd} harmonic (e.g., 6^{th}, 9^{th} etc) are called *triplen*. In power systems, the electrical components are symmetrical. Therefore, the current drawn in the positive half cycles is the exact mirror image of the current drawn in the negative half cycles. Such symmetrical waveforms cannot contain any even harmonics. Transformer saturation and rectifier loads are examples of components typically exhibiting these symmetries. There is another form of symmetry in a 3-phase, 3-wire system. Assume that the harmonic current in phases-b and c are identical to that of phase-a but is delayed by $2n\pi/3$ and $4n\pi/3$ respectively where n is the harmonic number. The currents at each triplen frequency are then in phase with each other. Without a neutral they have no return path to flow just like a zero sequence current and thus must individually be zero. The triplen currents may however circulate inside a Δ-connected winding of a transformer. The triplen currents may also be present in a three-phase, four-wire system as the neutral wire provides a path for them to flow. Usually in power system even harmonics are less common. There the harmonics in a three-phase system are of the type ($6q \pm 1$) and $3q$ where $q = 1, 2, 3, \ldots$

UNIT 2

ANALYSIS OF SINGLE PHASE AND THREE PHASE SYSTEM

Single phase linear and non-linear loads – single phase sinusoidal, non-sinusoidal source – supplying linear and nonlinear loads – three phase balanced system – three phase unbalanced system – three phase unbalanced and distorted source supplying non-linear loads – concept of power factor – three phase- three wire – three phase - four wire system.

Part – A

1. What is linear load and non-linear load?

Linear load is electrical load consuming AC power both real power and apparent power with a power factor of 1. Example of linear load is incandescent lamp. Non-linear load generates harmonic currents in addition to the original AC current and its power factor is less than 1.

2. What are the characteristics of linear and non-linear loads?

Linear loads are for example engines, transformers, reactors or capacitors. On the contrary, in the case of non-linear loads, the current is not proportional to the voltage and it fluctuates according to an alternating load impedance.

3. What is linear and non linear circuit examples?

Examples of linear circuits are resistance, resistive circuit, inductor and inductive circuit,capacitor and capacitive circuit. Examples of nonlinear circuits are diode, transformer, iron core, inductor, transistor.

4. Define Impedance.

Impedance is defined as the opposition of circuit to flow of alternating current. It is denoted by Z and its unit is ohms.

5. Define Resonance.

Resonance is defined as a phenomenon in which applied voltage and resulting current are in-phase. In other words, an AC circuit is said to be in resonance if it exhibits unity power factor condition, that means appliedvoltage and resulting current are in phase.

6. What is a Resonant frequency?

The frequency at which resonance occurs is called resonant frequency.
i.e. $X_L=X_C$.

7. What is the series resonance?

The inductive reactance increases as the frequency increases (XL=ωl) but the capacitive reactances decreases with frequency(XC=1/ωc). Thus inductive and capacitive reactances have opposite properties. So, for any LC combination there must be one frequency at which Xl=Xc. This case of equal and opposite reactance is called series resonance.

8. What is a parallel resonance?

The parallel circuit is said to be in resonance, when the power factor is unity. This is true when the imaginary part of the total admittance is zero.

9. Determine the power factor of a RLC series circuit with R=5ohm, XL=8ohm and XC=12ohm.

Cos Φ =R/Z=5/Square root$(R^2-(X_l-X_c)^2$=0.78

10. What are the three types of power used in AC circuits?

i) Real or Active or True power P=EI cosθ ii) Reactive power Q=EI sinθ
iii)Apparent power S=EI

11. Define Real power.

The actual power consumed in an AC circuits is called real power. And P=EI cosθ'

12. Define Reactive power.

The power consumed by the pure reactance (Xl or Xc) in an AC circuit is called reactive power. The unit is VAR. and Q=EI sinθ

13. Define Apparent power and Power factor.

The Apparent power (in VA) is the product of the rms values of voltage and current. S = Vrms Irms The Power factor is the cosine of the phase difference between voltage and current. It is also the cosine of the load impedance. And Power factor = cos φ The p.f is lagging if the current lags voltage (inductive load) and is leading when the current leads voltage(capacitive load).

14. What is meant by Complex power?

Complex power (in VA) is the product of the rms voltage phasor and the complex conjugate of the rms current phasor. As a complex quantity, its real part is real power, P and its imaginary part is reactive power, Q. and S = P + jQ

15. What are the advantages of 3 phase circuits over single phase circuits?

1. Generation, transmission and distribution of 3 phase power is cheaper
2. More efficient 3. Uniform torqueproduction occurs

16. State the relationship between line voltage & phase voltage and line current & phase current of a 3phase delta connected system.

Vph = VL ; Iph = IL / √3

17. State the relationship between line voltage & phase voltage and line current & phase current of a 3phase star connected system.

Vph = VL / √3; Iph = IL

18. Write the expression for the instantaneous values of emfs in a 3 phase circuit.

V_R = Vm sin wt; V_Y = Vm sin (wt-120^0); V_B = Vm sin (wt-240^0)

19. Define power factor.

Power factor is defined as the cosine of angle between voltage and current. If φ is the angle between voltage and current then cos φ is called as the power factor.

20. Explain the concept of balanced load.

The load is said to be balanced when magnitudes of all impedances Zph1, Zph2 and Zph3 are equal and the phase angles of all of them are equal and of same nature either all inductive or all capacitive or all resistive.

21. What is phase sequence?

The order in which the voltage in the three phases reach their maximum positive values is called the phase sequence.

22. Define Phasor and Phase angle.

A sinusoidal wave form can be represented or in terms of a Phasor. A Phasor is a vector with definite magnitude and direction. From the Phasor the sinusoidal wave form can be reconstructed. Phase angle is the angular measurement that specifies the position of the alternating quantity relative to a reference.

23. What are the advantages of 3Φ system?

1.Constant power 2. Higher rating 3. Power transmission economics

24. Which type of connection of 3Φ system is preferred at the point of utilization? Why?

Three phase , 4 wire system are used in utilization system so that either single phase or three phase load can be connected.

25. What is single-phase circuit?

Single-phase power is a two-wire alternating current (ac) power circuit. Typically, there is one power wire—the phase wire—and one neutral wire, with current flowing between the power wire (through the load) and the neutral wire.

26.What is the concept of power factor?

Power factor is an expression of energy efficiency. It is usually expressed as a percentage—and the lower the percentage, the less efficient power usage is. Power factor (PF) is the ratio of working power, measured in kilowatts (kW), to apparent power, measured in kilovolt amperes (kVA).

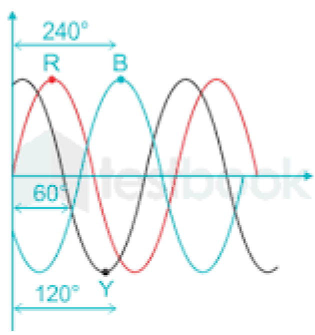
27. What is 3-phase balanced system?

A balanced three-phase voltage or current is one in which the size of each phase is the same, and the phase angles of the three phases differ from each other by 120 degrees. A balanced three-phase network is one in which the impedances in the three phases are identical.

28. What are the types of 3-phase connection?

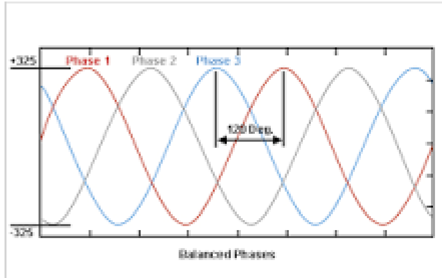
Two types of connections are possible, namely delta (Δ) connection and star or wye (Y) connection. The load and the source can be either in delta or star.

29. What is phase sequence in 3-phase system?



In a three-phase system, the order in which the voltages attain their maximum positive value is called Phase Sequence. There are three voltages or EMFs in the three-phase system with the same magnitude, but the frequency is displaced by an angle of 120° electrically.

30. What is 3-phase voltage balancing?



In a balanced 3 phase ac power system, the voltages are all equal in magnitude and each of the 3 phases are 120 degrees apart. Accordingly, an unbalanced 3 phase ac power system has voltages that are not all equal in magnitude and/or each of the 3 phases are not 120 degrees apart.

31. What is unbalanced three-phase system?

Phase unbalance of a three-phase system exists when one or more of the line-to-line voltages in a three-phase system are mismatched. Three-phase power systems and equipment are intended to operate with phases (Lines) balanced.

32. What is three-phase current unbalance?

For a three-phase supply, current unbalance is defined as the maximum deviation of any current phase from the average current, divided by the average current, often expressed as a percentage. Clear current unbalance - Red phase has a different RMS value compared with the other 2 phases.

33. What is voltage unbalance?

Voltage unbalance is a condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120° phase relationship, or both. The degree of unbalance is usually defined by the ratio of the negative sequence voltage component to the positive sequence component.

34. What is a type of electrical distortion caused by non-linear loads?

When there are nonlinear loads, the current does not look like the voltage on a waveform. Harmonics come from the loads so in this case we have current that is affecting the voltage. As we pull that current through the system, the nonlinear load creates current distortion, which then causes voltage distortion.

35. What is the effect of nonlinear distortion?

Nonlinear distortion results in a change in the signal's amplitude and phase as well as the generation of signal components at frequencies that weren't present in the input signal. This is often a more severe effect in real applications than linear distortion is.

36. What is a 3 phase 3-wire system?

Three-phase power is a three-wire ac power circuit with each phase ac signal 120 electrical degrees apart. Residential homes are usually served by a single-phase power supply, while commercial and industrial facilities usually use a three-phase supply.

37. How do you calculate the power of a 3phase 3-wire system?

The formula for power of a 3-phase circuit is Power = Voltage (V) x Current (I) x Power Factor (PF) x square root of three. If we assume the load on the circuit is resistive only, power factor is unity (or one) which reduces the formula to P = V x I x square root of three.

38. What is the voltage of a 3 phase 3-wire system?

The simplest three-phase system is the 3-wire Delta configuration, normally used for transmission of power in the intermediate voltage class from approximately 15,000 volts to 600 volts.

39. What is 3-phase 4 wire supply system?

Distribution of electrical energy to consumers in a town or village is carried out by the three-phase, four-wire system. In this country, the secondary windings of a three-phase star-connected transformer usually have a line voltage output of 415 V and so the voltage between any line and the neutral conductor is 240 V.

40. What is a 3-phase 4 wire system supplies a balanced star load?

The balanced star-connected system contains a neutral point and it is a three-wire system / four-wire system. As it is balanced, there is no current flow in neutral. So, sometimes no need to go for 4 wires also. But a star-connected system that has a neutral wire is considered an unbalanced system.

41. Which connection is best suited for 3-phase 4 wire system?

Delta-star connected distribution transformers are widely used in low power distribution for 3 phase 4 wire supply.

42. What is the advantage of 3-phase 4-wire system?

The 3 phase 4 wire system allows a selection of 2 voltages and allows small loads to be connected to a lower voltage while large loads can be connected to a higher voltage.

PART-B

SINGLE PHASE LINEAR AND NON-LINEAR LOADS

1. Write short notes on linear and non-linear loads.

(OR)

Describe in detail about linear and non-linear loads.

AC electrical loads are referred to either as linear or non-linear depending on how they draw current from the mains power supply waveform.

Basically Linear & Non-linear types of loads are being extensively used in any electrical load scenario. Linear load is defined as whose impedance is constant throughout its applied voltage cycle. Resistive, inductive & capacitive loads are coming under linear category. Whereas, non-linear load is defined as whose impedance is continuously varying to its applied voltage cycle. SMPS, electronic equipment, SCR/IGBT devices, UPS systems etc are coming under non-linear category. However, harmonics are distortion of the normal electrical current waveform, generally transmitted by nonlinear loads that draw a non sinusoidal current from a sinusoidal voltage source. A harmonic current increases power system heat losses, reduces system efficiency. Harmonic currents can have a significant impact on electrical distribution systems and the facilities they feed.

Switch-mode power supplies (SMPS), variable speed motors and drives, photocopiers, personal computers, laser printers, fax machines, battery chargers and UPSs are examples of nonlinear loads. Single-phase non-linear loads are prevalent in modern office buildings, while three-phase, non-linear

loads are widespread in factories and industrial plants. Harmonics should not be confused with spikes, dips, impulses, oscillations or other forms of transients.
Power system harmonics is an area that is receiving a great deal of attention recently. The increase in proportion of non-linear load has prompted more stringent recommendations (IEEE Std. 519 & IEC61000-4-7) and stricter limits imposed by utilities.

Sine waves are symmetric about origin. Figure 1 shows various harmonic contents like 3rd, 5th & 7th & the resultant yellow colour appears to be square wave. A square wave is actually combination of infinite series of sine wave harmonics, added together. With a **linear load**, the relationship between the voltage and current waveforms are sinusoidal and the current at any time is proportional to the voltage (Ohm's law). Examples of linear loads would include transformers, motors and capacitors. On the other hand, with a **non-linear load** the current isn't proportional to the voltage and it fluctuates based on the alternating load impedance. Common examples of non-linear loads include rectifiers, variable-speed drives and electronic devices such as computers, printers, TVs, servers and telecoms systems that use switched-mode power supply (SMPS) power conversion technologies. They are also typically found with blade servers.Non-linear loads draw in currents in abrupt short pulses. These pulses distort the current waveforms, which in turn generates harmonics that can lead to power problems affecting both the distribution system equipment and the loads connected to it. Harmonics can cause problems such as distortion of the mains supply voltage, equipment overheating, nuisance tripping of circuit breakers, and misfiring of variable speed drives.

HARMONICS BECAUSE OF LINEAR LOAD

FFT analysis result with linear load when connected to IEEE 9 bus system the total harmonic distortion becomes 0.01%. It shows that with the linear load the distortion present in the system is very less as current varies proportional to the voltage. Here, in this case three phase series RLC load is considered as a linear load as in case of three phase series RLC load current varies linearly with the voltage. Here the THD is calculated at the voltage at bus 6. This results show that the total harmonic distortions present in the line voltage is very less means negligible in case of linear load.

HARMONICS BECAUSE OF NON-LINEAR LOAD

Harmonics are one of the major power quality concerns. Harmonics cause distortions of the voltage and current waveforms, which have adverse effects on electrical equipment.

Some examples of nonlinear loads are:

• Electric arc furnace

• Adjustable drive systems

• Rectifiers • Switching mode power supplies

• Computers, copy machines, and television sets

• Static var compensators (SVCs)

• HVDC transmission

• Electric traction

• Wind and solar power generation

• Battery charging and fuel cells

Voltage current characteristics with diode bridge rectifier and electric arc furnace are shown in the fig. which shows clearly that with non linear load, current does not follow the linear relationship with the voltage. Here the study of harmonics with non linear load is done when the load is connected in the IEEE 9 bus system.

The diode bridge rectifier as non linear load is connected at the bus 6and after that FFT analysis is done for power quality analysis. The result with the diode bridge rectifier is shown in the form of FFT analysis in fig.4. It is found that with the diode bridge rectifier which is non linear load total harmonic distortion founds to be more i.e. 21.68%. DC components present in the voltage are 30.36%. Hence from it is clear that the numbers of harmonic present in the system are more and the power quality gets reduced because of diode bridge rectifier. As we know all the industries demands more power from the generating companies or from other utility as every industry have to supply various load at its terminal. In many industries electric arc furnace causes more power quality problems. It produces non linear current in the supply system because of that the power quality of the whole electrical system gets reduced. Hence, the problem with power quality because of electric arc furnace is studied and the total harmonic distortion (THD) is observed with the help of FFT analysis. total harmonic distortion in case of linear load are negligible but in case of non linear load diode bridge rectifier and electric arc furnace are observed to be 21.68 % and 85.41%. This shows that in case of electric arc furnace power quality gets reduced to very large extent.

SINGLE PHASE SINUSOIDAL AND NON SINUSOIDAL SOURCE

2. **With suitable example explain in detail about single phase sinusoidal and non-Sinusoidal source for linear and non linear loads.**

SINGLE PHASE SINUSOIDAL SOURCE FOR LINEAR LOAD.

A sinusoidal voltage source (dependent or independent) produces a voltage that varies as a sine wave with time. A sinusoidal current source (dependent or independent) produces a current that varies with time. The sinusoidal varying function can be expressed either with the sine function or cosine function.

SINGLE PHASE NON-SINUSOIDAL SOURCE FOR NON-LINEAR LOAD

Non-sinusoidal waveforms are prominent in the world of electronics and they are readily synthesized. A non-sinusoidal waveform can be constructed by adding two or more sine waves. The synthesis of a specific non-sinusoidal waveform is a matter of combining signals of the appropriate frequency, amplitude and phase

A non-sinusoidal waveform is one that is not a sine wave and is also not sinusoidal (sine-like). This may sound like a minor distinction but actually there are some substantive implications.

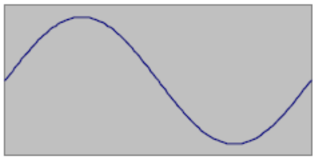
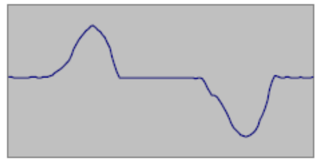
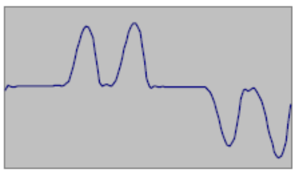
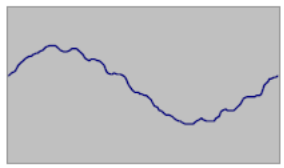
A sine wave is the graph of the sine function, usually with time as the independent variable. A cosine wave is sinusoidal. It has the same form but it has been phase-shifted one-half π radians.
A non-sinusoidal waveform is typically a periodic oscillation but is neither of these. Some examples are triangle waves, rectangle waves, square waves, trapezoid waves and saw tooth waves.

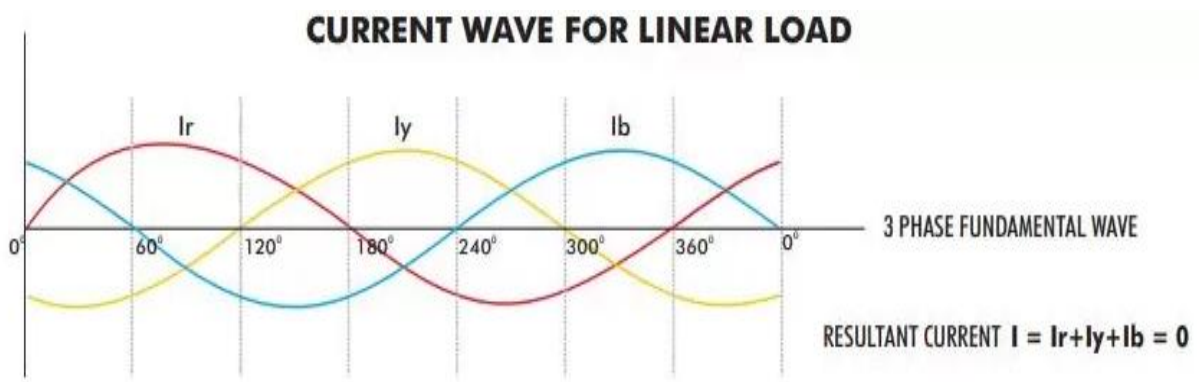
Non-sinusoidal waveforms are prominent in the world of electronics and they are readily synthesized. A non-sinusoidal waveform can be constructed by adding two or more sine waves. The synthesis of a specific non-sinusoidal waveform is a matter of combining signals of the appropriate frequency, amplitude and phase. In this manner square waves and similar non-linear waveforms can be constructed and represented graphically.

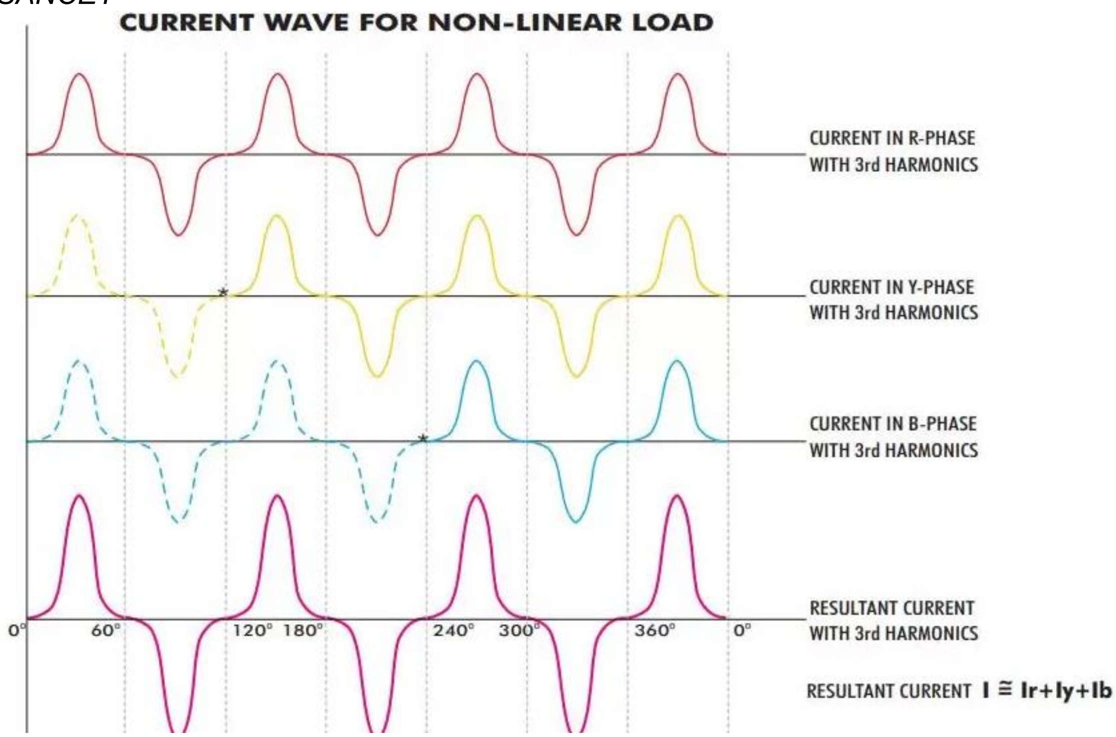
Such waveforms, known as complex waves, consist of one fundamental frequency and one or more harmonic frequencies. By convention, the fundamental wave is the lowest frequency and generally the highest amplitude.

Harmonics are what give complex waves their characteristic shape. Harmonics are integer multiples of the fundamental frequency. The integer may be odd or even, i.e. divisible by two.

Normally the greatest amount of power is in the fundamental. A square wave, to take one example of a non-sinusoidal waveform, has rapid rise and fall times which result in numerous high-order harmonics in its spectrum display. Even at low frequencies it has many high-frequency characteristics. For this reason, the harmonics contain a significant amount of power. The irregular traces along the bottoms of the frequency domain displays visible in the accompanying image are what is known as the noise floor, variously attributed to atomic motion in the oscilloscope circuitry and music of the spheres.

FIXED SPEED INDUCTION MOTOR (LINEAR LOAD)	***PERSONAL COMPUTER (NON-LINEAR)***
	
VFD with 6-pulse Rectifier (Non-linear)	**VFD with 12-pulse Rectifier (Non-linear)**
	





LINEAR AND NON LINEAR LOADS

3.State the difference between linear and non linear loads.

DEFFERANCE BETWEEN LINEAR LOADS AND NON-LINEAR LOADS

S.NO.	LINEAR LOADS	S.NO.	NON-LINER LOADS
1.	Ohms law is applicable	1.	Ohms law is not applicable
2.	Crest Factor= $\frac{\text{I Peak}}{\text{I RMS}} = \sqrt{2} = 1.41$	2.	Crest Factor could be 3 to 4
3.	Power factor= $\frac{\text{Watts}}{\text{V X I}} = \text{Cos } \varnothing$	3.	Power factor= $\frac{\text{Watts}}{\text{V X I}} \neq \text{Cos } \varnothing$ = Displacement factor X Distortion Factor
4.	Load current does not contain harmonics.	4.	Load current contains all ODD harmonics.
5.	Could be inductive or capacitive.	5.	Can't be categorized. As leading or lagging Loads.
6.	Resistive, Inductive or capacitive	6.	Usually an equipment with Diode and Capacitor.
7.	Zero neutral current if 1 Ph. loads are equally balanced on 3Ph. Mains (Vector sum of line current)	7.	Neutral current could be 2.7 times the line current even if 1Ph. loads are equally balanced on 3 Ph. Mains
8.	May not demand high inrush currents while starting.	8.	Essentially very high inrush current (20 time of I Normal) is drawn while starting for approx. One cycle.

4. Explain about Single Phase Circuit .

Single phase circuit components: – Voltage or current sources – Impedances (resistance, inductance, and capacitance) – The components are connected in series or in parallel. • The figure shows a simple circuit where a voltage source (generator) supplies a load (resistance and inductance in series).

Single phase AC supply (i.e, 230 V, 50 Hz) is used only for some application. Ex: House-hold applications. For industrial applications (or) for large consumers such a single phase voltage is very less and not enough to supply those loads. For supplying those loads we need a three phase voltage. A machine which generates three phase AC voltage is called to be three phase alternator. To develop three phase voltage, there will be three armature windings in an alternator. From three separate windings, three separate AC voltages will be available having same magnitude and frequency but they will have a phase difference of □360□/3□ □ 120□, with respect to each other. Also polyphase AC voltage can be generated by ‘*n*’ number of armature windings in the alternator with a phase difference of □360□/*n*□. But in practice only three phase electrical supply is found to be more economical and it has certain advantages over other polyphase systems. Hence three phase electrical supply is very popularly used for many of the applications.

BALANCED THREE-PHASE SYSTEM

5. Discuss about balanced three phase system.

In the case of the phase balance system, the values of current voltage can be found at any location in the system through the use of equivalent circuitry.

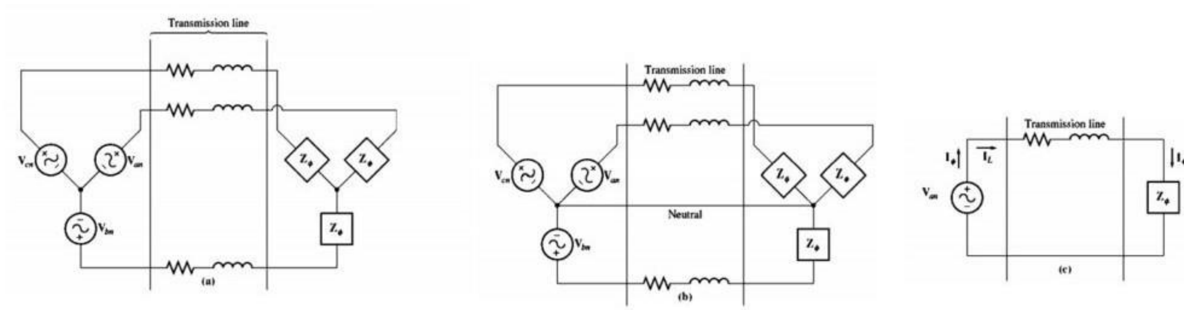
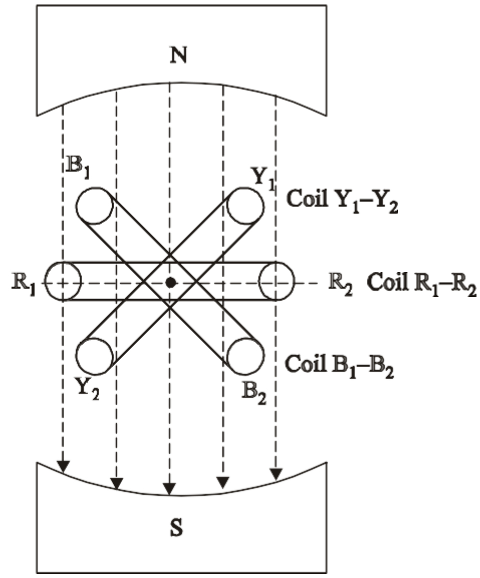


diagram indicates in this circuity generator is delivering power to such load that is also in wye connection arrangements like a generator.
In the case of a balanced system, there can be use of neutral wire but will affect the system due to the balance system 0 current flow in that wire. Can see in a diagram denoted as b
We can see that there is every phase has the same value with angle difference of one-twenty degrees.
In this system, there is easy to discuss the behavior of one phase and after that compare it other phases to see the results that will be similar.
Here is neutral wire is a link to send the current flow to the generator from the load.

Advantages of Three phase system

1. The output of three phase machine is always greater than single phase machine ofsame size, which results in reduced cost.
2. For transmission and distribution, three phase system needs less copper than a singlephase system. Hence it is very economical.
3. By using three phase system, we can create rotating magnetic field, hence threephase induction motors are self-starting.
4. Similarly single phase induction motors are non self-starting motors. Also its performanceis poor due to fluctuation and decreased output than three phase induction motor.
5. Single phase system itself is usually obtained from three phase system, not generatedindividually.
6. Power factor of three phase system is better than the single phase system.

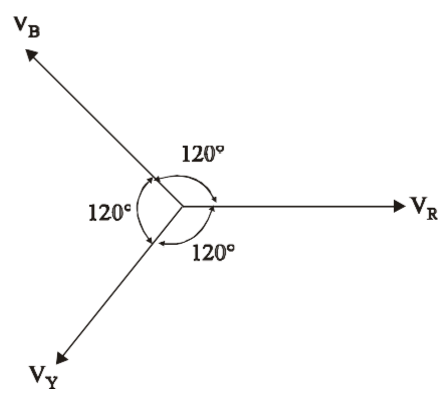
Generation of three phase voltage involves three individual armature windings which are displaced by 120°. Arrangement of three coils to generate three phaseac voltage is shown in fig 9.1.



Arrangement of three coils to generate three phase AC voltage.

Let v_R, v_Y and v_B be the voltages induced in three windings R, Y and B respectively. All are alternating voltages will have same magnitude and frequency as they are rotated at uniform speed.

When v_R is taken as reference phasor, v_Y logs the voltage v_R by 120° and v_B leads v_R by 120°. The vector representation and phasor representation of these three voltages is represented in fig.



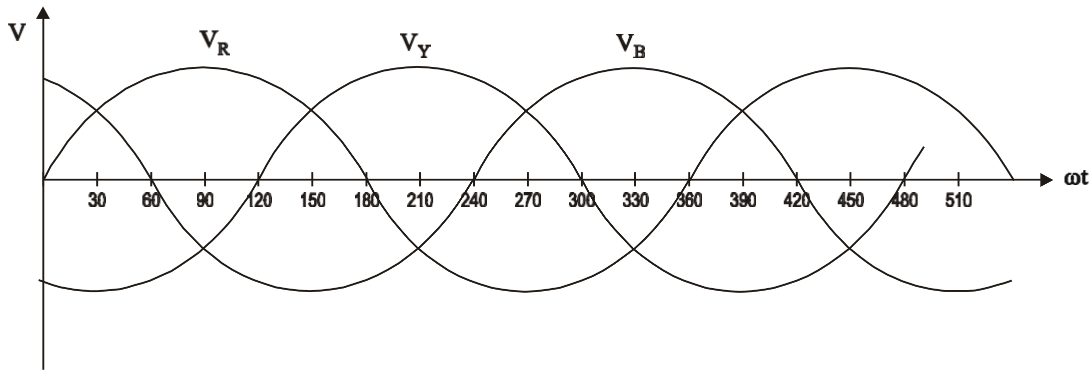
Vector representation of 3 phase AC voltage.

The equations for the induced voltages are:

$$v_R = V_m \sin \omega t$$

$$v_Y = V_m \sin (\omega t - 120°)$$

$$v_B = V_m \sin (\omega t - 240°) = \sin (\omega t + 120°)$$



Phasor representation of 3 phase AC voltage

The coils in the alternator will be rotated in anti clockwise direction, also the vectors of three coil voltages will be rotated in anticlockwise direction. If we add these three voltages vectorially, we can see an important result of any three phase voltage system. Now,

$$\bar{v}_R + \bar{v}_Y + \bar{v}_B = V_m \sin \omega t + V_m \sin (\omega t - 120°) + V_m \sin (\omega t + 120°)$$

$$= V_m [\sin \omega t + \sin \omega t \cos 120° - \cos \omega t \sin 120° + \sin \omega t \cos 120°$$

$$+ \cos \omega t \sin 120°]$$

$$= V_m [\sin \omega t + 2 \sin \omega t \cos 120°]$$

$$= V_m \left[\sin \omega t + 2 \sin \omega t \left(-\frac{1}{2} \right) \right]$$

$$= V_m [0]$$

$$\bar{V}_R + \bar{V}_Y + \bar{V}_B = 0$$

Thus, the vectorial addition of individual phase voltages at any instant in a three phase voltage system will be always zero.

DEFINITIONS RELATED TO THREE PHASE SYSTEM

6.What are the terms related to three phase system.

1. *Symmetrical System*

A three phase system in which the three phase voltages are having same magnitude, frequency and displaced from each other by 120° phase angle is called as symmetrical system.

2. *Phase Sequence*

The sequence in which the voltages of a three phase system, reaches their maximum positive value is called to be phase sequence. Generally the phase sequence is $R - Y - B$. This phase sequence is important in determining the direction of induction motors, lagging of phases, leading of phases etc.,

In 1 ϕ system, two wires are sufficient for transmitting voltage to another end i.e., phase and neutral. But in case of 3 ϕ system, two ends of each phase are available to supply voltage to the load. If all six terminals are used.

Independently to supply voltage to the load, then total six wires will be required and it will be very much costly.

To reduce the cost of reducing the number of windings, the three windings are interconnected in a particular fashion. This gives different three phase connections.

Star Connection

The star connection is formed by connecting starting ends of all the three windings together. This common point is called as neutral point. The remaining ends are left free for connection purpose.

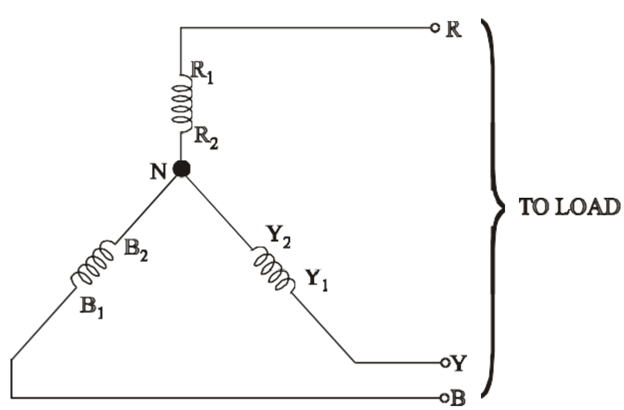


Fig. Star Connection

Delta Connection

It is formed by connecting one end of winding to starting end of other and connections are continued to form closed loop.

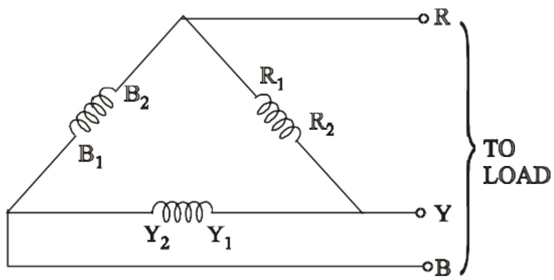


Fig. 9.5 Delta Connection

Concepts of Line voltage and Line current

1. *Line voltage and Line current*

The potential difference between any two wires of supply is called line voltage and current passing through any line is called line current.

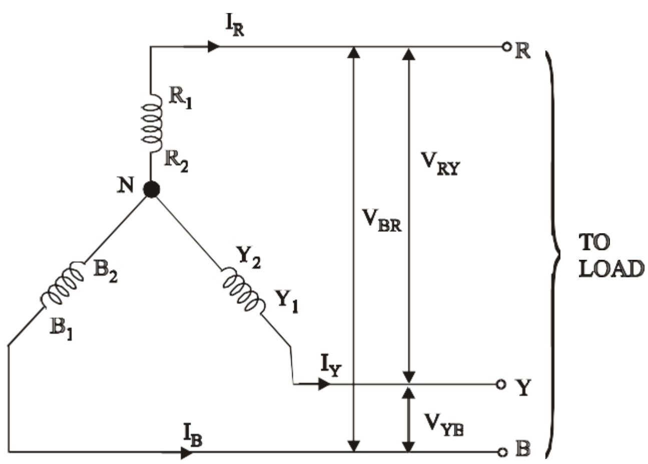


Fig. 9.6 Star connected system

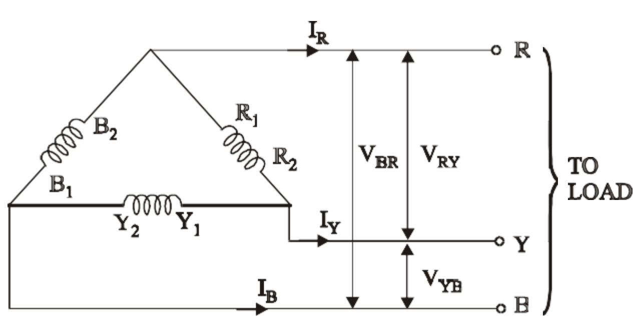


Fig. Delta connected system

V_{RY}, V_{YB} and V_{BR} are line voltages.

I_R, I_Y and I_B are line currents.

Concepts of Phase voltage and Phase current

1. *Phase Voltage*

The voltage measured between any phase and neutral point is called as phase voltage.

2. *Phase Current*

The current passing through any branch of the three phase load is called phase current.

BALANCED LOAD

7.Explain star connected balanced load.

The load is said to be balanced when magnitude of all the impedance Z_{Ph1}, Z_{Ph2} and Z_{Ph3} are equal and phase angle of all of them are equal, irrespective of load type.

Star Connected Load

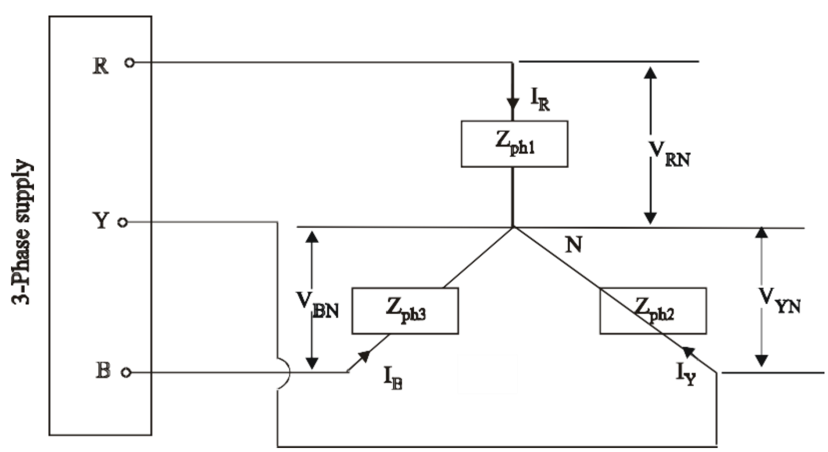


Fig. Star connected Load

In the above diagram,

V_{RN}, V_{YN} and V_{BN} are phase voltages and I_R, I_Y and I_B are phase current.

For star connected load, $I_{\text{line}} = I_{\text{phase}}$

ie, $I_L = I_R = I_Y = I_B = I_{ph}$

$I_L = I_{ph}$ for star connected load

$$V_{ph} = V_{RN} = V_{YN} = V_{BN}$$

$$\overline{V_{RY}} = \overline{V_{RN}} + \overline{V_{NY}}$$

But $\overline{V_{NY}} = -\overline{V_{YN}}$

$$\therefore \quad \overline{V_{RY}} = \overline{V_R} - \overline{V_Y} \qquad \text{... (9.1)}$$

Similarly,

$$\overline{V_{YB}} = \overline{V_{YN}} + \overline{V_{NB}} = \overline{V_{YN}} - \overline{V_{BN}}$$

$$\overline{V_{YB}} = \overline{V_Y} - \overline{V_B} \qquad \text{... (9.2)}$$

And $\overline{V_{BR}} = \overline{V_B} - \overline{V_R}$ ... (9.3)

(i) For star connected load,

$$Z_{\text{ph}} = \frac{V_{\text{ph}}}{I_{\text{ph}}}$$

The phase angle ϕ is the angle between V_{ph} and I_{ph}

If $Z_{\text{ph}} = R + jX_L$, then the current lags V_{ph} by the angle ϕ where $\phi = \tan^{-1}(X_L/R)$

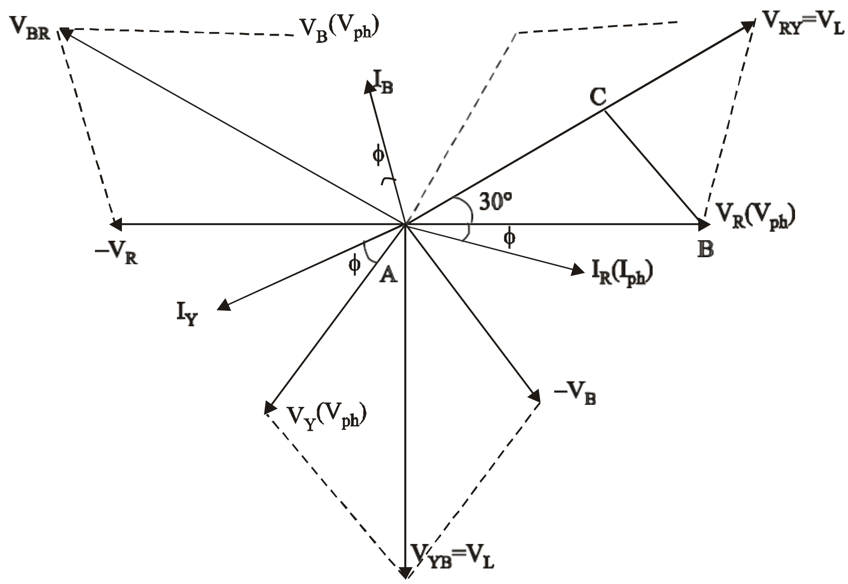


Fig. Vector diagram for balanced star connected load

If $Z_{ph} = R - jX_C$, then the current leads V_{ph} by the angle

$$\phi = \tan^{-1}(X_C/R)$$

Using above condition, draw the phasor diagram for star connected inductive load.

In ΔABC,

$$\cos 30 = \frac{AC}{AB}$$

$$\frac{\sqrt{3}}{2} = \frac{V_{RY}/2}{V_R}$$

$$V_{RY} = \sqrt{3}\, V_R$$

$$V_R = \frac{V_{RY}}{\sqrt{3}}$$

In general,

$$\boldsymbol{V_{ph} = \frac{V_{line}}{\sqrt{3}}}$$

$$\boxed{\boldsymbol{V_{line} = \sqrt{3}\, V_{ph}}}$$

The power consumed in each phase is single phase power.

So, $P_{ph} = V_{ph} I_{ph} \cos \phi$

In a 3ϕ system,

$\therefore$ Total power, $P_T = 3\, P_{ph}$

$$P_T = 3\, V_{ph}\, I_{ph} \cos \phi$$

$$P_T = 3\, V_l\, I_l \cos \phi/\sqrt{3}$$

$$\boldsymbol{P_T = \sqrt{3}\, V_L\, I_L \cos \phi}$$

Problems for balanced starconnected loads

EXAMPLE	1

In a balanced, three phase star connected system, the current through one of the phasesis $(10\ \angle 20°)$ A. Find the value of the three line currents. **(AU-June/July-09)**

Let, Current in R phase be,

$$I_R = I\ \angle\phi = (10\ \angle 20°)\ \text{A}$$

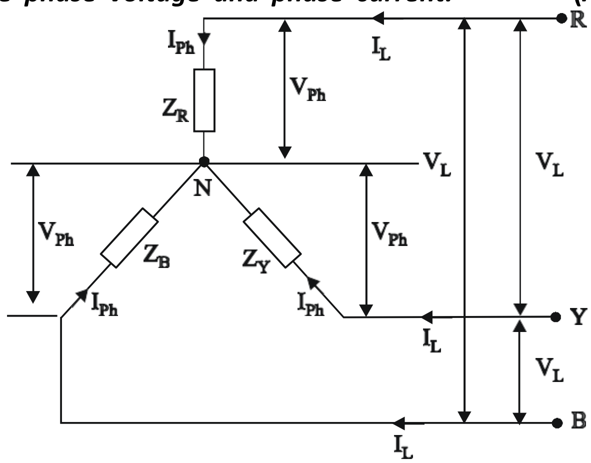
Then,

$$I_Y = (I\ \angle\phi - 120°) = (10\ \angle -100°)\ \text{A}$$

$$I_B = (I\ \angle\phi - 240°) = (10\ \angle -220°)\ \text{A}$$

EXAMPLE	2

A three phase balanced star connected load has 500 V line to line voltage and 10 A line current. Determine the phase voltage and phase current. **(AU-June/July-09)**



$I_L = 10$ A (Given)

$V_L = 500$ V (Given)

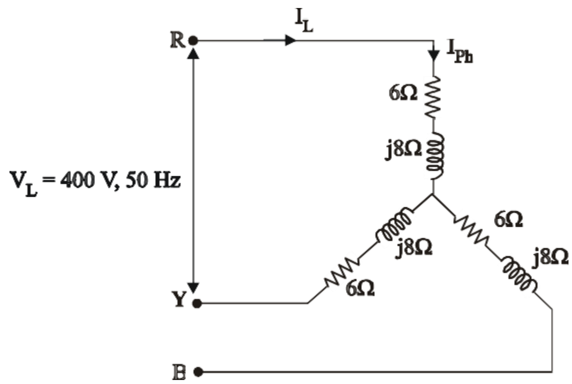
For star connection, $I_L = I_{ph} = 10$ A

For star connection, Phase voltage, $V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{500}{\sqrt{3}}$

$V_{ph} = 288.68$ V

EXAMPLE	3

A star connected load has $(6 + j8)\,\Omega$ ***impedance per phase. Determine the line current and total power, if it is connected to 400 V, 3 phase, 50 Hz supply.*** (AU-June-2011,Dec-2010)



Phase voltage for star connection $V_{ph} = V_L / \sqrt{3} = 400 / \sqrt{3}$

$$= 230.94 \text{ V}$$

Phase impedance, $Z_{ph} = 6 + j8 = (10 \angle 53.13°)\ \Omega$

Phase current, $I_{ph} = V_{ph} / Z_{ph} = 230.94/10$

$$= 23.09 \text{ A}$$

Line Current for star connection $I_L = I_{ph} = 23.09$ A

Total Power, $P = \sqrt{3}\ V_L I_L \cos\phi$

$$= \sqrt{3} \times 400 \times 23.09 \times \cos(53.13°)$$

$$P = 9598.86 \text{ W} = 9.6 \text{ kW}$$

EXAMPLE	4

A balanced star connected load of $(4 - j6)\ \Omega$ impedance is connected to 400 V 3 phase supply. What is the power and power factor? **(AU-April/May-2011)**

(i) Power factor, $\cos\phi = \dfrac{R}{Z} = \dfrac{4}{\sqrt{4^2 + 6^2}} = 0.55$

Phase voltage, $V_{ph} = V_L/\sqrt{3} = 230.94$ V

$I_{ph} = V_{ph}/Z_{ph}$

$$= \frac{230.94}{7.2\angle -56.31°}$$

$I_{ph} = (32.08\angle 56.31°)$ A

For star connection, Line current $I_L = I_{ph} = (32.08\angle 56.31°)$ A

Power, $P = \sqrt{3}\, V_l I_L \cos\phi$

$= \sqrt{3} \times 400 \times 32.08 \times 0.55$

$\Rightarrow P = 12.22$ kW

EXAMPLE	5

A 300 V sinusoidal AC supply is applied to a 50 Ω resistor. Determine the peak RMS and average values of the current through the resistor. Also calculate the power dissipated in the resistor. **(AU-June-11)**

$$I_{rms} = \frac{V_{rms}}{R} = \frac{300}{50} = 6 \text{ A}$$

We know that,

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

So, Peak (or) maximum value of current is,

$I_m = I_{rms} \times \sqrt{2}$

$I_m = 6 \times \sqrt{2}$

$I_m = 8.49$ A

Then,

$$I = \frac{I_m}{} = \frac{8.49}{}$$

avg π π

$I_{avg} = 2.7$ A

Power dissipated in the resistor, $P = I_{rm}^2 \times R$

$$= 6^2 \times 50$$

$$P = 1800 \text{ W}$$

$$P = 1.8 \text{ kW}$$

EXAMPLE	6

A three phase balanced load has 10 Ω resistance in each of its phases. The load is supplied by a 220 V, 3-phase source. Calculate the power absorbed by the load if it is connected in Wye. Calculate same if it is connected in delta. **(AU-May-2009)**

Star connection (or) Wye connection:

Phase Voltage Vph $V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{220}{\sqrt{3}}$

$$V_{ph} = 127.02 \text{ V}$$

Phase Current, $I_{ph} = \frac{V_{ph}}{R_{ph}} = \frac{127.02}{10} = 12.7 \text{ A}$

Phase Power, $P_{Ph} = V_{ph} I_{ph} \cos\phi$

$$= 127.02 \times 12.7 \times 1$$

[∵ Resistive load]

$$P_{ph} = 1613.15 \text{ W}$$

Total Power, $P = 3 \times P_{Ph} = 3 \times 1613.15$

$$P = 4839.45 \text{ W}$$

Phase Voltage, $V_{Ph} = V_L = 220 \text{ V}$

Phase C $I_{ph} = \frac{V_{Ph}}{R_{Ph}} \quad \frac{220}{10}$

=22A

Phase Power, $P_{Ph} = V_{Ph} I_{Ph} \cos\phi$

$= 220 \times 22 \times 1$ [$\because$ Resistive load]

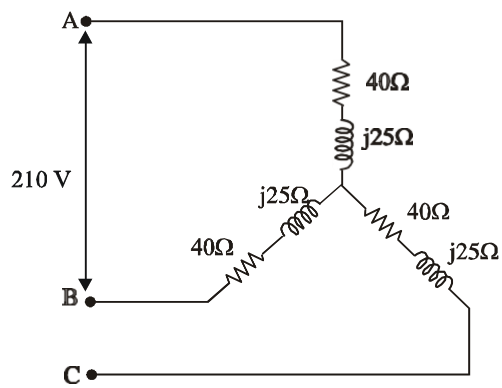
$P_{Ph} = 4840$ W

Total Power, $P = 3 \times P_{Ph} = 3 \times 4840$

$P = 14520$ W

EXAMPLE	7

A balanced star connected load with a phase impedance of $(40 + j25)\ \Omega$ is supplied by a balanced, positive sequence $\Delta -$ connected source with a line voltage of 210 V. Calculate the phase currents. Use V_{ab} as reference. **(AU-May-06)**



$V_{ab} = 210\ \angle 0°\ \text{V}$ $\quad Z_{an} = Z_{bn} = Z_{cn} = Z_{Ph} = 40 + j25$

$V_{bc} = 210\ \angle -120°\ \text{V}$ $\quad Z_{Ph} = (47.17\ \angle 32°)\ \Omega$

$V_{ca} = 210\ \angle -240°\ \text{V}$

Phase Voltage, $V_a = \dfrac{210\ \angle 0°}{\sqrt{3}} = (121.24\ \angle 0°)\ \text{V}$

$V_b = \dfrac{210\ \angle -120°}{\sqrt{3}} = (121.24\ \angle -120°)\ \text{V}$

$V_{cn} = \dfrac{210\ \angle -240°}{\sqrt{3}} = (121.24\ \angle -240°)\ \text{V}$

Phase Current, $I_a = \dfrac{V_{an}}{Z_{Ph}} = \dfrac{121.24\ \angle 0°}{47.17\ \angle 32°}$

$I_a = (2.57\ \angle -32°)\ \text{A}$

$I_a = (2.18 - j1.36)\ \text{A}$

$$\Rightarrow I_b = \frac{V_{bn}}{Z_{Ph}} = \frac{121.24\angle -120^\circ}{47.17\angle 32^\circ} = (2.57\angle -152^\circ)\ \text{A}$$

$$I_b = (-2.27 - j1.21)\text{ A}$$

$$\Rightarrow I_b = \frac{V_{cn}}{Z_{Ph}} = \frac{121.24\angle -240°}{47.17\angle 32°} = (2.57\angle -272°)\text{ A}$$

$$I_c = (0.09 + j2.57)\text{ A}$$

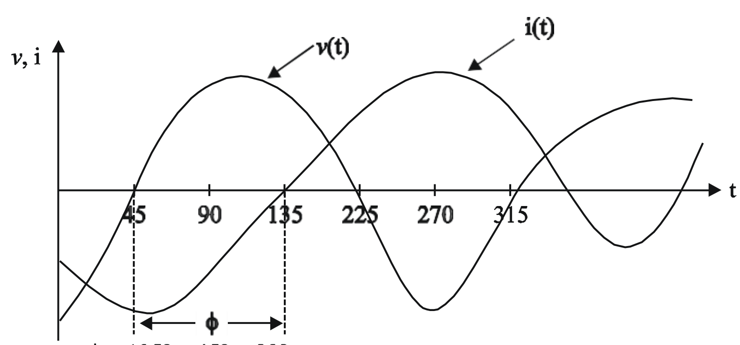
Not For balanced star connected load, phasor sum of the phase currents is zero.

i.e., $I_a + I_b + I_c = 0$

EXAMPLE	8

Calculate the power factor, if $v(t) = V\sin(\omega t - 45°)$ and $i(t) = I\sin(\omega t - 135°)$.

(AU-May-2009)



Power Factor, $\cos\phi = \cos 90°$

$\cos\phi = 0$

EXAMPLE	9

A balanced star-connected load of $(4 + j3)\,\Omega$ per phase is connected to a balanced 3-phase 400 V supply. Find the (i) Total active power (ii) Reactive power (iii) Total apparent power. **(AU-June/July-'09,May-'07)**

Impedance per phase, $|Z_{Ph}| = \sqrt{4^2 + 3^2} = 5\,\Omega$

Power Factor, $\cos\phi = \frac{R_{ph}}{Z_{Ph}} = \frac{4}{5} = 0.8$

$\sin\phi = 0.6$

Phase voltage, $V_{ph} = V_L/\sqrt{3}$

$= 400/\sqrt{3}$

$= 230.94$ V

Phase Current, $I_{ph} = V_{Ph}/Z_{Ph}$

$= 230.94/5$

$= 46.19$

A For star connection, $I_L = I_{Ph} = 46.19$ A

Active Power, $P = 3 V_L I_L \cos\phi$

$= \sqrt{3} \times 400 \times 46.19 \times 0.8$

$P = 25601.1$ Watts

Reactive Power, $Q = \sqrt{3} V_L I_L \sin\phi$

$= \sqrt{3} \times 400 \times 46.19 \times 0.6$

$Q = 19200.82\, VA_r$

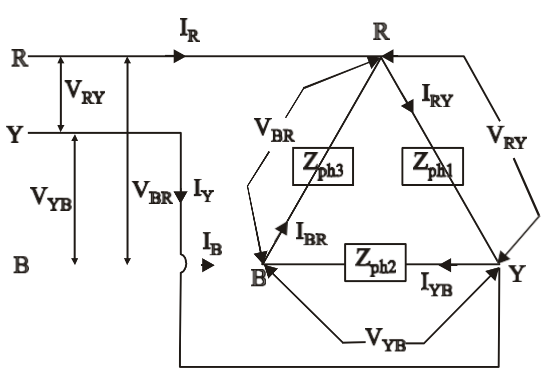
Apparent Power, $S = \sqrt{3} V_L I_L$

$= \sqrt{3} \times 400 \times 46.19$

$S = 32001.37$ VA

Delta Connected Load

8.Explain Delta connected balanced load.



Delta Connected Load

From Fig.

$\Rightarrow V_{\text{line}} = V_{RY} = V_{YB} = V_{BR}$

$\Rightarrow V_{\text{phase}} = V_{RY} = V_{YB} = V_{BR}$

$\Rightarrow I_{\text{line}} = I_R = I_Y = I_B$

$\Rightarrow I_{\text{phase}} = I_{RY} = I_{YB} = I_{BR}$

Also,

$$I_R = I_{RY} - I_{BR} I_Y$$

$$= I_{YB} - I_{RY}$$

$$I_B = I_{BR} - I_{YB}$$

So,

$$V_{\text{line}} = V_{\text{phase}}$$

$\boldsymbol{V_L = V_{ph}}$ for delta connected load.

Using above condition, draw the phasor diagram for star connected inductive load.

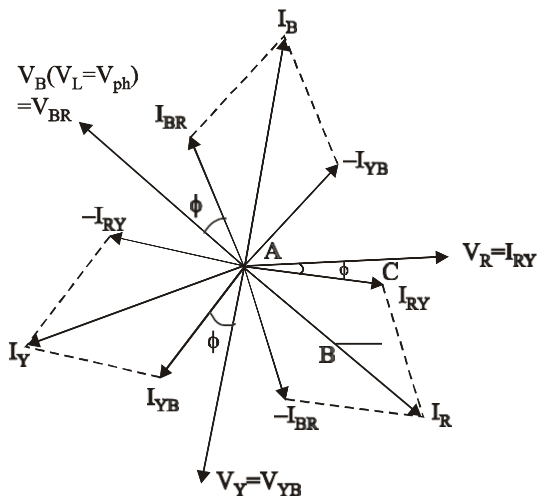


Fig. 9.11 Phasor diagram - star connected load

In ΔABC, $\cos 30° = \dfrac{AB}{AC}$

$$\frac{\sqrt{3}}{2} = \frac{I_R/2}{I_{RY}}$$

$$I_{RY} = \frac{I_R}{\sqrt{3}}$$

Thus, $$I_{\text{phase}} = \frac{I_{\text{line}}}{\sqrt{3}}$$

$$\boldsymbol{I_{ph} = \frac{I_L}{\sqrt{3}}}$$

$$I_{Line} = \sqrt{3}\ I_{ph}$$

Power consumed by each phase,

$$P_{ph} = V_{ph} I_{ph} \cos \phi$$

In a 3ϕ system,

$\therefore$ Total power, $P_T = 3 P_{ph}$

$$P_T = 3 V_{ph} I_{ph} \cos \phi$$

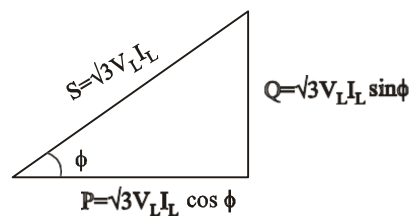


Fig. 9.12

$$P_T = 3 V_L \cdot \frac{I_L}{\sqrt{3}} \cdot \cos \phi$$

$$\boldsymbol{P_T = \sqrt{3} V_L I_L \cos \phi}$$

Total apparent power, $S = 3 \times$ Apparent power/ph

$$S = 3 V_{ph} \cdot I_{ph}$$

$$S = 3 \frac{V_L}{\sqrt{3}} \cdot I_L$$

$$S = \sqrt{3} V_L I_L (VA)$$

Total real (or) Active power, $P = \sqrt{3} V_L I_L \cos \phi$ (W)

Total Reactive power, $Q = \sqrt{3} V_L I_L \sin \phi (VAR)$

$$Q = \sqrt{3} V_L I_L \sin \phi$$

$$P = \sqrt{3} V_L I_L \cos \phi$$

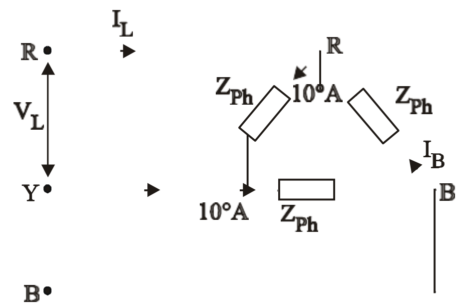
Power triangle, $\boldsymbol{S = \sqrt{P^2 + Q^2}}$ from power triangle

Problems for balanced delta connected loads

EXAMPLE	10

A symmetrical three phase 440 V system supplies a balanced delta connected load. The branch current is 10 A at a phase angle of 30° lagging. Find the total active power.

(AU-Nov/Dec-09)



Phase Current, $I_{Ph} = \sqrt{3} I_L$

$= \sqrt{3} \times 10$

$I_{Ph} = 17.32$ A

Total active power, $P = \sqrt{3} V_L I_L \cos \phi$

$= \sqrt{3} \times 440 \times 17.32 \times \cos(30°)$

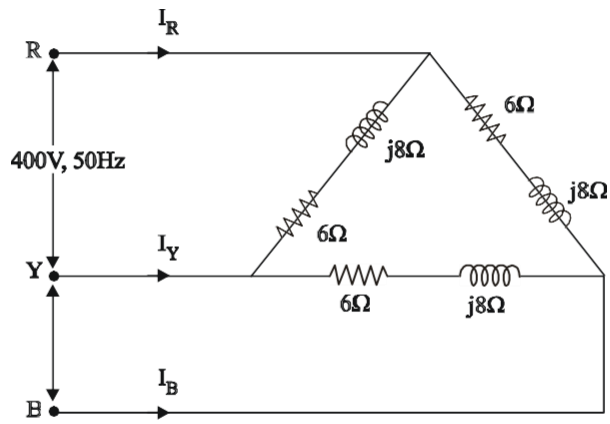
$P = 11431.2$ W

$= 11.43$ kW

EXAMPLE	11

A delta connected load has a series combination of resistance 6 Ω and inductive reactance j8 Ω in each phase. If a balanced 3 phase supply of 400 V, 50 Hz is applied between lines, find the phase current and line currents. **(AU-June-2010)**

Impedance per phase, $Z_{Ph} = 6 + j8 = (10 \angle 53.13°)\ \Omega$



For delta connection, $V_L = V_{Ph} = 400$ V

Phase Current, $I_{Ph} = V_{Ph}/Z_{Ph}$

$= 400/10$

$= 40$ A

Line current for delta connection, $I_L = \sqrt{3}\, I_{Ph} = \sqrt{3} \times 40$

$I_L = 69.28$ A

Power consumed by the load, $P = \sqrt{3}\, V_L I_L \cos\phi$

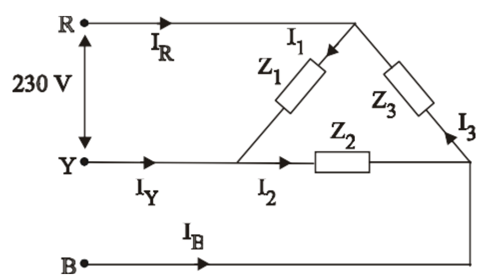
$= \sqrt{3} \times 400 \times 69.28 \times \cos(53.13)°$

$P = 28799.2$ W

$= 28.8$ kW

EXAMPLE	12

Three impedances each of $(3 - j4)\,\Omega$ is delta connected across a 3 phase 230 V balanced supply. Calculate the line and phase currents in the delta connected load and the power delivered to the load. **(AU-June-'11)**



Impedance per phase, $Z_{Ph} = 3 - j4 = (5 \angle -53.13°)\ \Omega$

For delta connection, $V_{Ph} = V_L = 230$ V

Phase current, $I_{ph} = \frac{V_{Ph}}{Z_{Ph}} = \frac{230}{5 \angle -53.13°} = (46 \angle 53.13°)$ A

Line current for delta connection, $I_L = \sqrt{3}\,|I_{Ph}| = \sqrt{3} \times 46$

$$I_L = 79.67 \text{ A}$$

Power delivered to the load, $P = \sqrt{3} V_L I_L \cos\phi$

$$= \sqrt{3} \times 230 \times 79.67 \times \cos(53.13)°$$

$$P = 19043 \text{ W} = 19.04 \text{ kW}$$

EXAMPLE	13

A three phase delta connected load having $(3 + j4)\ \Omega$ impedance per phase is connected across a 400 V three phase source. Calculate the magnitude of the line current throughthe load?

(AU-Nov-'07)

Phase impedance, $Z_{Ph} = 3 + j4 = 5 \angle 53.13°$

For delta connection, $V_L = V_{Ph} = 400$ V

Phase Current, $I_{ph} = \frac{V_{Ph}}{Z_{Ph}} = \frac{400}{5}$

$$I_{Ph} = 80 \text{ A}$$

Line current, $I_L = \sqrt{3} I_{Ph} = \sqrt{3} \times 80 = 138.56$ A

EXAMPLE	14

A symmetrical 3-phase 400 V system supplies a balanced delta connected load. The current in each branch is 20 A and phase angle 40° (lag). Calculate the line current and totalpower.

(AU-May-'05)

For delta connection line current $I_L = \sqrt{3} I_{Ph}$

$$= \sqrt{3} \times 20$$

$$I_L = 34.64 \text{ A}$$

Phase angle, $\phi = 40° \ (lag)$

Power factor, $\cos\phi = \cos 40° = 0.766$ (lag)

Total Power, $P = \sqrt{3}\, V_L I_L \cos\phi$

$= \sqrt{3} \times 400 \times 34.64 \times 0.766$

$\Rightarrow P = 18383.46 = 18.38$ kW

EXAMPLE 15

A delta connected balanced load is supplied from a 3-phase 400 V supply. The line current is 20 A, total power taken by load is 10,000 W. Calculate the impedance in each branch, the line current, power factor and total power consumed if the same load is connected in star. **(AU-Dec-'06)**

Delta Connection

Phase Voltage, $V_{Ph} = V_L = 400$ V

Phase Current, $I_{Ph} = \frac{I_L}{\sqrt{3}} = \frac{20}{\sqrt{3}} = 11.55$ A

Phase impedance, $Z_{Ph} = \frac{V_{ph}}{I_{Ph}} = \frac{400}{11.55} = 34.63\ \Omega$

Power, $P = \sqrt{3} V_L I_L \cos\phi$

$\Rightarrow \cos\phi = \frac{\text{Power}}{\sqrt{3}\ V_L I_L} = \frac{10000}{\sqrt{3} \times 400 \times 20}$

$\cos\phi = 0.722$

Star Connection

$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.94$ V

Phase Current, $I_{ph} = \frac{V_{Ph}}{} = \underline{230.94}$

Z_{Ph} 34.63

$I_{Ph} = 6.67$ A

Line Current, $I_L = I_{Ph} = 6.67$ A [Since, star connection]

Power factor, $\cos\phi = 0.722$

Total Power, $P = \sqrt{3}\, V_L\, I_L \cos\phi$

$= \sqrt{3} \times 400 \times 6.67 \times 0.722$

$P = 3336.44$ W

EXAMPLE	16

A three phase balanced delta connected load of $(4.3 + j7)\,\Omega$ is connected across a 400 V, 3-phase balanced supply. Determine the phase currents and line currents. Assume RYB sequence. Also calculate the complex power drawn by the load. **(AU-Jan-'09)**

For delta Connection, $V_{Ph} = V_L = 400$ V

Phase impedance, $Z_{Ph} = 4.3 + j7 = (8.22\angle 58.44°)\,\Omega$

Phase Current, $I_{Ph} = \dfrac{V_{Ph}}{Z_{Ph}} = \dfrac{400}{8.22\angle 58.44}$

$I_{Ph} = (48.66\angle -58.44°)$ A

Line Current, $I_L = \sqrt{3} I_{Ph} = \sqrt{3} \times 48.66$

$I_L = 84.28$ A

Active Power, $P = \sqrt{3} V_L I_L \cos\phi$

$= \sqrt{3} \times 400 \times 84.28 \times \cos(58.44°)$

$P = 30561.28$ W

Reactive Power, $Q = \sqrt{3} V_L I_L \sin\phi$

$= \sqrt{3} \times 400 \times 84.28 \times \sin 58.44°$

$Q = 49754.45\, VA_r$

Complex Power, $S = P + jQ$

$$= 30561.28 + j49754.45$$

$$S = 58390.9 \text{ VA}$$

UNBALANCED LOAD

When the load impedance are not equal in each phase of the available three phases of a load, then it is called to be unbalanced load. So the voltage and current are also different in each phase. Such an unbalanced load also can be connected either in star or in delta connection.

As done in balanced load case, here we cannot multiply individual phase power by three, to get the total power. Since now the load is an unbalanced one.

So in unbalanced condition, we have to calculated individual phase power and then we can add those to get total power. For unbalanced condition also the phase difference between phases will be 120°.

Unbalanced Four Wire Star Connected Load

9.Explain Unbalanced four wire star connected load.

A three phase star connected 4 wire unbalanced system is shown in fig. 9.13.

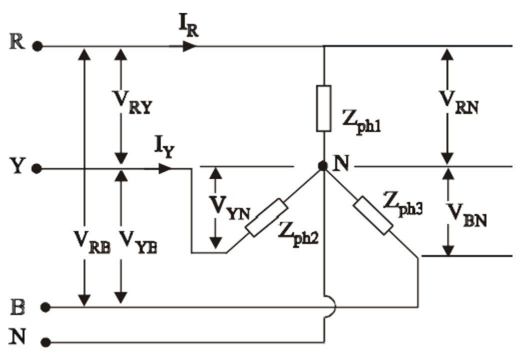


Fig. 9.13 Unbalanced star connected load.

The vector diagram of the circuit shown in fig. 9.13 will be as shown in fig. 9.14. Three phase impedances are,

$$\bar{Z}_{Ph1} = Z_{Ph1} \angle\phi_R \,;\, \bar{Z}_{Ph2} = Z_{Ph2} \angle\phi_Y \,;\, \bar{Z}_{Ph3} = Z_{Ph3} \angle\phi_B$$

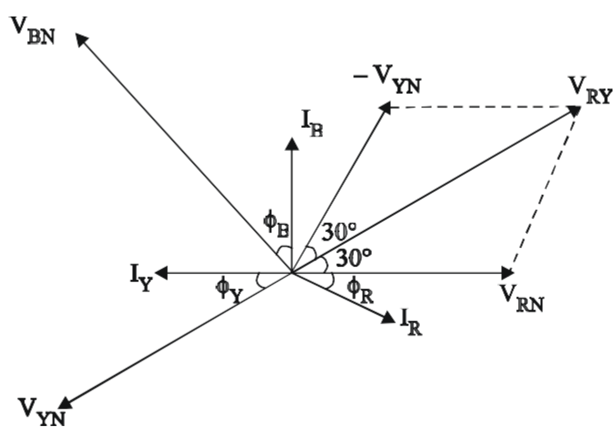


Fig. Vector diagram

Here, $V_{RN} = V_{Ph}\angle 0^\circ$ (Reference Vector)

Then, $V_{YN} = V_{Ph}\angle -120^\circ$

$V_{BN} = V_{Ph}\angle +120^\circ$

If, Z_{Ph1}, Z_{Ph2} and Z_{Ph3} are the unbalanced load impedances (which are not equal), then the individual currents are,

$$\Rightarrow I_R = \frac{V_{RN}}{Z_{Ph1}} = \frac{V_{Ph}\angle 0^\circ}{Z_{Ph1}\angle \phi_R} = \frac{V_{Ph}}{Z_{Ph1}}\angle -\phi_R \quad \text{(Amps)}$$

$$\Rightarrow I_Y = \frac{V_{YN}}{Z_{Ph2}} = \frac{V_{Ph}\angle -120^\circ}{Z_{Ph2}\angle \phi_Y} = \frac{V_{Ph}}{Z_{Ph2}}\angle -120^\circ - \phi_Y \quad \text{(Amps)}$$

$$\Rightarrow I_B = \frac{V_{BN}}{Z_{Ph3}} = \frac{V_{Ph}\angle +120^\circ}{Z_{Ph3}\angle \phi_B} = \frac{V_{Ph}}{Z_{Ph3}}\angle +120^\circ - \phi_B \quad \text{(Amps)}$$

Current in neutral wire can be found by the use of Kirchoff's law and it is,

$$I_N = I_R + I_Y + I_B$$

Unbalanced three wire star connected load

10.Discuss in detail about three wire star connected load.

An unbalanced three wire star connected load is shown in fig.

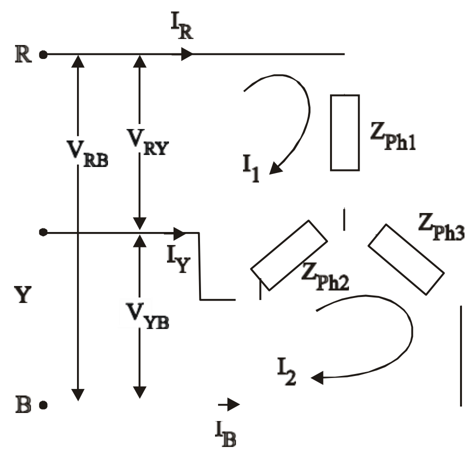


Fig. Unbalanced wire star connected load

Let the phase difference between current and voltages of each phase be ϕ_R, ϕ_Y and ϕ_B.

$$\bar{Z}_{Ph1} = Z_{Ph1} \angle\phi_R \text{ ;(three phase unbalanced impedances)}$$

$$\bar{Z}_{Ph2} = Z_{Ph2} \angle\phi_Y \text{ ;}$$

$$\bar{Z}_{Ph3} = Z_{Ph3} \angle\phi_B \text{ ;}$$

Line Voltages are,

$$V_{RY} = V_L \angle 0°$$

$$V_{YB} = V_L \angle -120°$$

$$V_{BR} = V_L \angle +120°$$

The loop currents are assumed to be I_1 and I_2.

The voltage equation for loop 1 is, written using KVL and it is,

$$\bar{Z}_{Ph1} \bar{I}_1 + \bar{Z}_{Ph2} (\bar{I}_1 - \bar{I}_2) = V_{RY} = V_L \angle 0°$$

$$(\bar{Z}_{Ph1} + \bar{Z}_{Ph2}) \bar{I}_1 - \bar{Z}_{Ph2} \bar{I}_2 = V_L \angle 0°$$

The voltage equation for loop 2 is also written using KVL and it is,

$$\bar{Z}_{Ph2}\left(\bar{I}_2-\bar{I}_1\right)+\bar{Z}_3\bar{I}_2=\bar{V}_{YB}=V_L\angle-120°$$

$$-\bar{Z}_{Ph2}\bar{I}_1+\left(\bar{Z}_{Ph2}+\bar{Z}_{Ph3}\right)\bar{I}_2=V_L\angle-120°$$

Solving the above two equations, we get $\bar{I}_1$ and $\bar{I}_2$. Then the line value of current is found to be,

$$\bar{I}_R=\bar{I}_1$$

$$\bar{I}_Y=\bar{I}_2-\bar{I}_1$$

$$\bar{I}_B=-\bar{I}_2$$

Power consumption can be found by the above current and voltages

Unbalanced Delta Connected Load

11.Write unbalanced delta connected impedances .

An unbalanced three phase delta connected load is shown in fig.Let the unbalanced load impedances be,

$$\bar{Z}_{Ph1}=Z_{Ph1}\angle\phi_R$$

$$\bar{Z}_{Ph2}=Z_{Ph2}\angle\phi_Y$$

$$\bar{Z}_{Ph3}=Z_{Ph3}\,\phi_B$$

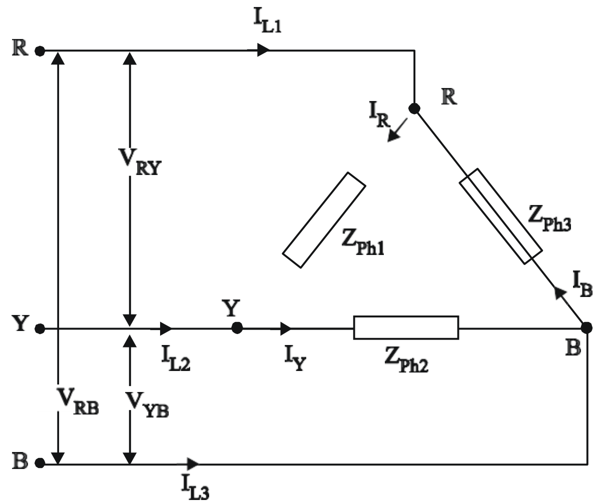


Fig. Unbalanced 3 phase delta connected load.

Line voltages for delta connection can be written as,

$$\Rightarrow V_{RY} = V_{YB} = V_{BR} = V_L = V_{Ph}$$

Let, the current in each phase be,

$$\Rightarrow I_R = \frac{V_{Ph}\angle 0^\circ}{Z_{Ph1}\angle\phi_R} = \frac{V_{Ph}}{Z_{Ph1}}\angle 0^\circ - \phi_R \text{ (Amps)}$$

$$\Rightarrow I_Y = \frac{V_{Ph}\angle -120^\circ}{Z_{Ph2}\angle\phi_Y} = \frac{V_{Ph}}{Z_{Ph2}}\angle -120^\circ - \phi_Y \text{ (Amps)}$$

$$\Rightarrow I_B = \frac{V_{Ph}\angle +120^\circ}{Z_{Ph3}\angle\phi_B} = \frac{V_{Ph}}{Z_{Ph3}}\angle +120^\circ - \phi_B \text{ Amps}$$

Applying KCL at the three nodes of the delta connection,

$$I_{L1} = I_R - I_B$$

$$I_{L2} = I_Y - I_R$$

$$I_{L3} = I_B - I_Y$$

Power consumed by load 1 $= V_{Ph}\, I_R \cos \phi_R = P_R$

Power consumed by load 2 $= V_{Ph}\, I_Y \cos \phi_Y = P_Y$

Power consumed by load 3 $= V_{Ph}\, I_B \cos \phi_B = P_B$

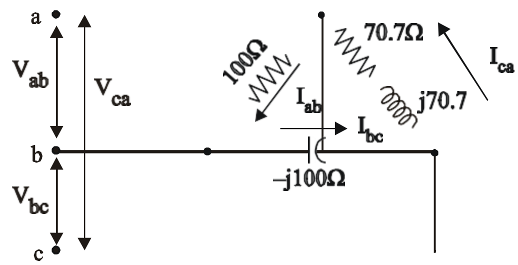
Total Power, $P = P_R + P_Y + P_B$

$$P = V_{Ph}\, I_R \cos \phi_R + V_{Ph}\, I_Y \cos \phi_Y + V_{Ph}\, I_B \cos \phi_B$$

Problems for unbalanced delta connected load

EXAMPLE	17

A three phase delta connected load has $Z_{ab} = 100\ \Omega$, $Z_{bc} = -j100\ \Omega$ and $Z_{ca} = (70.7 + j70.7)\ \Omega$ is connected to a balanced 3 phase 400 V supply. Determine the line currents I_a, I_b and I_c. **(AU-June/July-09)**



For Delta Connection, $V_{ab} = (400\ \angle 0°)$ V

$$V_{bc} = (400\ \angle -120°)\ \text{V}$$

$$V_{ca} = (400\ \angle -240°)\ \text{V}$$

Phase Current, $I_{ab} = \dfrac{V_{ab}}{Z_{ab}} = \dfrac{400\ \angle 0°}{100\ \angle 0°} = (4\ \angle 0°)$ A

$$I_{ab} = (4 + j0)\ \text{A}$$

Phase Current, $I_{bc} = \dfrac{V_{bc}}{Z_{bc}} = \dfrac{400\ \angle -120°}{100\ \angle -90°} = (4\ \angle -30°)$ A

$$I_{bc} = (3.47 - j2)\ \text{A}$$

Phase Current, $I_{ca} = \dfrac{V_{ca}}{Z_{ca}} = \dfrac{400\ \angle -240°}{99.98\ \angle 45°} = (4\ \angle -285°)$ A

$$I_{ca} = (1.04 + j3.86)\ \text{A}$$

Line Currents,

$$I_a = I_{ab} - I_{ca} = (4 + j0) - (1.04 + j3.86)$$

$$\Rightarrow I_a = (2.96 - j3.86) = (4.86 \angle - 52.52°) \text{ A}$$

$$I_b = I_{bc} - I_{ab} = (3.47 + j2) - (4 + j0)$$

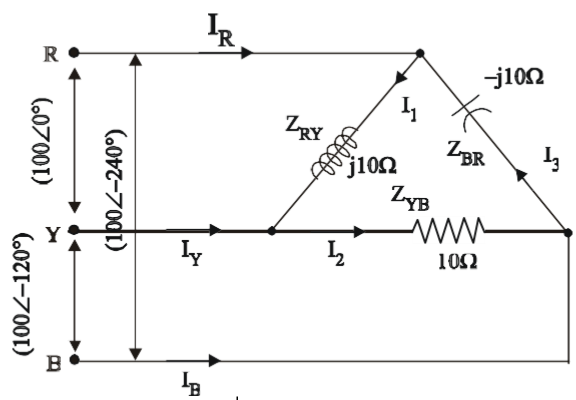
$$\Rightarrow I_b = (-0.53 - j2) = (2.07 \angle - 104.84°) \text{ A}$$

$$I_c = I_{ca} - I_{bc} = (1.04 + j3.86) - (3.47 - j2)$$

$$\Rightarrow I_c = (-2.43 + j5.86) = (6.34 \angle + 112.52°) \text{ A}$$

EXAMPLE	18

A delta connected load as shown in figure, is connected across 3-phase 100 V supply. Determine all the line currents. **(AU-Dec-'05)**



$$V_{RY} = (100 \angle 0°) \text{ V} \qquad Z_{RY} = (0 + j10) = 10 \angle 90°)\ \Omega$$

$$V_{YB} = (100 \angle - 120°) \text{ V} \qquad Z_{YB} = (10 + j0) = (10 \angle 0°)\ \Omega$$

$$V_{BR} = (100 \angle - 240°) \text{ V} \qquad Z_{Br} = (0 - j10) = (10 \angle - 90°)\ \Omega$$

Phase Current, $I_1 = \dfrac{V_{RY}}{Z_{RY}} = \dfrac{100 \angle 0°}{10 \angle 90°} = (10 \angle - 90°) \text{ A}$

$$I_1 = (0 - j10) \text{ A}$$

Phase Current, $I = \dfrac{V_{YB}}{} = \dfrac{100 \angle - 120°}{} = (10 \angle - 120°) \text{ A}$

$$^{2} \quad Z_{YB} \qquad 10$$

$$I_2 = (-5 - j8.66) \text{ A}$$

Phase Current, $I_3 = \frac{V_{BR}}{Z_{BR}} = \frac{100 \angle -240°}{10 \angle -90°} = (10 \angle -150°)$ A

$$I_3 = (-8.66 - j5) \text{ A}$$

Line Current, $I_R = I_1 - I_3 = (0 - j10) - (-8.66 - j5)$

$$\Rightarrow I_R = (8.66 - j5) = (10 \angle -30°) \text{ A}$$

Line Current, $I_Y = I_2 - I_1 = (-5 - j8.66) - (0 - j10)$

$$\Rightarrow I_Y = (-5 + j1.34) = (5.18 \angle 165°) \text{ A}$$

Line Current, $I_B = I_3 - I_2 = (-8.66 - j5) - (-5 - j8.66)$

$$\Rightarrow I_B = (-3.66 + j3.66) = (5.18 \angle 135°) \text{ A}$$

Phasor addition of the phase current is zero, i.e., $I_R + I_Y + I_B = 0$

12.With neat vector diagram explain unbalanced and balanced loads.

1. *Unbalanced Loads*

Let,

$i_R -$ Instantaneous value of current through W_{112}

$v_{RY} -$ Instantaneous value of voltage across W_1

$i_B -$ Instantaneous value of current through W_2

$v_{BY} -$ Instantaneous value of voltage across W_2

Now,

$$W_{\text{inst}} = i_{CC} \times v_{PC}$$

Y $$\Rightarrow W_1 = i_R \times v_{RY} \text{ and } W_2 = i_B \times v_{BY}$$

But, $v_{RY} = v_{RN} - v_{YN}$ and $v_{BY} = v_{BN} - v_{YN}$

So, $W_1 = i_R \times (v_{RN} - v_{YN})$ and $W_2 = i_B \times (v_{BN} - v_{YN})$

$$W_1 + W_2 = i_R\,(v_{RN} - v_{YN}) + i_B\,(v_{BN} - v_{YN})$$

$$= i_R v_{RN} - i_R v_{YN} + i_B v_{BN} - i_B v_{YN}$$

$$= i_R v_{RN} + i_B v_{BN} - \left(i_R + i_B \right) v_{YN}$$

By applying KCL at neutral point,

We get,

$$i_R + i_Y + i_B = 0$$

$$i_R + i_B = -\, i_Y$$

Substituting in the above equation,

$$W_1 + W_2 = i_R v_{RN} + i_B v_{BN} - (-\, i_Y)\, v_{YN}$$

$$W_1 + W_2 = i_R v_{RN} + i_Y v_{YN} + i_B v_{BN}$$

$$W_1 + W_2 = p_R + p_Y + p_B$$

Where,

$p_R, p_Y, p_B -$ instantaneous power consumed by each phase of load

This is true for Star/Delta, balanced unbalanced loads.

2. Balanced loads

Let,

I_R, I_Y, I_B – Phase Currents of respective phases.

V_{RN}, V_{YN}, V_{ZN} – Phase Voltages of respective phases w.r.t neutral.

V_{RY}, V_{YB}, V_{BR} – Line Voltages

ϕ – Phase angle between voltage and current in every phases.

Let us consider the RMS values of current and voltages to calculate the total power consumed by the load.

$$W_1 = I_R \times V_{RY} \times \cos(I_R \wedge V_{RY})$$

$$W_2 = I_B \times V_{BY} \times \cos(I_B \wedge V_{BY})$$

Assume the power factor ϕ to be lagging and a vector diagram is drawn as shown in fig .

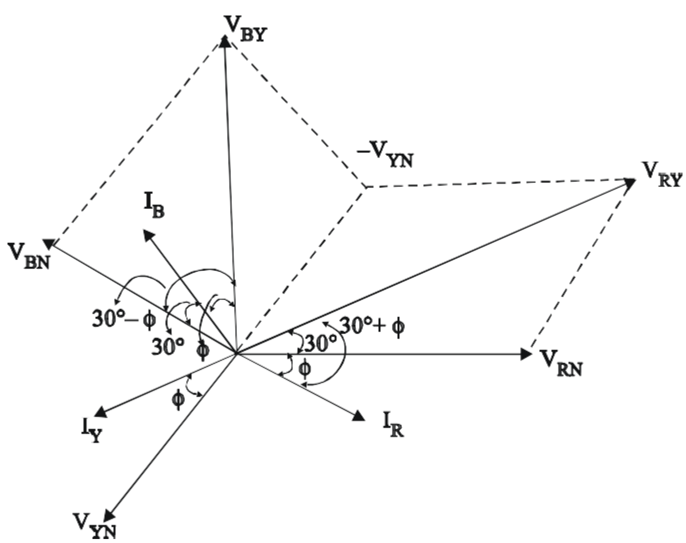


Fig. Vector diagram for star connected load

$$V_{RY} = V_{RN} - V_{YN} \text{ and } V_{BY} = V_{BN} - V_{YN}$$

Phase angle, $\phi = I_R \wedge V_{RY}$ and phase angle $\phi = I_B \wedge V_{BY}$

For Balanced load, $V_{RY} = V_{BY} = V_L$

Also, $I_R = I_B = I_L = I_{Ph}$ [For star load]

From fig 9.21, $I_R \wedge V_{RY} = 30 + \phi$ and $I_B \wedge V_{BY} = 30 - \phi$

$$\therefore W_1 = I_R V_{RY} \cos(30 + \phi)$$

$$\Rightarrow W_1 = I_L V_L \cos(30 + \phi)$$

and, $W_2 = I_B V_{BY} \cos(30 - \phi)$

$$W_2 = I_L V_L \cos(30 - \phi)$$

Then, $W_1 + W_2 = \left[I_L V_L \cos(30 + \phi) \right] + \left[I_L V_L \cos(30 - \phi) \right]$

$$= V_L I_L [\cos(30 + \phi) + \cos(30 - \phi]$$

$$= V_L I_L [\cos 30 \cos\phi + \sin 30 \sin\phi + \cos 30 \cos\phi - \sin 30 \sin\phi]$$

$$= V_L I_L [2 \cos 30^\circ \cos\phi]$$

$$= V_L I_L [2 \times \frac{\sqrt{3}}{2} \times \cos\phi]$$

$W_1 + W_2 = \sqrt{3} V_L I_L \cos\phi =$ Total Power.

This equation will be same irrespective of load type i.e., star or delta.

Power Factor Measurement

13.Mention the equations for power factor measurement.

We have found that,

$$W_1 = V_L I_L \cos(30 + \phi)$$

And $W_2 = V_L I_L \cos(30 - \phi)$

$$W_1 + W_2 = \sqrt{3} V_L I_L \cos\phi$$

Then, $W_1 - W_2 = V_L I_L [\cos(30 + \phi) - \cos(30 - \phi)]$

$$= V_L I_L [\cos 30 \cos\phi + \sin 30 \sin\phi - \cos 30 \cos\phi + \sin 30 \sin\phi]$$

$$= V_L I_L \, [2 \sin 30 \sin \phi]$$

$$= V_L I_L \left[2 \times \frac{1}{2} \times \sin \phi \right]$$

$$W_1 - W_2 = V_L I_L \sin \phi$$

Ratio, $$\frac{W_1 - W_2}{W_1 + W_2} = \frac{V_L I_L \sin \phi}{\sqrt{3} V_L I_L \cos \phi} = \frac{\tan\phi}{\sqrt{3}}$$

$$\therefore \phi = \tan^{-1}\left[\frac{\sqrt{3}\,(W_1 - W_2)}{(W_1 + W_2)}\right]$$

$$\therefore \text{ Power factor, } \cos\phi = \cos\left\{\tan^{-1}\left[\frac{\sqrt{3}\,(W_1 - W_2)}{(W_1 + W_2)}\right]\right\}$$

Note

If any of the wattmeter coil's connection is interchanged during measurement, then that reading should be noted as negative value.

For example if wattmeter W_2 is inter changed then,

$$\tan\phi = \frac{\sqrt{3}\,(W_1 - (-W_2))}{(W_1 + (-W_2))}$$

$$\tan\phi = \left[\frac{\sqrt{3}\,(W_1 + W_2)}{W_1 - W_2}\right]$$

Unbalanced Three-Phase Systems

14.Write the effects of three phase unbalanced load systems.

Learning and understanding three-phase systems would be incomplete without learning and analyzing unbalanced three-phase systems.

An unbalanced three-phase system is not a rare thing in power transmission and distribution.

When we are dealing with either:

1. Balanced three-phase system
2. Unbalanced three-phase system

We need to know what caused them to go "balanced" or "unbalanced".

There are two causes of this unbalanced system:

1. The voltage sources are not equal in magnitude and/or have differences in phase angle from each other phase.
2. The load impedances are unequal from each other.

In balanced system, we always have:

1. Equal voltage sources in magnitude and phase angle. For example, a three-phase system with a voltage source at 120V and 50Hz frequency for each phase.
2. Equal load impedance. For example, a three-phase system with only resistance loads or inductive loads or capacitive loads with the same value for all lines.

Thus,

An unbalanced system is due to unbalanced voltage sources or an unbalanced load.

There is also one thing to remember that an unbalanced three-phase voltage source is a very rare phenomenon.

Analyzing unbalanced three-phase systems will take a lot of time. Hence, in this post we will assume that every circuit we use has balanced voltage sources and unbalanced load impedances

Unbalanced Load in Three-Phase System

A three-phase system is balanced if all the line loads are equal to each other. If one of the loads is increased, then it will be an unbalanced system.Because that line will draw more current than the other two.

Effects of Unbalanced Three-Phase System

- Increased heat by three-phase motors.
- Reduced lifetime of machine by increased heat.
- Power losses I^2R increased.
- Motor drives become unreliable.

Properties of Unbalanced Three-Phase System

- The three-phase waveform is disturbed.
- The line currents are not equal to each other.
- Neutral wire is needed.
- Higher power losses.

DISTORTED SOURCE SUPPLYING NON-LINEAR LOADS

15. Explain nonlinear loads supplying the source.

Distortion in current and voltage waveforms at the lower frequency range is defined to have an upper limit of 2 kHz. This limit represents the 40th harmonic order for the fundamental 50-Hz frequency. These waveform distortions are often generated from regulated power supplies and found as discrete spectral lines at multiples of the fundamental frequency, as shown in Figure 2. Other loads can create sub harmonics at frequencies below the fundamental frequency, or inter-harmonics, which are harmonics whose frequencies are non-integer multiples of the fundamental frequency. Both types are also found in the lower-frequency range.

The switch-mode power supply (SMPS), used in most digital electronic equipment, is an excellent example of a non-linear load. Because it draws current in non-sinusoidal pulses, the SMPS is a significant generator of harmonic currents. When found in high densities multiple SMPS can be a major contributor to voltage distortion.

We can calculate the RMS value of the voltage or current distortion if we know the RMS values of all of the components. Parseval's Theorem tells us that the RMS value of a waveform is equal to the square root of the sum of the squares of the RMS values of the fundamental component and all of the harmonic components of the waveform. The fundamental is not a distortion component, so the RMS value of the distortion is just the square root of the sum of the squares of the harmonic components. Usually this is expressed as percentage of the value of the fundamental component and is called the *Total Harmonic Distortion*, or *THD*.

Voltage total harmonic distortion (V_{thd}) is calculated as:

$$V\ thd = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \dots}}{V_1} \times 100\%$$

Similarly, current total harmonic distortion is calculated as:

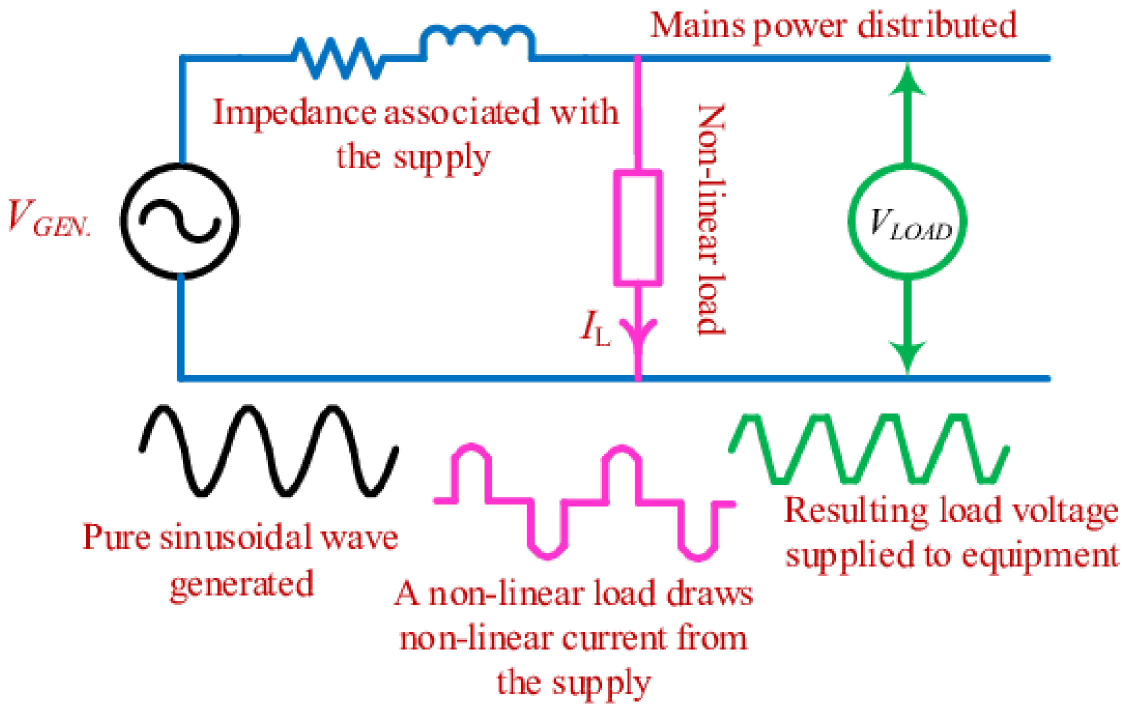
$$I\ thd = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_1} \times 100\%$$

Voltage distortion then is a function of both the system impedance and the amount of harmonic current in the system. The higher the system impedance (ie. long cable runs, high impedance transformers, the use of diesel generators or other weak sources) the higher the voltage distortion.

In Figure, we see that voltage distortion is greatest at the loads themselves, since the harmonic currents are subjected to the full system impedance (cables, transformer and source) at that point.

This is a characteristic most often misunderstood. It means that even if voltage distortion levels are low at the service entrance, they can be unacceptably high at the loads themselves. It also emphasizes the importance of keeping system impedances relatively low when servicing non-linear loads.

Voltage distortion can be minimized by removing the harmonic currents (I_h) and/or lowering the system impedance (Z_h) to the harmonics.



THE POWER FACTOR WITH NONLINEAR LOADS (Electric Motor)

16.Discuss the concept of power factor with non linear loads.

The growing use of power semiconductors has increased the complexity of system power factor and its correction. These power semiconductors are used in equipment such as rectifiers (converters) DC motor drive systems Adjustable-frequency AC drive systems Solid-state motor starters Electric heating.

In the discussion about the power factor in sinusoidal systems, only two components of power contributed to the total kilovolt-amperes and the resultant power factor: the active or real component, expressed in kilowatts, and the reactive component, expressed in kilo vars. When nonlinear loads using power semiconductors are used in the power system, the total power factor is made up of three components:

1. Active, or real, component, expressed in kilowatts.
2. Displacement component, of the fundamental reactive elements, expressed in kilo vars or kilovolt-amperes.

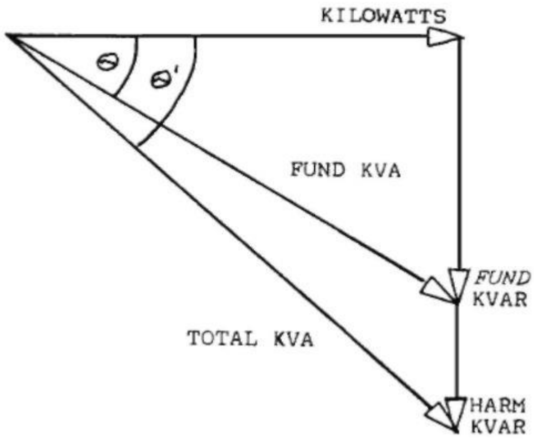
3. Harmonic component. The result of the harmonics and the distorted sinusoidal current and voltage waveforms generated when any type of power semiconductor is used in the power circuit, the harmonic component can be expressed in kilovars or kilovolt-amperes. The effect of these nonlinear loads on the distribution system depends on (1) the magnitude of the harmonics generated by these loads, (2) the percent of the total plant load that is generating harmonies, and (3) the ratio of the short-circuit current available to the nominal fundamental load current. Generally speaking, the higher the ratio of short-circuit current to nominal fundamental load current, the higher the acceptable level of harmonic distortion.
Therefore, more precise definitions of power factors are required for systems with nonlinear loads as follow:
Displacement power factor. The ratio of the active power of the fundamental in kilowatts to the apparent power of the fundamental in kilovolt-amperes.

Total power factor. The ratio of the active power of the fundamental in kilowatts to the total kilovolt-amperes.

Distortion factor, or harmonic factor. The ratio of the root-mean-square (rms) value of all the harmonics to the root-mean-square value of the fundamental. This factor can be calculated for both the voltage and current.
Figure illustrates the condition in which the total power factor is lower than the displacement power factor as a result of the harmonic currents.

$$\text{Displacement power factor} = \frac{\text{kW}}{\sqrt{\text{kW}^2 + \text{fund. kvar}^2}}$$

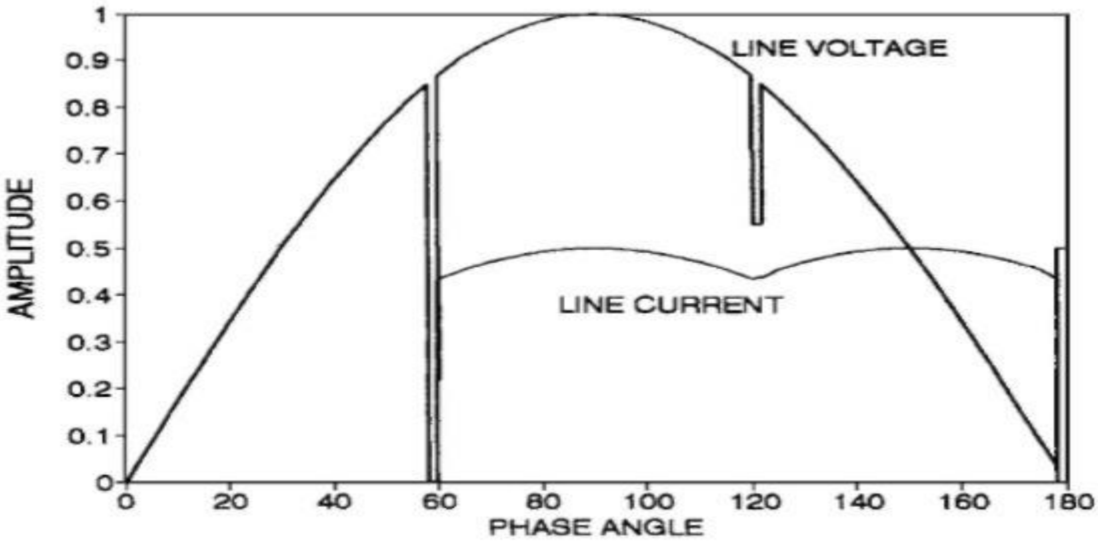
$$\text{Total power factor} = \frac{\text{kW}}{\sqrt{\text{kW}^2 + (\text{fund. kvar} + \text{harm. kvar})^2}}$$



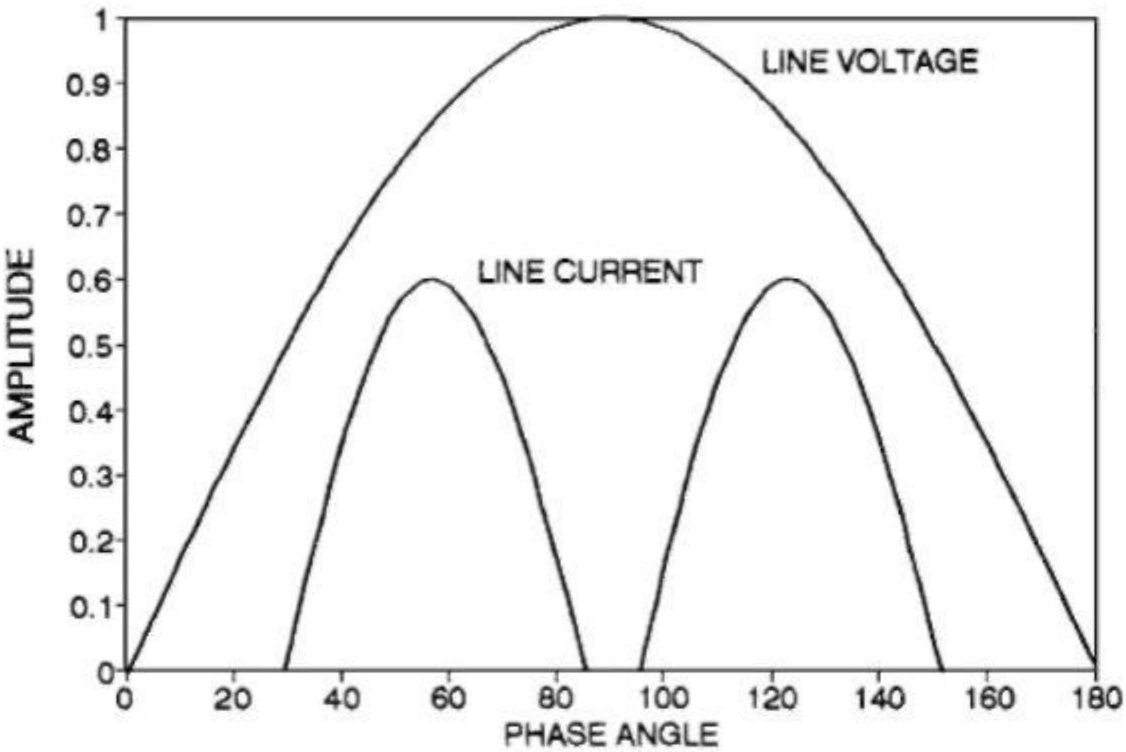
Power factor, non sinusoidal system.

Unfortunately, conventional var-hour meters do not register the total reactive energy consumed by nonlinear loads. If the voltage is nonsinusoidal, the var-hour meter measures only the displacement volt-ampere-hours and ignores the distortion volt-ampere-hours. Therefore, for nonlinear loads, the calculated power factor based on kilowatt-hour and var-hour meter readings will be higher than the correct total power factor. The amount of the error in the power factor calculation depends on the magnitude of the total harmonic distortion.

The harmonics result from distorted AC line currents caused by the power semiconductor devices. Typical current wave shapes caused by AC adjustable-frequency drives are shown in Figs. Figure illustrates the wave shape of the AC line current produced by an adjustable-frequency drive system with the converter section containing silicon control rectifiers (SCRs) or other controllable power switching devices, such as those used in current source inverters and DC drive systems. The harmonic problem for this type of converter is complicated by the voltage notch and voltage spikes that occur during the switching of the converter solid-state devices. The displacement power factor for this type of converter is linear with load.



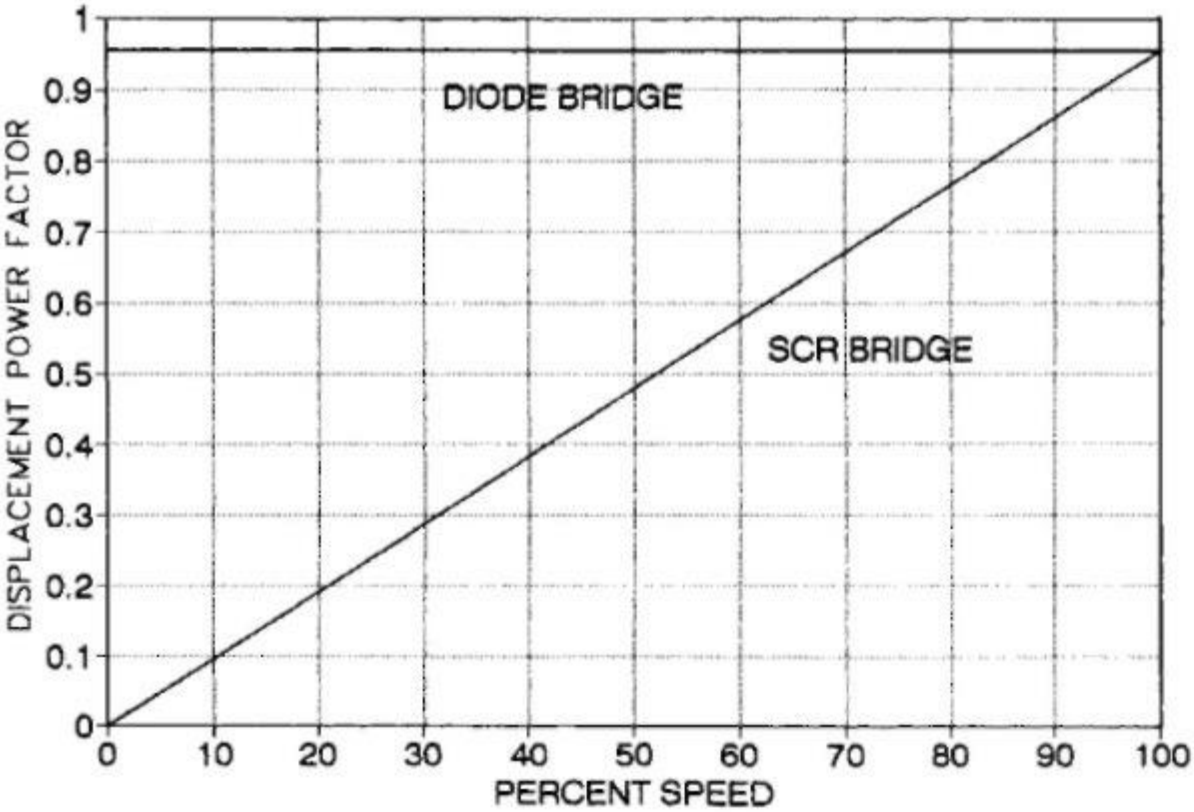
Typical AC line wave shapes, SCR converter.



Typical AC line wave shapes, diode converter

The total power factor and the harmonic component depend on the system reactance and short-circuit capacity. Figure illustrates the wave shape of the AC line current produced by an adjustable-frequency drive system with the converter section operating as a voltage source with a typical diode bridge rectifier converter, such as those used in voltage source and pulse width

modulation (PWM) inverters. Again, the total power factor and the current wave shape vary depending on the system impedance, the capacitance on the output of the converter, and the power semiconductor characteristics. The lower the line inductance, the higher the harmonics and the higher the value of the peak current. The displacement power factor for this type of converter is constant over the speed range. However, the total power factor depends on the harmonic distortion factor.
For both types of converters, there is a difference between the displacement power factor and the total power factor.



Comparison displacement power factor diode bridge versus SCR bridge.

The total power factor depends on the harmonics generated, the harmonic distortion factor, and the power system characteristics.

UNIT 3
MITIGATION OF POWER SYSTEM HARMONICS

Introduction - Principle of Harmonic Filters – Series-Tuned Filters – Double Band-Pass Filters – damped Filters – Detuned Filters – Active Filters – Power Converters – Harmonic Filter Design – Tuned Filter – Second-Order Damped Filter – Impedance Plots for Filter Banks – Impedance Plotsfor a Three-Branch 33 kV Filter.

1. What are the mitigation techniques in power system?

Mitigation techniques are also discussed such as constancy of power supply, Dynamic voltage restorer, filters, static var compensator, energy storage system, flexible alternating current transmission systems and transformers.

2. Why are filters used?

Filters can remove unwanted frequency components from the signal to get a proper signal. Filters can change the amplitude and phase characteristics of a signal with respect to frequency. Filters won't add new frequencies to the input signal, filters are used in many electronic systems.

3. What is IEC standard for harmonics?

IEC 61000-3-2 aims to set limits to the harmonic currents drawn by electrical apparatus and so maintain mains voltage quality. It is a compromise between cost and the performance of extra electronic front end circuits, the so called active power factor correcting circuits.

4. What are the two types of harmonic filters?

Harmonic filtering is an option for both consumers and network operators. There are two filter technologies to be considered: passive filters and active filters. In the case of passive filters, there are many designs in use (e.g. single tuned, double tuned, c-type).

5. What is the principle of harmonic filter?

Harmonic filters reduce distortion by diverting harmonic currents in low-impedance paths. Harmonic filters are capacitive at the fundamental frequency, so they are also used to produce the reactive power required by converters and for power factor correction.

6. Which type of harmonics filters are used?

However, there are two main types of harmonics filters available which are Passive Harmonic Filters and Active Harmonic Filter. The main difference between these two types of harmonic filters is the components used for the filter design.

7. What are the components of harmonic filter?

The basic components of a passive harmonic filter are a reactor and a capacitor connected in series on the power system and attached to perhaps a bus, a main switchboard, switchgear or even inside a motor control center.

8. What are the types of harmonics?

Harmonics are usually classified by two different criteria: the type of signal (voltage or current), and the order of the harmonic (even, odd, triplen, or non-triplen odd); in a three-phase system, they can be further classified according to their phase sequence (positive, negative, zero).

9. What are the 4 main filter types?

Filters can be active or passive, and the four main types of filters are low-pass, high-pass, band-pass, and notch/band-reject (though there are also all-pass filters). I hope you've learned a bit about how to describe filters and what they can accomplish.

10. Why do we need harmonic filter?

As previously mentioned, harmonic filters are used to eliminate harmonic distortion caused by excess currents in and out of appliances. It can prevent large quantities of harmonics from causing damage to equipment, downtime of operation, and preventing an increase in operating costs.

11. Where are harmonics used?

The term harmonic is used across different fields such as electronic power transmission, music, radio and all technologies that use waves in other forms.

Their frequencies always relate to these waves and are always found in whole-numbered multiples.

12. Where are harmonic filters installed?

It is also installed in industrial electronics applications such as UPS systems, data centres and semiconductor production equipment. Photovoltaic systems and wind turbines also use these filters. You can also find harmonic filter installations in many office buildings and shopping centres.

13. What is 1st 2nd and 3rd harmonics?

Harmonics are integer multiples of the fundamental frequency. For example, if the fundamental frequency is 50 Hz (also known as the first harmonic) then the second harmonic will be 100 Hz (50 * 2 = 100 Hz), the third harmonic will be 150 Hz (50 * 3 = 150 Hz), and so on.

14. What is harmonic mean filters?

The harmonic mean is defined as: A larger region (filter size) yields a stronger filter effect with the drawback of some blurring. The harmonic mean filter is better at removing Gaussian type noise and preserving edge features than the arithmetic mean filter.

15. What is the cause of harmonics?

Harmonics are caused by non-linear loads on a power system. Typically, electric current is produced as a sine wave: these loads draw power that is not a sine wave, and as a result, produce harmonics.

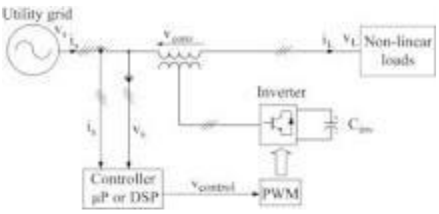
16. What is a tuned filter?

Tuned Harmonic Filter consist of capacitors connected in series with a specially designed reactor. The capacitors produces reactive power at the filter's fundamental frequency & reduce the THDV, (I) of the system.

17. What is a single or series tuned filter?

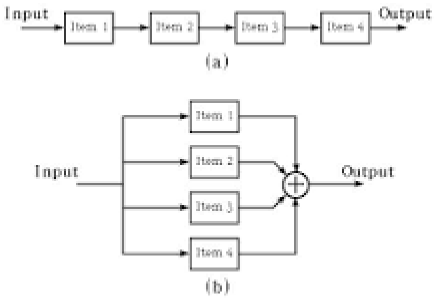
The single-tuned (ST) passive filter is the most commonly used in the application, which provides a low-impedance path for the harmonic at a specific tuned frequency. Meanwhile, the filter also provides the reactive power to the point of connection.

18. What is series active filter?



Series active filters are operated mainly as a voltage regulator and harmonic isolator between a nonlinear load and the utility grid. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply.

19. What are filters in series vs parallel?



In series, the filters run one after the other. This means the second filter will effect the whole signal regardless of what the first is doing. In parallel mode the filters will run, you guessed it, in parallel.

20. What is series passive filter?

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 a high impedance at a selected harmonic frequency.

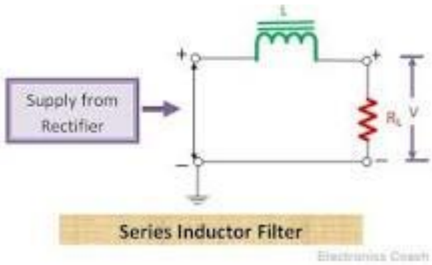
21. What is tuned and detuned filter?

Single-tuned filter and the detuned reactor is the type of harmonic filter that commonly used to mitigate harmonic distortion. The harmonic filter also has benefit to improve power factor and voltage profile on the system.

22. What is double-tuned filter?

Double-tuned filter and two parallel single tuned filters have the same function that both of them can filter two different frequency harmonics. However, double-tuned filter has a lower cost than the two parallel single tuned filters.

23. What is series inductor filter?



In series inductor filter the inductor is connected in series with the rectifier output and the load resistor. Thus, it is called series inductor filter. The property of an inductor to block AC and provides zero resistance to DC is used in filtering circuit.

24. What is the difference between shunt and series filter?

Series passive filter will block the source harmonic current, hence induce spikes in the source current. Whereas in case of passive shunt filter, low impedance path is offered to the source harmonic current due to which, the filter is highly capacitive in nature with lower inductance.

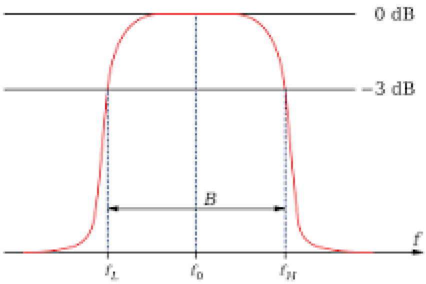
25. What is series vs parallel resonator?

The major difference between series resonance and parallel resonance is that a series resonance results in the minimum impedance and maximum current flow in the circuit, while a parallel resonance results in maximum impedance and minimum current flow in the circuit.

26. Why are filters cascaded?

Cascading filters in series is commonly used to enhance stopband rejection and steepness in the transition band. The technique can also be used to combine high pass and low pass filters to create a band pass response.

27. What is a band pass filter used for?

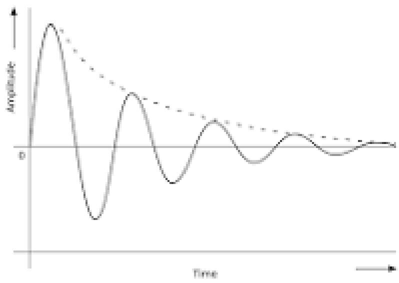


In a receiver, a bandpass filter allows signals within a selected range of frequencies to be heard or decoded, while preventing signals at unwanted frequencies from getting through.

28. What is dual-band bandpass filter?

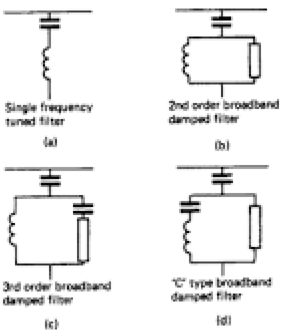
Dual-band bandpass filters (BPFs) provide the functionality of two separate filters, but in the size of a single filter.

29. What is called damping?



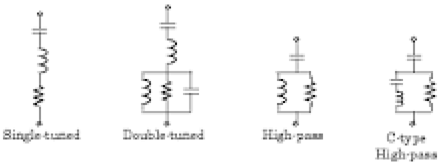
Damping is the method of removing energy in order to control vibratory motion like noise, mechanical oscillation, and alternating electric current. In physics, damping is the process of dissipating energy to prevent vibratory motion such as mechanical oscillations, noise, and alternating electric currents.

30. What is damped filter?



The damped filter type is mostly used to control higher-order harmonics in the network. It contains higher resistance than single- and double-tuned filters, so this type of filter is not used to remove harmonics near a power frequency. Commonly, damped filters are used to reduce the 11th and 13th, 17th, 19th, etc.

31. How do filters reduce harmonics?



Harmonic filters reduce distortion by diverting harmonic currents in low-impedance paths. Harmonic filters are capacitive at the fundamental frequency, so they are also used to produce the reactive power required by converters and for power factor correction.

32. What is detuned filter?

Detuned filtering is a reliable and time-tested method to improve the power factor and also mitigating the risk of resonance; this is achieved by shifting the resonance frequency to lower levels, thereby ensuring that no harmonic currents are present.

33.What is detuned harmonic filter?

The harmonic filter (Detuned) is to limit the flow of harmonic current from non-linear loads on the reactor to the fixed impedance loads (eg capacitor).

34. What is active filter and its types?

Active filters are the electronic circuits, which consist of active element like op-amp(s) along with passive elements like resistor(s) and capacitor(s). Active filters are mainly classified into the following four types based on the band of frequencies that they are allowing and / or rejecting − Active Low Pass Filter.

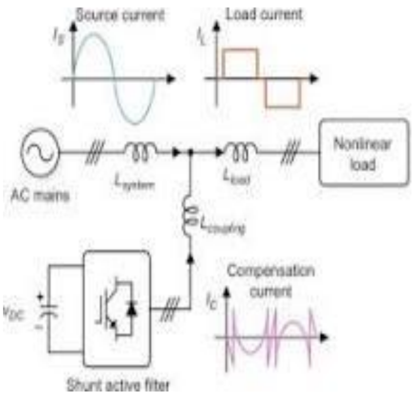
35. How many types of active filters are there?

Filters can be active or passive, and the four main types of filters are low-pass, high-pass, band-pass, and notch/band-reject (though there are also all-pass filters).

36. What is the active filter in VFD?

The active filter works by measuring the power system current and injecting the necessary harmonic current to cancel the VFD harmonics. As the filter is an active device is can quickly respond to changes in VFD loading and power system voltage, frequency, unbalance and background voltage distortion conditions.

37. What is the principle of active filter?



Active Filters

Series active power filters compensate current system distortion caused by non-linear loads by imposing a high impedance path to the current harmonics, which forces the high-frequency currents to flow through the LC passive filter connected in parallel to the load .

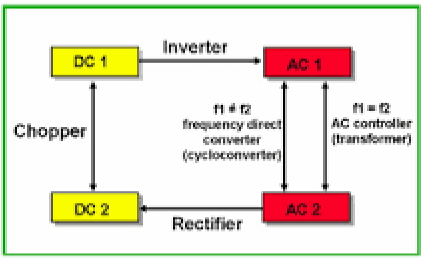
38. What is shunt active filters?

A shunt active filter senses the load current and injects a current into the system to compensate current harmonics or reactive load.

39. What is meant by power converter?

A power converter is an electrical or electro-mechanical device for converting electrical energy. A power converter can convert alternating current (AC) into direct current (DC) and vice versa; change the voltage or frequency of the current or do some combination of these.

40. What are the different types of power converters?



There are several kings of converters based on the source input voltage and the output voltage and these falls into four categories namely the AC to DC converter known as the rectifier, the AC to AC cycloconverter or frequency changer, the DC to DC voltage or current converter, and the DC to AC inverter.

41. What are power converters used for?

Power converters are components needed for converting the AC power from the grid into something that can be used for the storage process, and vice versa. This can be, for instance, mechanical power for pumping of compressing gases or DC power for charging batteries.

42. What is the name of power converter?

DC to AC converters: DC to AC converters take direct current and convert it to an alternating current of the desired voltage and frequency. These are inverters. DC to DC converters: These converters convert either a constant current to a variable or a constant direct current. These devices are also called choppers.

43. What are the advantages of power converters?

They are highly reliable and have a long life. There is very less power loss while using electronic converters. Power electronic converters are efficient, and they have a quick response; they are small in size and less in weight.

44. What is the difference between a power converter and a transformer?

Voltage converters and transformers are two types of methods that perform this voltage conversion. The key difference between voltage converter and transformer is that transformer is only able to convert AC voltages whereas voltage converters are made to convert between both types of voltages.

45. Why DC converter is used?

Unstable or improper voltage supplies can lead to characteristics degradation and even malfunction. To prevent this, a DC-DC converter is needed to convert and stabilize the voltage. A device that stabilizes the voltage using a DC-DC converter is referred to as a voltage regulator.

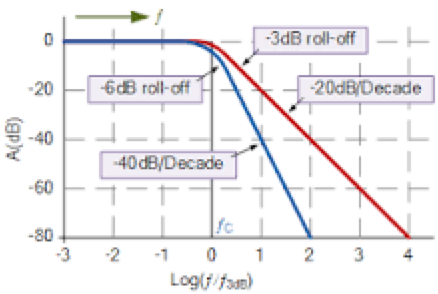
46. What are the components of harmonic filter?

The basic high pass harmonic filter design use three passive components, resistor, capacitor, and inductor.

47. What is 2nd order filter?

The Second-Order Filter block implements different types of second-order filters. Filters are useful for attenuating noise in measurement signals. The block provides these filter types: Low pass — Allows signals, f , only in the range of frequencies below the cutoff frequency, f c , to pass.

48. Why use second order filters?



Second order (two-pole) active filters whether low pass or high pass, are important in Electronics because we can use them to design much higher order filters with very steep roll-off's and by cascading together first and second order filters, analogue filters with an n^{th} order value, either odd or even can be .

49. What is damping ratio of a filter?

Damping ratio Zeta (Q = 1/(2*Zeta))

The damping ratio is typically a value between 0 and 1. Default is 0.707 . The damping ratio is related to the filter quality factor Q.

50. Why do we use second order system?

The second-order system is unique in this context, because its characteristic equation may have complex conjugate roots. The second-order system is the lowest-order system capable of an oscillatory response to a step input. Typical examples are the spring-mass-damper system and the electronic RLC circuit.

51. What is output impedance of a filter?

The output impedance is the ratio of change in output voltage to change in load current. Power supply input and output impedance are used to verify the supply's stability and dynamic performance when subjected to various loads.

52. What is the product of the impedance in a constant k filter?

'Constant-k' implies that the product of underlying impedances Z_1 and Z_2 must be a constant independent of frequency. Therefore, L_1 C_1 has to be equal to L_2 C_2 if the filter is to be of a constant-k type.

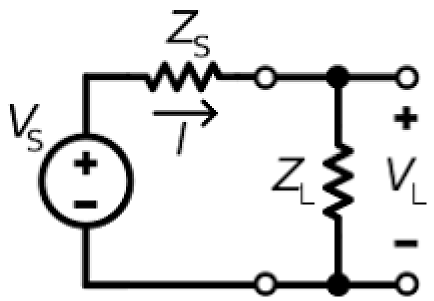
53. What is characteristic impedance in filter?

Characteristic impedance is determined by the geometry and materials of the transmission line and, for a uniform line, is not dependent on its length. The SI unit of characteristic impedance is the ohm.

54. How do you measure the impedance of a filter?

The input impedance is measured from the ratio of the input voltage of the supply and the current into the terminals. The output impedance of the filter can be measured with the same injection setup with the voltage probe at the output of the filter.

55. What is filtering and impedance matching?



In electronics, impedance matching is the practice of designing or adjusting the input impedance or output impedance of an electrical device for a desired value. Often, the desired value is selected to maximize power transfer or minimize signal reflection.

56.What is the Q factor of a harmonic filter?

The quality factor Q of the filter is the quality factor of the reactance at the tuning frequency $Q = (nX_L)/R$. The quality factor determines the bandwidth B, which is a measure of the sharpness of the tuning frequency.

57. How do you reduce third harmonics?

Certain methods can be used to reduce harmonics they are: Adding a line reactor or transformer in series will significantly reduce harmonics, as well as provide transient protection benefits. Isolation transformers provide a good solution in many cases to mitigate harmonics generated by non-linear loads.

58. What is acceptable level of harmonics?

The limits on voltage harmonics are thus set at 5% for THD and 3% for any single harmonic. It is important to note that the suggestions and values given in this standard are purely voluntary. However, keeping low THD values on a system will further ensure proper operation of equipment and a longer equipment life span.

59. What is cut off frequency of a filter?

The cut-off frequency of a filter is the frequency characterizing a boundary between a passband and a stopband. Passband consists of the range of frequencies the filter lets through (minimal attenuation), and the stopband consists of the range of frequencies the filter rejects (high attenuation).

60. How do you calculate filter coefficient?

The numerator coefficients for a low-pass filter can be calculated as follows: b0 = K / α b1 = K / α. The numerator coefficients for a high-pass filter can be calculated as follows: b0 = 1 / α b1 = -1 / α. K = tan(θC / 2) W = K2 α = 1 + K / Q + W.

Principle of Harmonic Filters – Series-Tuned Filters – Double Band-Pass Filters – damped Filters – Detuned Filters-Active Filters-Power converters.

PART B

1. What are the preventive and precautionary solutions to avoid harmonics.

(OR)

Write short notes on measures to mitigate power system harmonics.

(OR)

What are the solutions to harmonic problems.

Precautionary (Preventive) solutions are those policies sought for at discretion to avoid harmonics and their consequences. These include:

- Phase cancellation or harmonic control in power converters.
- Developing procedures and methods to control, reduce or eliminate harmonics in power system equipment; mainly capacitors, transformers and generators.

Attempting at keeping harmonics at a low "damage-free" level, standards are further developed setting limits on the level of individual frequency harmonics and/or harmonic distortion factors.

Corrective (Remedial) solutions are those techniques recoursed to aiming at overcoming existing harmonic problems. They include:

- The use of filters.
- Circuit detuning which involves the reconfiguration of feeders or relocation of capacitor banks to overcome resonance.

2. Discuss in brief about Harmonic filters.

Harmonics can be efficiently reduced through the use of a passive filter [3] which consists, basically, of a series combination of a capacitor and a reactor tuned to a specific harmonic frequency. Filters provide a low impedance "trap" to a harmonic to which the filter is tuned. Theoretically, the filter has a zero impedance at the tuning frequency thus absorbing the harmonic of interest. Shown in Fig. 5.1, typical harmonic filters are discussed hereafter.

report on the details of passive filters; their configurations and design tactics. Design steps for series-tuned and second-order damped filters are discussed in Section 5.7.

3. Write short notes on series tuned and double band pass filters.

Series-Tuned Filters

A series-tuned filter consists of a series combination of a capacitor and a reactor and is tuned to low harmonic frequencies. At the tuned harmonic, the capacitor and the reactor have equal reactances and the filter has a purely resistive impedance. The filter's impedance is capacitive for lower harmonics and inductive for higher harmonics, a consequence of which is aggravating the impedance below the lowest tuned frequency

Double Band-Pass Filters

A double band-pass filter is a series combination of a main capacitor, a main reactor and a tuning device which consists of a tuning capacitor and a tuning reactor connected in parallel. The impedance of such a filter is low at two tuned frequencies.

4. Discuss in detail about damped, detuned and active filters.

Damped Filters

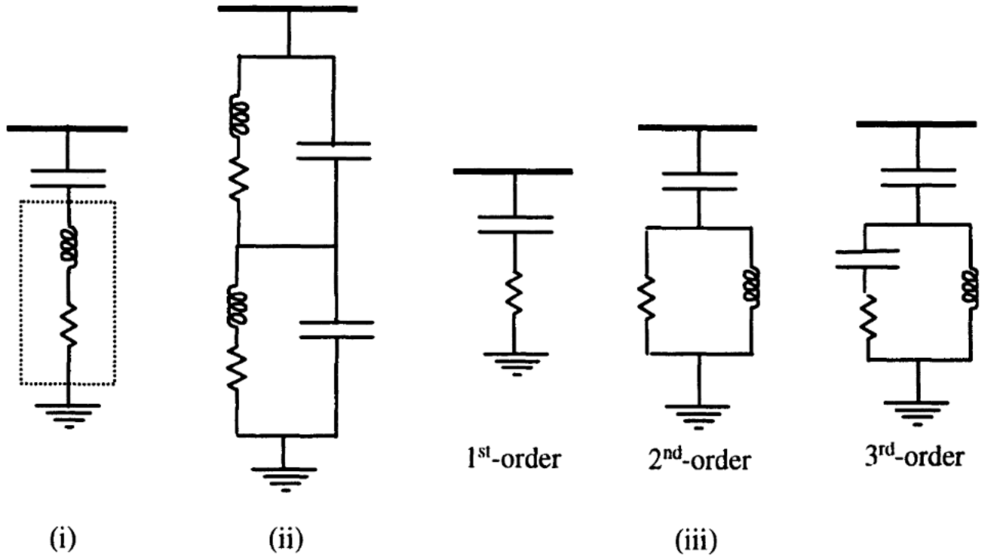
Damped filters can be 1^{st}, 2^{nd} or 3^{rd}-order. However, the most commonly used is the 2^{nd}-order. A 2^{nd}-order damped filter consists of a capacitor in series with a parallel combination and of a reactor and a resistor. It provides a low impedance for a moderately wide range of frequencies.

When used to eliminate high order harmonics (17^{th} and above), a damped filter is referred to as a high-pass filter, providing a low impedance for high frequencies but stopping low ones.

Damped filters have a low quality factor, $0.5 < Q < 5$, and are usually tuned to $h_n < h_r$, that is 10.7, 16.5, ...

Detuned (Anti-Resonant) Filters

A detuned filter is tuned below a characteristic harmonic (usually tuned to the fourth harmonic), thus absorbing some of the harmonic but not as much as a higher tuned one.



Typical harmonic filters: **(i)** Series-tuned **(ii)** Double band-pass **(iii)** 1^{st}, 2^{nd} and 3^{rd}-order damped

Active Filters

Active filters are being developed to alleviate the disadvantages of conventional passive filters, namely:

- The filtering characteristics being dependent on the source impedance.
- Aggravating the impedance below the lowest tuned harmonic.
- Being inadequate for filtering non-characteristic harmonics (different from the filter's tuned frequency), such as those produced by cycloconverters.

5. Write short notes on Power Converters

Power Converters

It has been shown in Powersystemthat harmonics of pulse converters constructed through the operation of lower pulse number converters can be eliminated through the proper selection of phase shifts. This is called phase cancellation [3] or phase multiplication. Analysis revealed that 5^{th}, 7^{th}, 17^{th}, 19^{th}, $\cdots$ harmonics are eliminated in two six-pulse converters operating in parallel or series with 0 and -30° phase shifts. This means that a twelve-pulse converter has a lower harmonic impact than two six-pulse units of a comparable size. Grady [3] further points out that two twelve-pulse converters operating in parallel or series through $+7.5°$ and -7.5° phase shifts eliminate eleventh and thirteenth harmonics. A consequential conclusion is to use converters with higher number of pulses.

6. What is the purpose of harmonic filter.

(OR)

Explain with suitable equations of harmonic filter design.

(OR)

What are the design steps in a harmonic filter.

(OR)

With tuned capacitor and filter design the equations for harmonic filter.

(OR)

Write the equations for reactive power absorbed and delivered by the inductor and capacitor.

HARMONIC FILTER DESIGN

As for the resonance condition the inductive reactance should be equal to the capacitive reactance.

$$X_l = X_c$$

For harmonic filter design the reactive power should be delivered to load or absorbed in case of the need of the application.

Harmonic filters are series or parallel resonant circuits designed to shunt or block the harmonic currents. They reduce the harmonic currents flowing in the power system from the source and there by reduce the harmonic voltage distortion in the system.Harmonic current distortion is shown in the graph form of THDi.

There are two type of harmonic filter used active and passive filter , where transistors and Op-amp for active filter , Resistor , inductor and Capacitor for passive filters.

Applicable standards and optional features are also important factors to consider when selecting harmonic filters.Features for harmonic filters include UL marks, performance monitors , operating temperature , and form factor.

Harmonic filters are used to eliminate harmonic distortion caused by excess currents in and out of the appliances.It can prevent large quantity of harmonics from causing damage to the equipment , down time of operation , and preventing an increase in operating costs. The working principle of harmonic filter is to decrease harmonic distortion through deflecting harmonic currents within less impedance path or lanes. Filters are capacitive at the basic frequency , so to generate reactive power and also for power factor correction.

Tuning a capacitor to a certain harmonic, alternatively, designing the capacitor to trap (filter) a certain harmonic, requires the addition of a reactor. At the tuned harmonic

$$X_{Ln} = h_n X_{L1} = X_{Cn} = \frac{X_{C1}}{h_n} = X_n$$

so that

$$X_n = \sqrt{X_{L_1} \, X_{C_1}} = \sqrt{\frac{L_1}{C_1}}$$

The tuned frequency is then

$$f_n = h_n f_o = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad \text{Hz}$$

and the tuning order is

$$h_n = \frac{f_n}{f_o} = \frac{1}{\omega_o \sqrt{L_1 C_1}} = \sqrt{\frac{X_{C_1}}{X_{L_1}}}$$

The reactor's inductive reactance can now be found as

$$X_{L1} = \frac{X_{C1}}{h_n^2}$$

Being sensitive to peak voltages, the capacitor needs to be able to withstand the total peak voltage across it. That is, it needs to have a voltage rating equal to the algebraic sum of the fundamental and tuned harmonic voltages [3, 4].

$$V_C = V_{C_1} + V_{C_n} = X_{C_1} \, I_{C_1} + X_{C_n} \, I_{C_n}$$

However, since it is likely that a capacitor tuned to a certain harmonic will absorb other harmonics, a safety measure would be to let the capacitor have a voltage rating of

$$V_{C_{LL}} = \sum_{h=1} V_{C_{h_{LL}}} = \sum_{h=1} \sqrt{3}\, X_{C_h}\, I_{C_h} = \sum_{h=1} \sqrt{3}\, \frac{X_C}{h}\, I_{C_h}$$

while the rms voltage is

$$V_{C_{rms}} = \sqrt{\sum_{h=1} V^2_{C_{h_{LL}}}} = \sqrt{3 \sum_{h=1} \left(\frac{X_C}{h}\, I_{C_h}\right)^2}$$

The reactive power absorbed by the reactor is

$$Q_L = \sum_{h=1} V_{L_h} I_{L_h} = \sum_{h=1} h X_L\, I^2_{L_h} = \sum_{h=1} \frac{V^2_{L_h}}{h X_L}$$

$$\frac{Q_L}{Q_{L_1}} = \sum_{h=1} h \left(\frac{I_{L_h}}{I_{L_1}}\right)^2 = \sum_{h=1} \frac{1}{h} \left(\frac{V_{L_h}}{V_{L_1}}\right)^2$$

The reactive power delivered by the capacitor bank is

$$Q_C = \sum_{h=1} V_{C_h} I_{C_h} = \sum_{h=1} \frac{X_C}{h} \cdot I^2_{C_h} = \sum_{h=1} \frac{h}{X_C} \cdot V^2_{C_h}$$

$$\frac{Q_C}{Q_{C_1}} = \sum_{h=1} h \left(\frac{V_{C_h}}{V_{C_1}}\right)^2 = \sum_{h=1} \frac{1}{h} \left(\frac{I_{C_h}}{I_{C_1}}\right)^2$$

7. Write short notes on series tuned filters.

(OR)

Design Series tuned filter.

SERIES TUNED FILTER

A series-tuned filter is a capacitor designed to trap a certain harmonic by adding a reactor with $X_L = X_C$ at the tuned frequency f_n.

Design steps: For a series-tuned filter tuned to the h_n harmonic:

- Determine the capacitor size Q_C in MVAr, say the reactive power requirement of the harmonic source.
- The capacitor's reactance is

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

- To trap the h_n harmonic, the reactor should have a size of

$$X_L = \frac{X_C}{h_n^2}$$

- The reactor's resistance is found as

$$R = \frac{X_n}{Q}$$

where Q is the filter's quality factor, $30 < Q < 100$.

The characteristic reactance is given by

$$X_n = X_{Ln} = X_{Cn} = \sqrt{X_L\, X_C} = \sqrt{\frac{L}{C}}$$

Filter size is then

$$Q_{\text{Filter}} = \frac{\text{kV}^2}{X_C - X_L} = \frac{\text{kV}^2}{X_C - \dfrac{X_C}{h_n^2}}$$

$$= \frac{h_n^2}{h_n^2 - 1} \cdot \frac{\text{kV}^2}{X_C} = \frac{h_n^2}{h_n^2 - 1} \cdot Q_C$$

For a series-tuned filter, the impedance at any harmonic h becomes

$$Z_F(h) = R + j\left(hX_L - \frac{X_C}{h}\right)$$

so that

$$|Z_F(h)| = \sqrt{R^2 + \left(hX_L - \frac{X_C}{h}\right)^2}$$

The voltage appearing across the capacitor would be

$$\frac{V_{C1}}{V_{bus1}} = \frac{-\jmath X_{C1}}{\jmath(X_{L1} - X_{C1})} = \frac{X_{C1}/X_{L1}}{X_{C1}/X_{L1} - 1} = \frac{h_n^2}{h_n^2 - 1}$$

and

$$\frac{V_{Cn}}{V_{busn}} = \frac{-\jmath X_{Cn}}{R + \jmath(X_{Ln} - X_{Cn})} = -\jmath\frac{X_n}{R} = -\jmath Q$$

where

V_{C1} is the fundamental component of the voltage across the capacitor
V_{bus1} is the fundamental component of the voltage at the bus
V_{Cn} is the capacitor voltage at the tuned frequency
V_{busn} is the bus voltage at the tuned frequency
X_n is the filter's characteristic reactance, $X_n = X_{Ln} = X_{Cn} = \sqrt{L_1/C_1} = \sqrt{X_{L_1}X_{C_1}}$
Q is the filter's quality factor defined as $Q = X_n/R$.

The bus voltage is then

$$V_{bus_1} = \frac{h_n^2 - 1}{h_n^2} \cdot V_{C_1} = V_{C_1} - \frac{V_{C_1}}{h_n^2} = V_{C_1} - V_{L_1}$$

Example 5.3. A filter is tuned to the 13^{th} harmonic. Given $X_C = 507\ \Omega$, calculate the filter elements and plots its impedance.

Solution The reactor has a size of

$$X_L = \frac{X_C}{h_n^2} = 3\ \Omega$$

The characteristic reactance is

$$X_n = \sqrt{X_L\ X_C} = 39\ \Omega$$

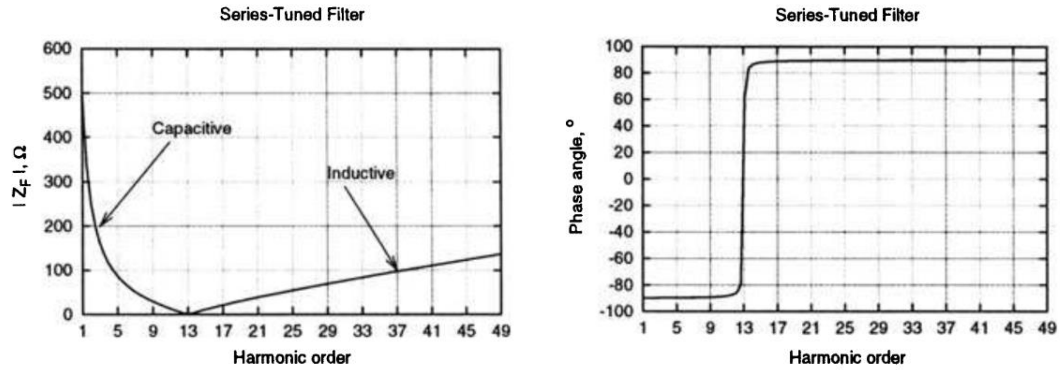
For a quality factor of 100, the reactor would have a resistance of

$$R = \frac{X_n}{Q} = 0.39\ \Omega$$

Example 5.4. What is the tuning order and the quality factor for a 33 kV series-tuned filter with $X_C = 544.5\ \Omega$, $X_L = 4.5\ \Omega$ and $R = 0.825\ \Omega$?

Solution The tuning order is

$$h_n = \sqrt{\frac{X_C}{X_L}} = 11$$



, Impedance of a series-tuned filter

The filter's quality factor is

The filter's quality factor is

$$Q = \frac{X_n}{R} = \frac{\sqrt{X_L X_C}}{R} = 60$$

The reactive power delivered by the capacitor bank is

$$Q_C = \frac{33^2}{544.5} = 2 \text{ MVAr}$$

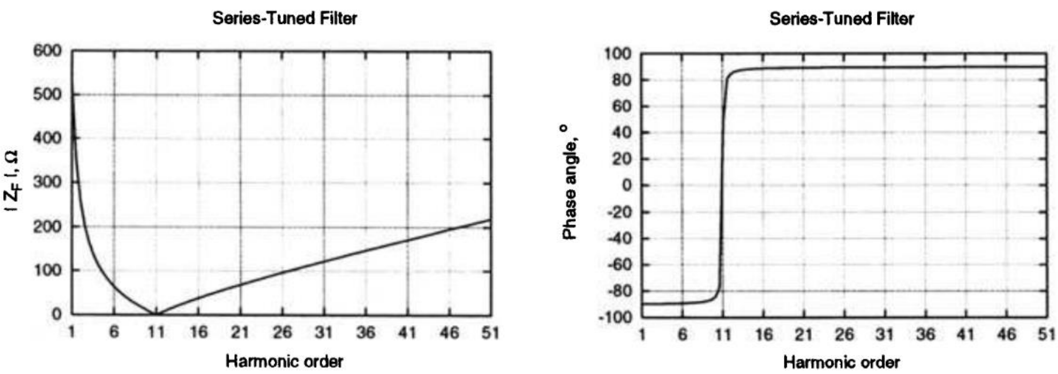
The filter's rated size is

$$Q_{\text{Filter}} = \frac{\text{kV}^2}{X_C - X_L} = \frac{h_n^2}{h_n^2 - 1} \cdot Q_C = 2.017 \text{ MVAr.}$$

Assuming the filter were intended to tackle resonance at the eleventh harmonic, the SCC (SCMVA) at the bus where the filter is installed would be

$$\text{SCC} = h_r^2 \cdot Q_C = 242 \text{ MVA.}$$

The filter's impedance, $Z_F(h) = R + \jmath(hX_L - X_C/h)$, is plotted in Fig.



Eleventh-tuned 33 kV filter impedance

Example 5.5. Which harmonics are being trapped by a filter comprising four series-tuned circuits with 3ϕ, 50 Hz, 400 V, Y−connected, 1x30+3x20 kVAr capacitor banks and 0.779, 0.583, 0.233 and 0.166 mH reactors?

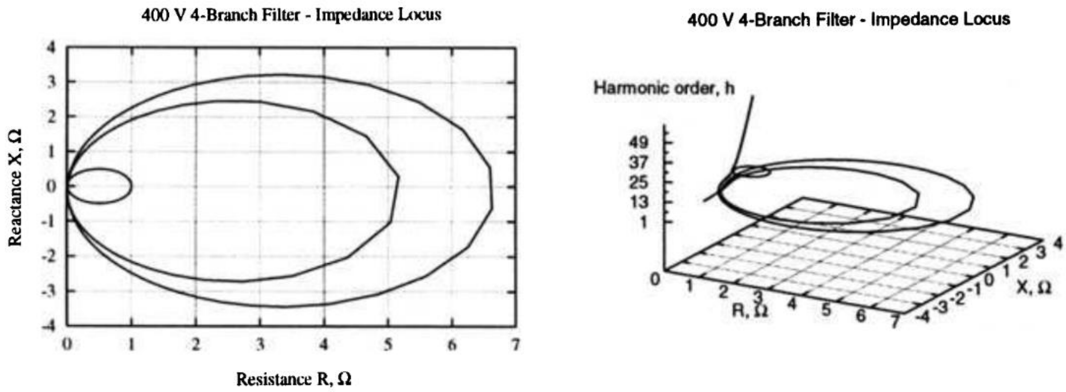
Solution With $X_C = \mathrm{kV}^2/Q_C$ (Q_C in MVAr) and $h_n = \sqrt{X_C/X_L}$, one finds that the filter is designed to trap the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics. The reactor's resistance ($R = X_n/Q$, where $X_n = \sqrt{X_L\, X_C}$) is calculated with a quality factor of 100.

Filters are tuned to 4.7, 6.6, 10.5 and 12.4 to compensate for the variation of capacitance with time. As capacitor units age, their dielectric material degrades resulting in a decrease of capacitance (increase of reactance), and thus an increase of the filter's resonant frequency.

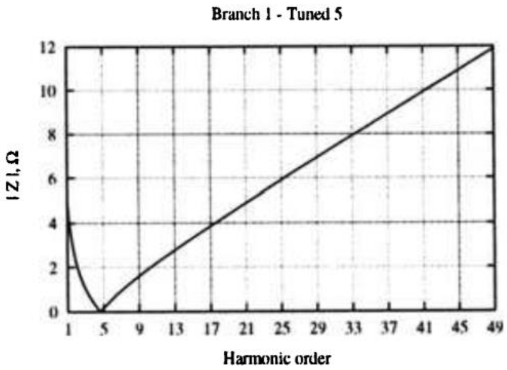
Table [illegible]. Four-branch filter data - 400 V

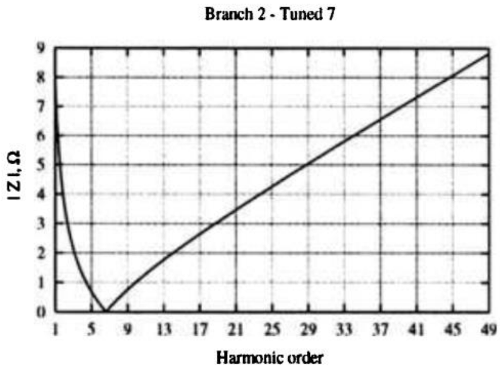
	Filter 1	Filter 2	Filter 3	Filter 4
Q_C, kVAr	30	20	20	20
X_C, Ω	5.33	8	8	8
I_C, A	43.33	28.87	28.87	28.87
L, mH	0.779	0.583	0.233	0.166
X_L, Ω	0.24473	0.18315	0.07320	0.05215
h_n	4.67	6.61	10.45	12.39
X_n, Ω	1.142	1.210	0.765	0.646
Q	100	100	100	100
R, mΩ	11.42	12.10	7.65	6.46

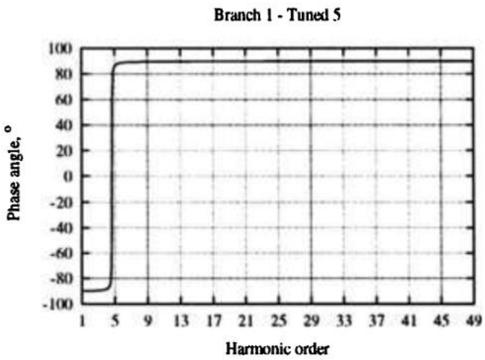
The filter's impedance, which is the parallel equivalent of four series-tuned circuits with $Z_F(h) = R + \jmath(hX_L - X_C/h)$, is plotted

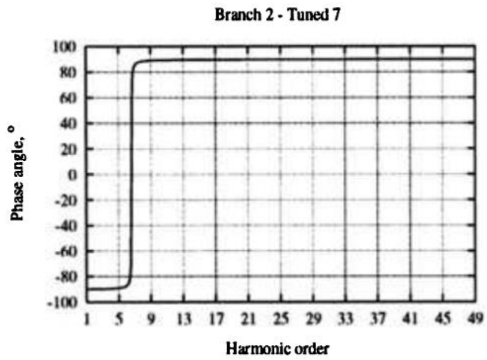


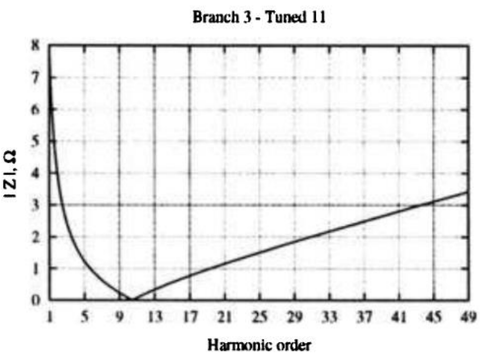
Four-branch 400 V filter impedance locus

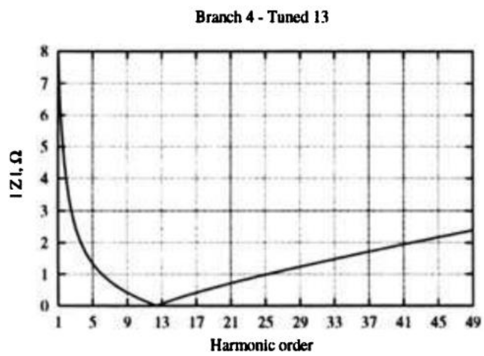


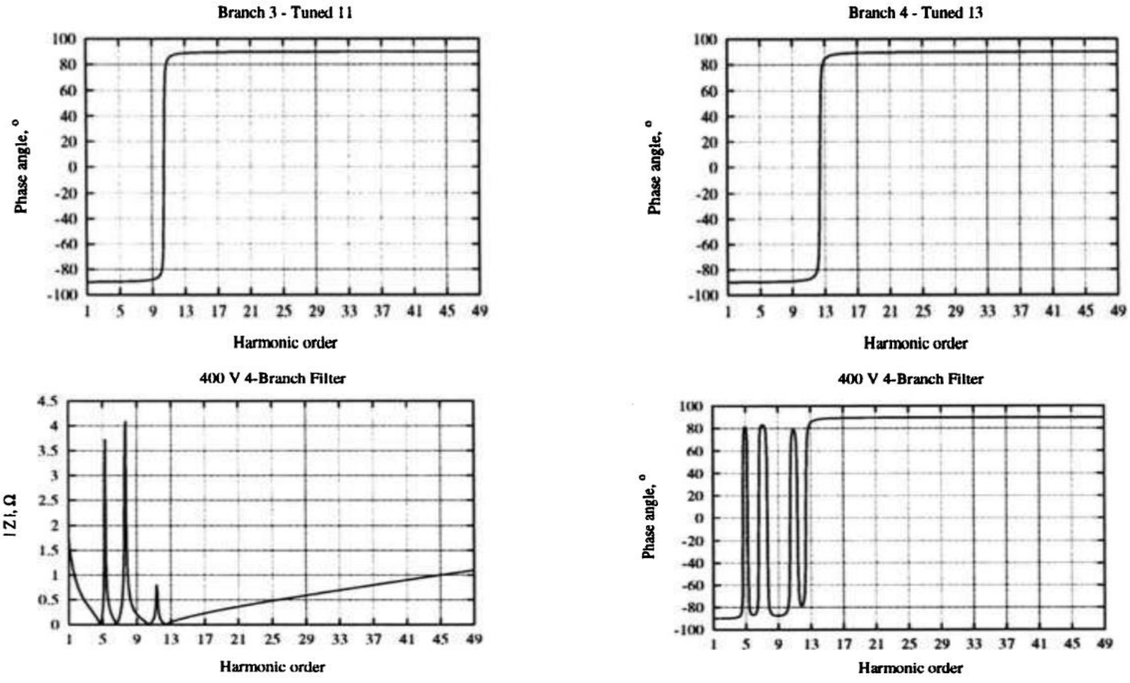












Four-branch 400 V filter impedance as a function of frequency

SECOND ORDER DAMPED FILTERS

8. What are design steps for second order damped filters.

Second-Order Damped Filters

Design steps: For a second-order damped filter tuned to the h_n harmonic:

- Determine the capacitor size Q_C in MVAr, say the reactive power requirement of the harmonic source.
- The capacitor's reactance is

$$X_C = \frac{\text{kV}^2}{Q_C}$$

- To trap the h_n harmonic, the reactor should have a size of

$$X_L = \frac{X_C}{h_n^2}$$

- The resistor bank has a size of

$$R = X_n \cdot Q$$

where Q is the filter's quality factor, $0.5 < Q < 5$.

The characteristic reactance is given by

$$X_n = X_{Ln} = X_{Cn} = \sqrt{X_L\, X_C} = \sqrt{\frac{L}{C}}$$

Filter size is then

$$Q_{\text{Filter}} = \frac{\text{kV}^2}{X_C - X_L} = \frac{h_n^2}{h_n^2 - 1} \cdot Q_C$$

For a second-order damped filter, the impedance at any harmonic h becomes

$$\begin{aligned} Z_F(h) &= \frac{jRhX_L}{R + jhX_L} - j\frac{X_C}{h} \\ &= \frac{R(hX_L)^2}{R^2 + (hX_L)^2} + j\left(\frac{R^2hX_L}{R^2 + (hX_L)^2} - \frac{X_C}{h}\right) \end{aligned}$$

The current in the reactor is

$$I_{L_h} = \frac{R}{\sqrt{R^2 + X_{L_h}^2}} \cdot I_{F_h} = \frac{Q}{\sqrt{Q^2 + (h/h_n)^2}} \cdot I_{F_h}$$

The current in the resistor is

$$\begin{aligned} I_{R_h} &= \frac{X_{L_h}}{\sqrt{R^2 + X_{L_h}^2}} \cdot I_{F_h} = \frac{h/h_n}{\sqrt{Q^2 + (h/h_n)^2}} \cdot I_{F_h} \\ &= \frac{h}{h_n} \cdot \frac{I_{L_h}}{Q} = \frac{hX_L}{R} \cdot I_{L_h} \end{aligned}$$

Power loss in the resistor is

$$P_R = \sum_{h=1} R\, I_{R_h}^2 = \frac{X_L^2}{R} \sum_{h=1} (h\, I_{L_h})^2$$

Example 5.6. A second-order damped filter is tuned to $h_n \geq 17$. Knowing $X_C = 1.734\ \Omega$, calculate the filter elements and plot its impedance.

Solution The reactor size is

$$X_L = \frac{X_C}{h_n^2} = 0.006\ \Omega$$

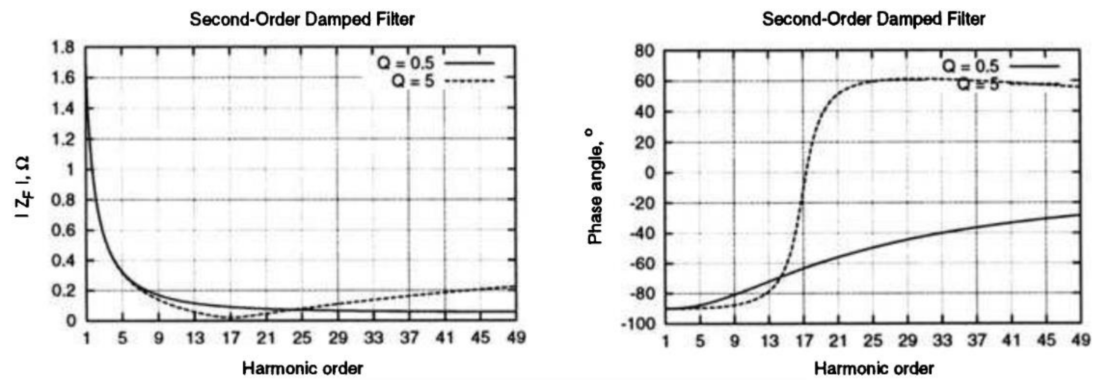
The characteristic reactance is

$$X_n = \sqrt{X_L\ X_C} = 0.102\Omega$$

For a quality factor of 0.5 and 5, the resistor bank size is

$$R = X_n \cdot Q = \begin{cases} 0.051\ \Omega & \text{for } Q = 0.5 \\ 0.51\ \Omega & \text{for } Q = 5 \end{cases}$$

The filter impedance is plotted in Fig.



Impedance of a second-order damped filter

Example 5.7. A 33 kV, 6.8 MVAr capacitor bank is to be used as a second-order damped filter tuned to $h_n \geq 4$. Find the elements of the filter.

Solution Filter elements are calculated as follows and the impedance is plotted in Fig. 5.9.

$$X_C = \frac{33^2}{6.8} = 160\ \Omega$$

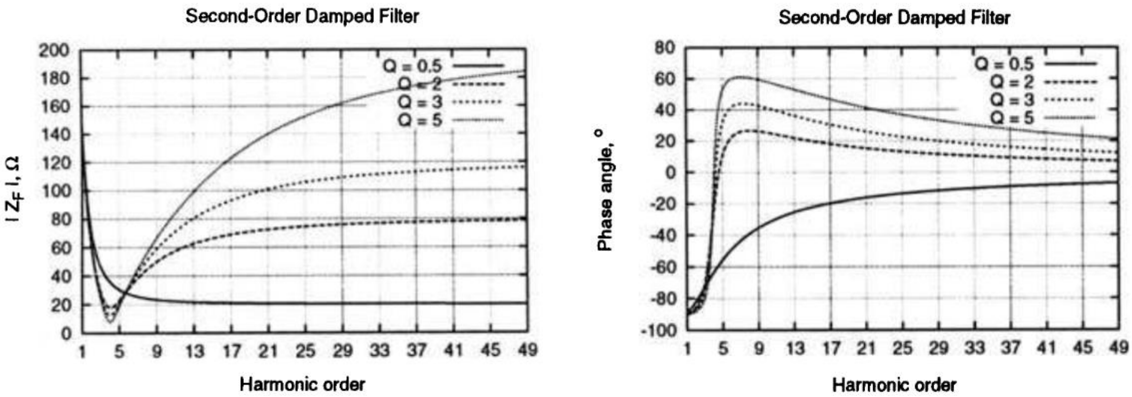
$$X_L = \frac{X_C}{h_n^2} = 10\ \Omega$$

$$X_n = \frac{X_C}{h_n} = h_n X_L = \sqrt{X_L X_C} = 40\ \Omega$$

$$R = X_n \cdot Q = 20\ \Omega,\ 80\ \Omega,\ 120\ \Omega,\ 200\ \Omega \text{ for Q=0.5, 2, 3, 5}$$

Rated filter size is

$$Q_{\text{Filter}} = \frac{\text{kV}^2}{X_C - X_L} = \frac{h_n^2}{h_n^2 - 1} \cdot Q_C = 7.25 \text{ MVAr}$$



. Second-order damped filter impedance

IMPEDANCE PLOTS FOR FILTER BANKS

9. Write short notes on impedance plots for filter banks.

Impedance Plots for Filter Banks

In the following, we present plots for the impedance of three different filter banks, namely:

- a three-branch 33 kV filter; 7^{th} and 11^{th} tuned plus a highpass (second-order damped) branch for all harmonics from the 17^{th} and above.
- a four-branch 20 kV filter; 5^{th}, 7^{th}, 11^{th} and 13^{th} tuned.
- a five-branch 690 V filter; 5^{th}, 7^{th}, 11^{th} and 13^{th} tuned plus a highpass (second-order damped) branch for all harmonics from the 17^{th} and above.

IMPEDANCE PLOTS FOR 3 BRANCH 33 KV FILTER

10. Discuss Impedance plots for 3 branch 33 kV filter.

Consider the 33 kV filter of Table Requested is to provide plots for the filter impedance and calculate the filter rating.

Recalling that

$$X_C = \frac{\mathrm{kV}^2}{Q_C}$$
$$X_L = \frac{X_C}{h_n^2}$$
$$X_n = \frac{X_C}{h_n} = h_n\, X_L = \sqrt{X_L\, X_C}$$
$$R = \begin{cases} \dfrac{X_n}{Q} & \text{for a series-tuned filter} \\ X_n \cdot Q & \text{for a damped filter,} \end{cases}$$

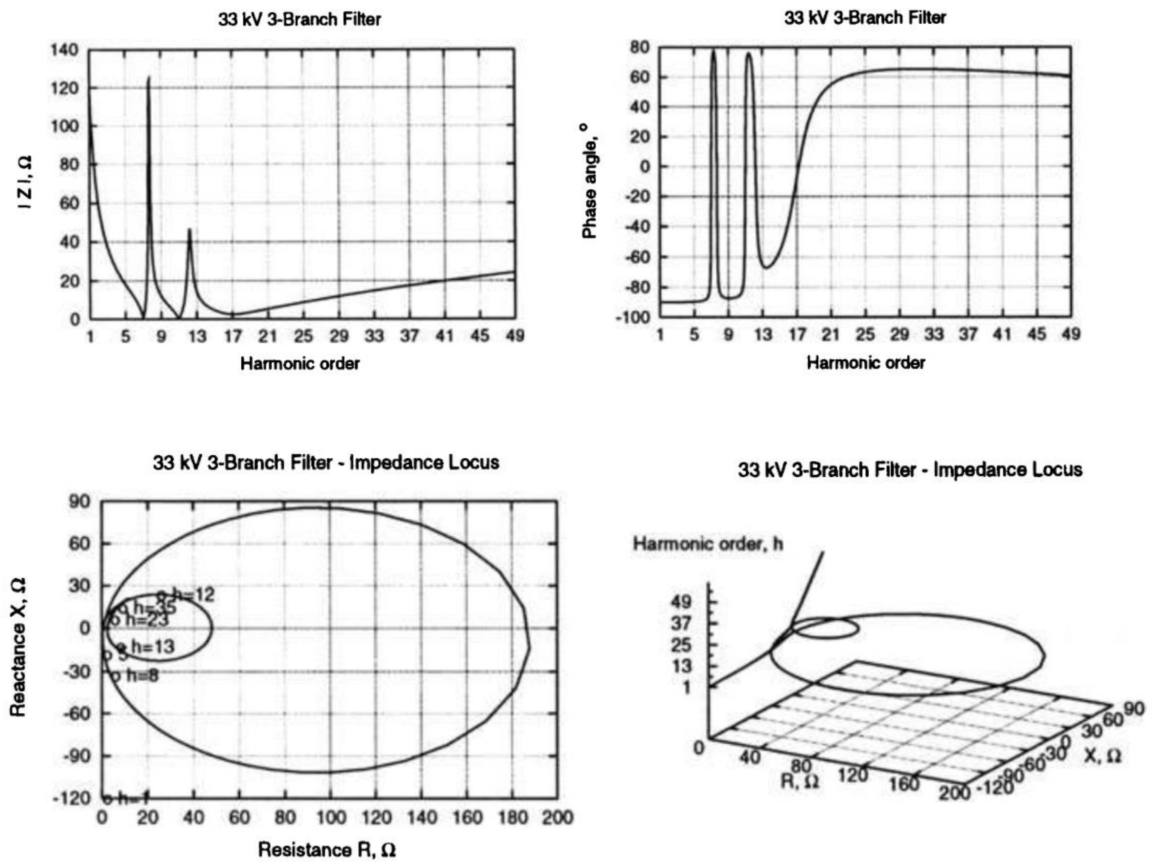
filter elements are readily calculated and provided in Table The filter rated size is calculated as

$$Q_{Filter} = \sum \frac{\mathrm{kV}^2}{X_C - X_L} = \sum \frac{h_n^2}{h_n^2 - 1} \cdot Q_C = 9.076 \text{ MVAr}$$

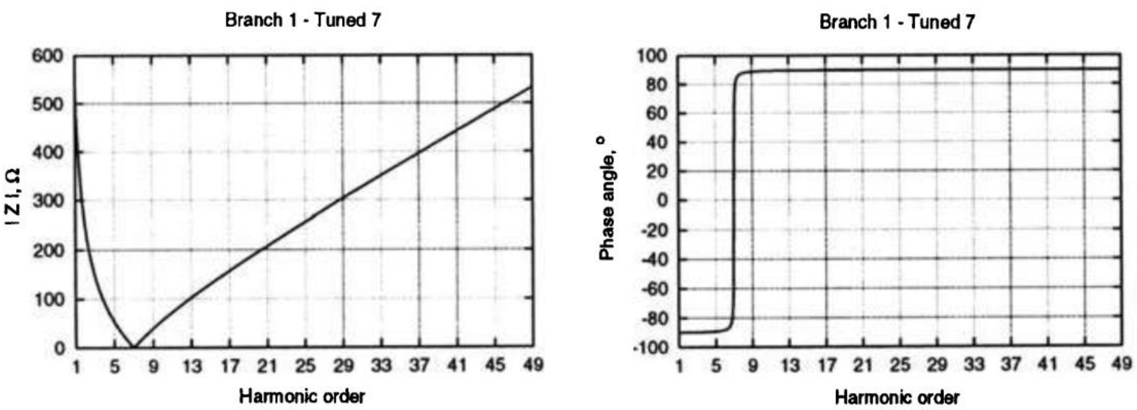
Ten plots for the filter impedance (magnitude and angle) are presented in Figs.

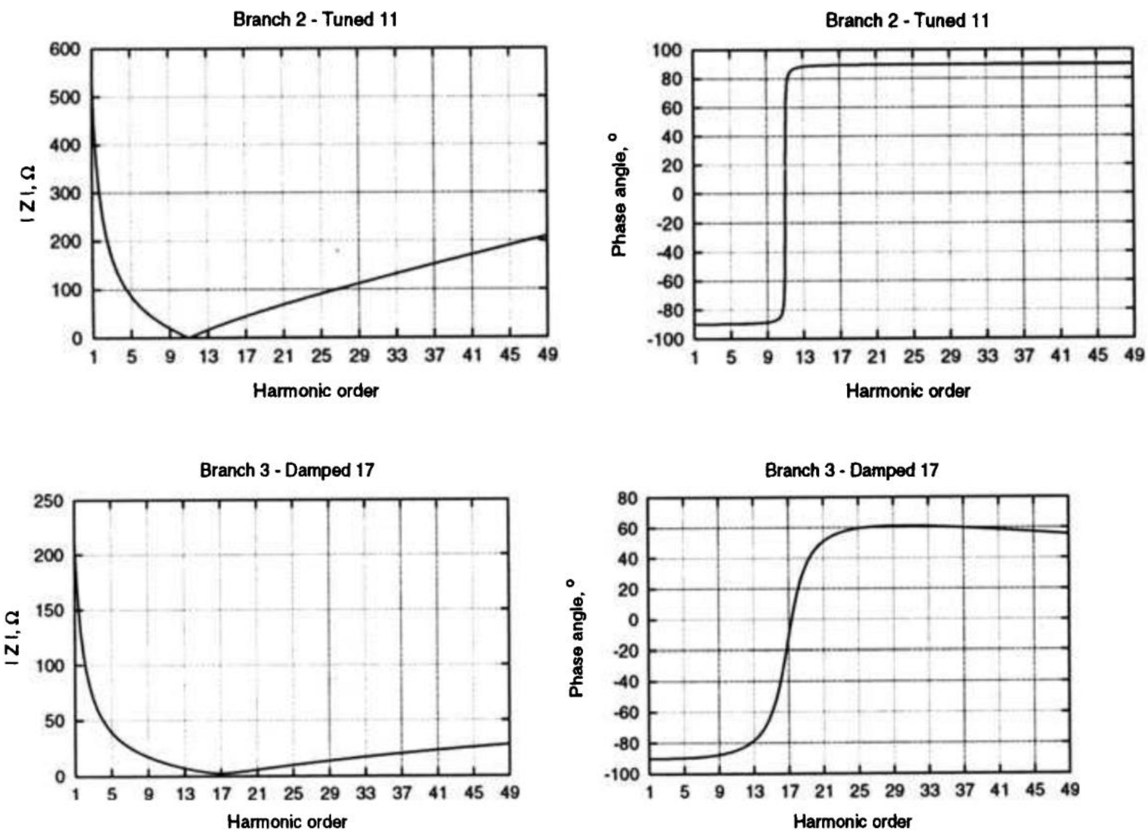
Table Filter data – 33 kV

#	Type	h_n	Q	Q_C (MVAr)	R (Ω)	X_L (Ω)	X_C (Ω)	X_n (Ω)
1	Tuned	7	100	2	0.77786	11.1122	544.5	77.7857
2	Tuned	11	100	2	0.495	4.5	544.5	49.5
3	Damped	17	5	5	64.0588	0.7536	217.8	12.8118



Three-branch filter impedance and impedance locus





Impedance plots for the three-branch filter

UNIT – 4

LOAD COMPENSATION USING DSTATCOM

Compensating single - phase loads – Ideal three phase shunt compensator structure – generating reference currents using instantaneous PQ theory – Instantaneous symmetrical components theory – Generating reference currents when the source is unbalanced –Realization and control of DSTATCOM – DSTATCOM in Voltage control mode.

1. What is load compensation?

Load compensation is the management of reactive power to improve power quality i.e. V profile and pf. Here the reactive power flow is controlled by installing shunt compensating devices (capacitors/reactors) at the load end bringing about proper balance between generated and consumed reactive power.

2. How load compensation is achieved using DSTATCOM?

Conversely, DSTATCOM is a custom power device connected in shunt with the load. It injects currents in the ac system such that the load compensation is achieved irrespective of unbalance or distortion in either source or load side.

3. What are the needs of load compensation?

The main objectives in load compensation are: Improved voltage profile • Power factor improvement • Balanced load. It is important to maintain the voltage profile within +-5% of the rated value. The main reason for voltage variation is unbalanced parameters in the generation side and consumption side.

4. What is the function of load compensator?

A load compensator coupled between the voltage regulator output and the reference voltage, the load compensator being operable to substantially suppress ringing on the voltage regulator output. a second voltage regulator operable to generate the third supply voltage from the first supply voltage.

5. What is compensation in power system?

The term compensation is used to describe the intentional insertion of reactive power devices, capacitive or inductive, into a power network to achieve a desired effect. This may include improved voltage profiles, improved power factor, enhanced stability performance, and improved transmission capacity.

6. What is single phase load compensation?

Single phase load compensation is uses for the purpose of the reducing the reactive and harmonic parts of the load currents.

7. What is the difference between compensated and uncompensated transmission lines?

Series compensated transmission lines allow power transfer at the same voltage level over longer transmission lines than uncompensated lines. This better utilizes the existing transmission network, which is cost effective and quicker rather than building new or additional parallel lines 5.

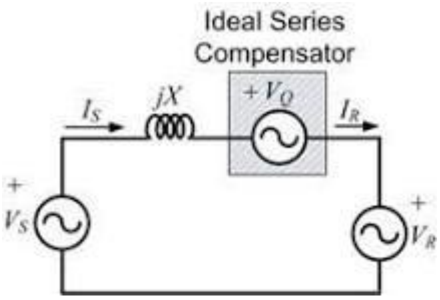
8. What is shunt compensation?

Shunt compensation is applied by using shunt capacitors and shunt reactors that are permanently connected to the network or switched on and off according to operating conditions. Shunt capacitors help increase the system load ability and reduce the voltage drop in the line by improving the power factor.

9. What are the types of compensators?

There are three types of compensators: lag, lead and lag-lead compensators. Adjusting a control system in order to improve its performance might lead to unexpected behaviour (e.g. poor stability or even instability by increasing the gain value).

10. What is ideal compensator?



Let us assume that the series compensator is represented by an ideal voltage source. This is shown in Fig. Let us further assume that the series compensator is ideal, i.e., it only supplies reactive power and no real power to the system.

11. What is generating reference currents using instantaneous PQ theory?

The basic PQ theory method of reference current generation involves conversion of three phase measured voltage and current data acquired into two phase data in the first step. Next total active power and reactive power that can be generated from this measured current and voltage amount, is extracted.

12. What is the basic principle of P and Q control?

As shown above, the p − q Theory is very precise for the calculation of the compensating currents in shunt active fil- ters if the voltages are balanced and sinusoidal. In addi- tion, the compensation may be perfect if the inverter used to synthesize the compensation current has a high frequency response.

13. What is the formula for instantaneous reactive power?

$p_{\beta p} = u_\beta \, i_{\beta p}$: β-phase instantaneous active power. $p_{\alpha q} = u_\alpha \, i_{\alpha q}$: α-phase instantaneous reactive power. $p_{\beta q} = u_\beta \, i_{\beta q}$: β-phase instantaneous reactive power.

14. What is instantaneous power in a three-phase circuit?

The instantaneous power of a 3-phase system is constant and equal to equal to 3 times of power per phase. $P_{instantaneous} = 3\ Vp\ Ip \cos \phi$ = constant for a 3-phase balanced system.

15. What is instantaneous active power?

The portion of instantaneous power that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as instantaneous active power, and its time average is known as active power or real power.

16. What is the difference between instantaneous power and complex power?

It is the product of the time functions of the voltage and current. This definition of instantaneous power is valid for signals of any waveform. The unit for instantaneous power is VA. Complex power is the product of the complex effective voltage and the complex effective conjugate current.

17. What is the instantaneous power theory in instantaneous power theory and applications to power conditioning?

The instantaneous power theory, or “the p-q theory,” makes clear the physical meaning of what instantaneous real and imaginary power is in a three-phase circuit. Moreover, it provides insight into how energy flows from a source to a load, or circulates between phases, in a three-phase circuit.

18. What is instantaneous symmetrical components theory?

The instantaneous symmetrical components are used for dynamic compensation, balancing and control of power systems by means of static compensators.

19. What is the theory of symmetrical components?

The method of symmetrical components is used to simplify fault analysis by converting a three-phase unbalanced system into two sets of balanced phasors and a set of single-phase phasors, or symmetrical components. These sets of phasors are called the positive-, negative-, and zero-sequence components.

20. Why symmetrical components are used in power system fault analysis?

In conclusion, the symmetrical components are used in fault analysis because they simplify the analysis of unbalanced systems, reduce the number of equations required for analysis, and provide the sequence voltages and currents required for many applications.

21. What are the symmetrical components of balanced three-phase systems?

In the most common case of three-phase systems, the resulting "symmetrical" components are referred to as direct (or positive), inverse (or negative) and zero (or homopolar).

22. What are the advantages of symmetrical components?

Is a powerful analytical tool and also conceptually useful.

In case of symmetrical networks the calculation of unbalanced conditions is quite simple because the unbalanced system is converted in balanced systems easy to solve.

23. What happens when current is unbalanced in a motor?

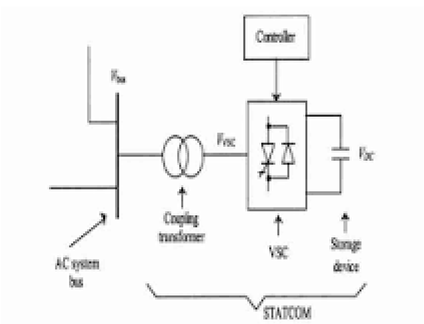
Voltage unbalance at the motor terminals causes high current unbalance, which can be 6 to 10 times as large as the voltage unbalance. Unbalanced currents lead to torque pulsation, increased vibration and mechanical stress, increased losses, and motor overheating.

24. What is the effect of unbalanced load on a generator?

Unbalanced loads can produce adverse harmonics.

When a generator is connected to both three-phase loads, such as motors, and single-phase loads, any out of balance can create electrical supply problems to the motor load.

25. What is the operation and control of DSTATCOM?



There are two control objectives implemented in the DSTATCOM. One is the ac voltage regulation of the power system at the bus where the DSTATCOM is connected. And the other is dc voltage control across the capacitor inside the DSTATCOM.

26. What is the principle of DSTATCOM?

The basic operating principle of a DSTATCOM is similar to that of the Synchronous machine. The Synchronous machine will provide lagging current when under-excited (Ex < V) and leading current when over-excited (Ex > V).

27. What are the components of DSTATCOM?

The major components of a DSTATCOM are a dc capacitor, one or more inverter modules, ac filter, coupling transformer and a control strategy

28. What is DSTATCOM in voltage control mode?

In a voltage control mode, the DSTATCOM is connected at a utility bus to maintain a balanced voltage at that bus, irrespective of unbalance or distortion in either side of the bus. In this mode, the operation and maintenance of the DSTATCOM is the responsibility of the utility.

29. What are the control methods of STATCOM?

Control strategies of a STATCOM. In general, the three basic control strategies of a STATCOM are used: a) constant reactive power, b) voltage control according to the U/I control characteristic presented in constant reactive current when the STATCOM's current limits are reached.

30. What is DSTATCOM in power quality?

The distribution static compensator (DSTATCOM) provides fast control of active and reactive powers to enable load compensation, harmonics current elimination, voltage flicker mitigation, voltage and frequency regulation.

31. What are the disadvantages of DSTATCOM?

The three-phase four-wire DSTATCOM has a main drawback of generating the harmonics distortion. When the three-phase four-wire DSTATCOM uses voltage controller to stabilize the voltage, the harmonics distortion is generated in the current waveform.

32. What is the application of DSTATCOM?

Distribution Static Power Compensator (D-STATCOM) is a device for reactive power compensation in electric distribution networks that presents advantages over conventional capacitors since it avoids power resonances and can perform a continuous compensation reaching a power factor near to unity.

33. What is the difference between DVR and DSTATCOM?

A DVR is a series compensation device which injects a voltage in series with system and a DSTATCOM is a shunt compensation device which injects a current into the system to correct the power quality problems.

34. What is the voltage control method?

By operating grid or main sub-distribution on load/off load tap changing arrangement of the transformer. By addition of extra feeders. This reduces the load carrying of the feeder and hence results in reduced voltage drop and improve regulation.

35. What are the methods of controlling power factor?

There are several methods used for power factor correction. The 2 most used are capacitor banks and synchronous condensers. Capacitor banks are systems that contain several capacitors used to store energy and generate reactive power. Capacitor banks might be connected in a delta connection or a star(wye) connection.

36. What are the power quality problems in distribution system?

Some examples of problems that occur due to power quality problems are: Automatic Resets, Data Errors, Equipment Failure, Circuit Board Failure, Memory Loss, Power Supply Problems, UPS Alarms, Software Corruption, and Overheating of electrical distribution systems.

37. What is the importance of voltage control?

Transmission lines simultaneously consume and generate reactive power. The net reactive effect of a transmission line is determined by its loading. Voltage control is performed to maintain the voltage level on the system within acceptable limits. Voltages remain within a specified range for proper equipment operation.

38. Mention DSTATCOM in voltage control mode.

In a voltage control mode, the DSTATCOM is connected at a utility bus to maintain a balanced voltage at that bus, irrespective of unbalance or distortion in either side of the bus. In this mode, the operation and maintenance of the DSTATCOM is the responsibility of the utility.

39. What is the controller in DSTATCOM?

The STATCOM is connected at the load end or distribution side is termed as D-STATCOM in order to achieve the voltage stability. The D-STATCOM is controlled by PI controller. A Distribution Static Compensator is a three phase shunt connected device. It consists of a Voltage Source Converter (VSC) and DC link capacitor.

40. What are the 4 components of a controller?

There are four basic elements of a typical motion control system. These are the controller, amplifier, actuator, and feedback. The complexity of each of these elements will vary depending on the types of applications for which they are designed and built.

PART B

COMPENSATING SINGLE PHASE LOADS.

1. WRITE SHORT NOTES ON COMPENSATING SINGLE PHASE

LOADS.

Compensating Single-Phase Loads

The schematic diagram of a single-phase load compensator is shown in Figure . In this diagram a voltage source is supplying a load that could be nonlinear as well. The point of connection of the load and the source is the point of common coupling (PCC). Since there is no feeder joining the source and the load, we shall designate the source to be stiff. Here the compensator consists of an H-bridge inverter and an interface inductor (L_f). The resistance R_f represents the resistance of the interface inductor due to its finite Q-factor as well as the losses in the inverter. One end of the compensator is connected at the PCC through the interface inductor while the other end is connected with the load ground. The dc side of the compensator is supplied by a dc capacitor C_{dc}. The inverter is expected to be controlled to maintain a voltage V_{dc} across this capacitor.

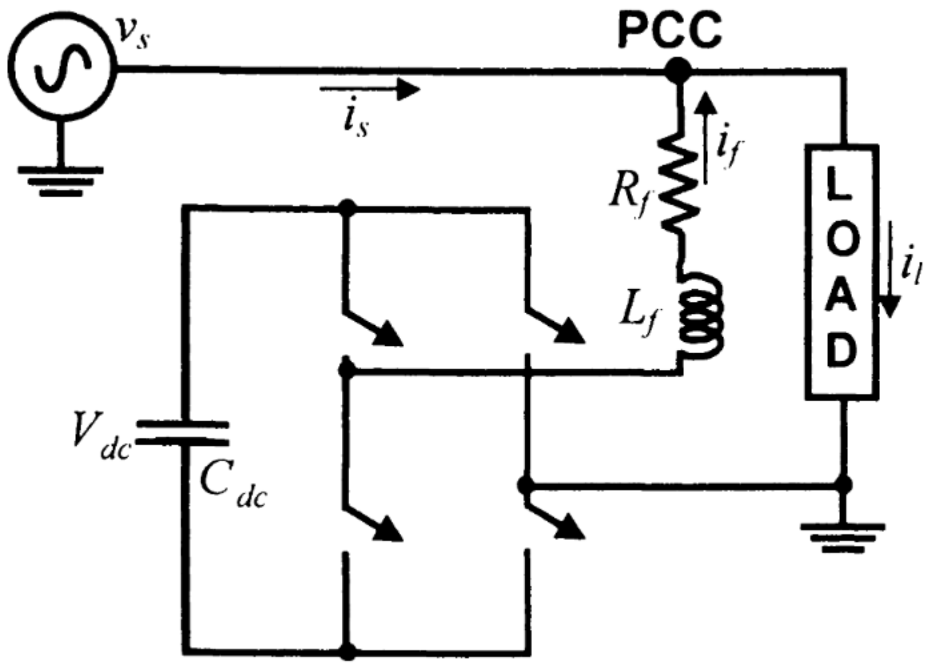
Let us assume that the load is nonlinear and draws a current that has a poor power factor. The instantaneous load current then can be decomposed as

$$i_l = i_{lp} + i_{lq} + i_{lh}$$

where i_{lp} and i_{lq} are respectively the real and reactive parts of the current required by the load and i_{lh} is the harmonic current drawn by the load. The purpose of the compensator is to inject current i_f such that it cancels out the reactive and harmonic parts of the load current.

Now applying KCL at the PCC we get

$$i_l = i_s + i_f \Rightarrow i_s = i_l - i_f$$



Schematic diagram of a single-phase compensator

We assume that the compensator operates in a hysteresis current control loop in which the compensator current tracks a reference current I_f^*. Let us now choose this reference current as

$$i_f^* = i_{lq} + i_{lh}$$

If the inverter accurately tracks this reference current, then the source current will be equal to the unity power factor current drawn by the load. Since the compensator does not draw or inject any real current, the average power consumed by the compensator is zero. Note that the above approach requires the on-line determination of the instantaneous reactive and harmonic components of the load current. There are however simpler approaches for the determination of the reference current. The following example illustrates one such approach.

Example : Let us assume that a 240 V (rms), 50 Hz source supplies a load that draws a current that has a fundamental and a harmonic part. The fundamental part of the load current has an rms value of 15 A at a power factor of 0.5 (lagging) and the harmonic part contains 5^{th} and 7^{th} harmonics. The instantaneous source voltage and the load current are given by

$$v_s = \sqrt{2} \times 240 \sin(\omega t)$$

$$i_s = \sqrt{2} \times 15\left\{\sin(\omega t - 60^\circ) + \frac{1}{5}\sin 5(\omega t - 60^\circ) + \frac{1}{7}\sin 7(\omega t - 60^\circ)\right\}$$

where $\omega = 100\pi$. The load current is shown in Figure

Note that the source must supply only the real power required by the load. This can be accomplished by calculating the average power required by the load through a moving average filter that has an averaging window of half a cycle (10 ms). Let this average be denoted by p_{lav}. Since the desired source current must be unity power factor, its expression is then given by

$$i_s^* = \sqrt{2} \times \frac{p_{lav}}{240} \sin(\omega t)$$

Since the source voltage is assumed to be a pure sinewave, the desired source current can be obtained through template matching, i.e., by taking samples of the instantaneous source voltage and scaling it by the factor $p_{lav}/240^2$. The reference compensator current is then given by the relation $I_f^* = I_l - I_s^*$.

The system response is shown in Figure In this study, the system parameters chosen are

$$R_f = 0, \quad L_f = 20\,\text{mH}, \quad V_{dc} = 600\,\text{V}$$

It is assumed that the compensator is supplied by a constant voltage source and not a dc capacitor. Figure 7.2 (b) shows the scaled version of the source voltage and the source current. The source voltage is scaled by a factor of 10 such that its magnitude is comparable to that of the source current. The compensator is switched on once the p_{lav} is obtained after the first half cycle. It can be seen that the source current becomes sinusoidal and in phase with the source voltage after the first half cycle (10 ms). The current tracking error ($I_f^* - I_f$) is shown in Figure (c). This error jumps as soon as the compensator is connected but then settles immediately. The compensator power is shown in Figure (d). Even though the power is oscillating, its mean is zero. This implies that the compensator supplies the reactive and harmonic power required by the load, but no real power.

The above example assumes that the compensator is supplied by a dc source. This however is an invalid assumption and in practical cases the source is replaced by a dc capacitor. Also we have assumed that the system is lossless (i.e., $R_f = 0$). This is also an invalid assumption. Therefore an additional loop must be incorporated for the control of the dc capacitor voltage control. Note that the losses in the system must be replenished by the supply itself. Thus the dc capacitor voltage can be held constant equal to a reference value if the current drawn from the source is higher than that given

by . The additional amount of current is supplied to the capacitor to maintain its voltage constant. To accomplish this the dc capacitor voltage is averaged over one cycle. It is then compared with the reference voltage. The error is then put through an additional proportional-plus-integral (PI) or proportional-plus-differential (PD) loop. The output of this controller is added to the magnitude of the current calculated in (7.4).

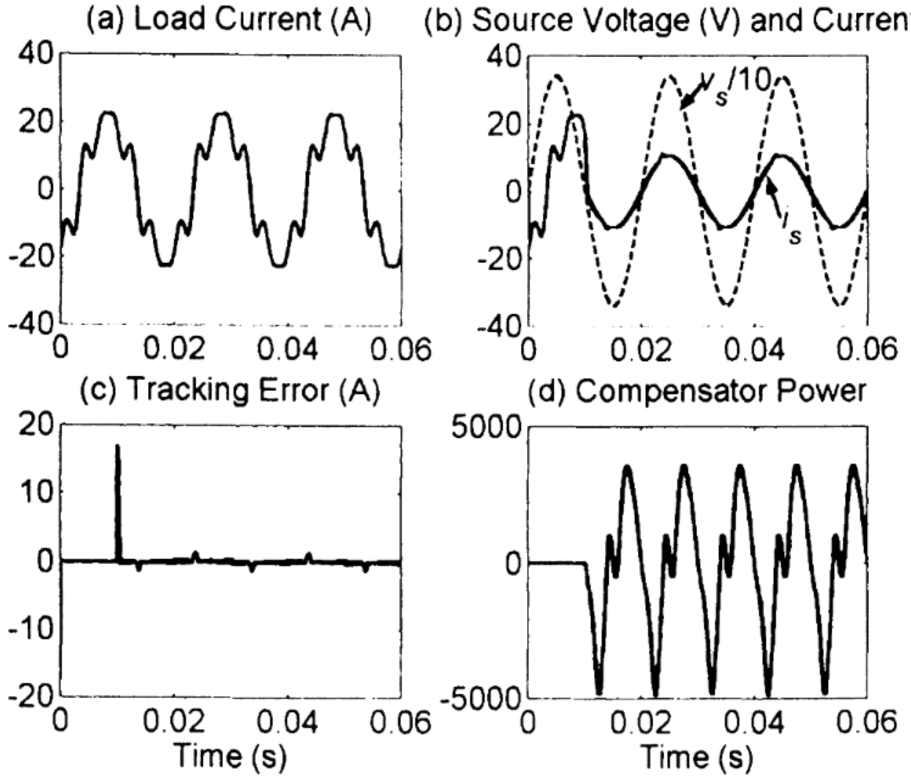


Figure . System response with single-phase compensator

The implementation aspects and dc capacitor loop control of a single-phase DSTATCOM are discussed However since the power system is three-phase, the single-phase compensator has little value. Suppose we take the simplistic view that if we put three single-phase compensators then we can compensate a three-phase system. Even though this will enable us to cancel the reactive and harmonic currents in each phase, we shall not be able to balance an unbalanced load. The load balancing requires redistribution of real power equally between the phases. This will not be possible by three separate single-phase compensators. We shall therefore not consider this structure any further and will only discuss three-phase compensators.

IDEAL THREE PHASE SHUNT COMPENSATOR STRUCTURE

2. DISCUSS IDEAL THREE PHASE SHUNT COMPENSATOR STRUCTURE .

Ideal Three-Phase Shunt Compensator Structure

To illustrate the functioning of shunt compensator, consider the three-phase, four-wire (3p4w) distribution system shown in Figure All the currents and voltages that are indicated in this figure are instantaneous quantities. Here a three-phase balanced supply (v_{sa}, v_{sb}, v_{sc}) is connected across a star (Y) connected load. The loads are such that the load currents

(i_{la}, i_{lb}, i_{lc}) may not be balanced, may contain harmonics and dc offset. In addition, the power factor of the load may be poor. One implication of load not being balanced in this system is that there may be zero-sequence current i_{Nn} flowing in the 4th wire, i.e., in the path n-N as shown in Figure

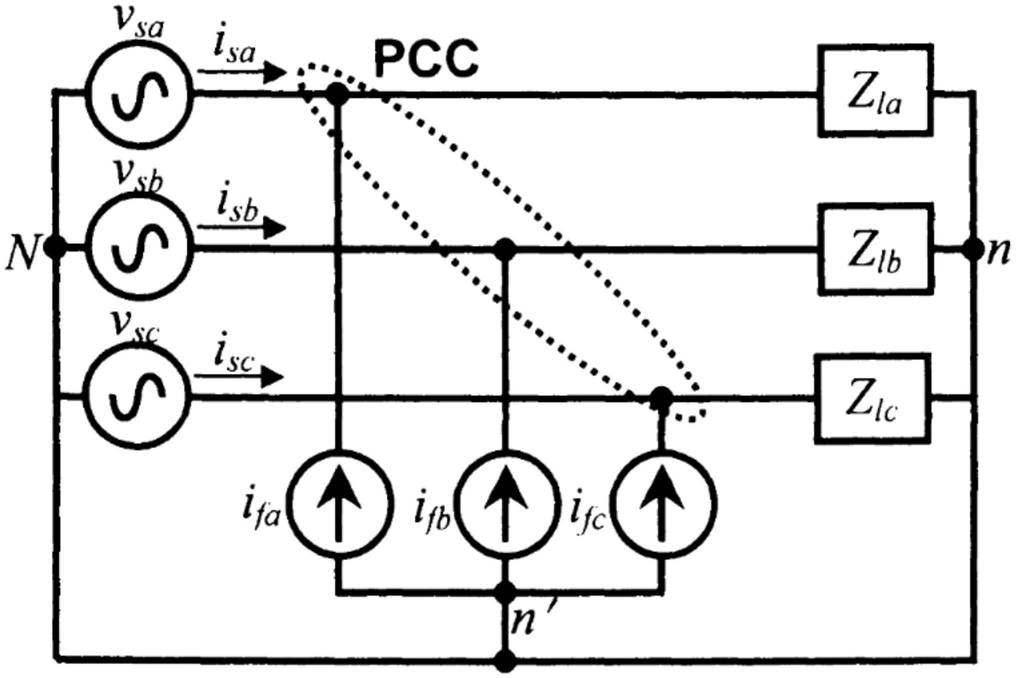


Figure Schematic diagram of a shunt compensator for 3p4w distribution system that is supplying a Y-connected load

The shunt compensator is represented by three ideal current sources i_{fa}, i_{fb} and i_{fc}. The point of common coupling (PCC) is encircled in Figure . The current sources are connected in Y with their neutral n' being connected to the 4th wire. The purpose of the shunt compensator is to inject currents in such a way that the source currents (i_{sa}, i_{sb}, i_{sc}) are harmonic free balanced sinusoids and their phase angle with respect to the source voltages (v_{sa}, v_{sb}, v_{sc}) has a desired value. Let us illustrate the idea with the help of the following example. Note that in this chapter all the plots of load instantaneous real and reactive powers are shown in solid lines, the source powers are shown in dashed lines and the compensator powers are shown in dotted lines.

Example : Let the three phase instantaneous source voltages be given in per unit by

$$v_{sa} = \sqrt{2}\sin\omega t\,,\ v_{sb} = \sqrt{2}\sin\left(\omega t - 120^\circ\right) \text{ and } v_{sc} = \sqrt{2}\sin\left(\omega t + 120^\circ\right)$$

with $\omega = 100\pi$. Three unbalanced RL loads are connected across the supply. They are given in per unit as

$$Z_{la} = 6.0 + j3.0\,,\ Z_{lb} = 3.0 + j1.5 \text{ and } Z_{lc} = 7.5 + j1.5$$

In addition, it is assumed that the load is drawing a 5^{th} harmonic current of magnitude 0.05 per unit. The three load currents are then given in per unit by

$$i_{la} = 0.2108\sin\left(\omega t - 26.57^\circ\right) + 0.05\sin 5\omega t$$
$$i_{lb} = 0.4216\sin\left(\omega t - 146.57^\circ\right) + 0.05\sin 5\left(\omega t - 120^\circ\right)$$
$$i_{lc} = 0.1849\sin\left(\omega t + 108.69^\circ\right) + 0.05\sin 5\left(\omega t + 120^\circ\right)$$

The load currents are shown in Figure (a).

Let us now design a shunt compensator that does not supply any real power to the load. The entire amount of real power must then come from the supply. As per the discussion of the previous section, the real power supplied by the source is strictly utilized by the fundamental component of the load. The instantaneous power to the load is shown in Figure 7.4 (b). This power consists of a dc component and an oscillating component. The dc component with a mean value of 0.5282 per unit is the average real power supplied by the source. The average power in each phase will then be 0.1761 per unit.

It has been mentioned before that the shunt compensator can also correct the supply side power factor. Let us choose the desired supply power factor to be unity. The three source currents for this power level and power factor, are then given in per unit by

$$i_{sa} = \sqrt{2} \times 0.1761 \sin \omega t = 0.249 \sin \omega t$$
$$i_{sb} = 0.249 \sin\left(\omega t - 120^\circ\right)$$
$$i_{sc} = 0.249 \sin\left(\omega t + 120^\circ\right)$$

Applying KCL at the PCC we can write the following expression for the compensator currents

$$i_{f\beta} = i_{l\beta} - i_{s\beta}, \quad \beta = a, b, c$$

The various instantaneous quantities of the compensated system are shown in Figure 7.4. From Figure 7.4 (a) it can be seen that the load currents are distorted due to the presence of the 5th harmonic component. The three instantaneous powers are shown in Figure 7.4 (b). It can be seen that the instantaneous power drawn from the source (p_s) is constant even when the instantaneous power into the load (p_l) is oscillating and distorted. It is obvious then that the average component of the power comes from the source while the oscillating component comes from the compensator (p_f). It can also be seen that the compensator power (p_f) has mean of zero. This

implies that the compensator does not supply any real power. The compensator currents are shown in Figure (c). The source voltage and current of phase-a are shown in Figure (d). In this figure the source voltage is scaled by a factor of 4 such that its magnitude is of the same order as the source current. Figure 7.4 (d) clearly demonstrates that the source voltage and current are in the same phase. This example clearly demonstrates that the shunt compensator balances the source currents, corrects their power factor to unity and eliminates harmonic from the source currents.

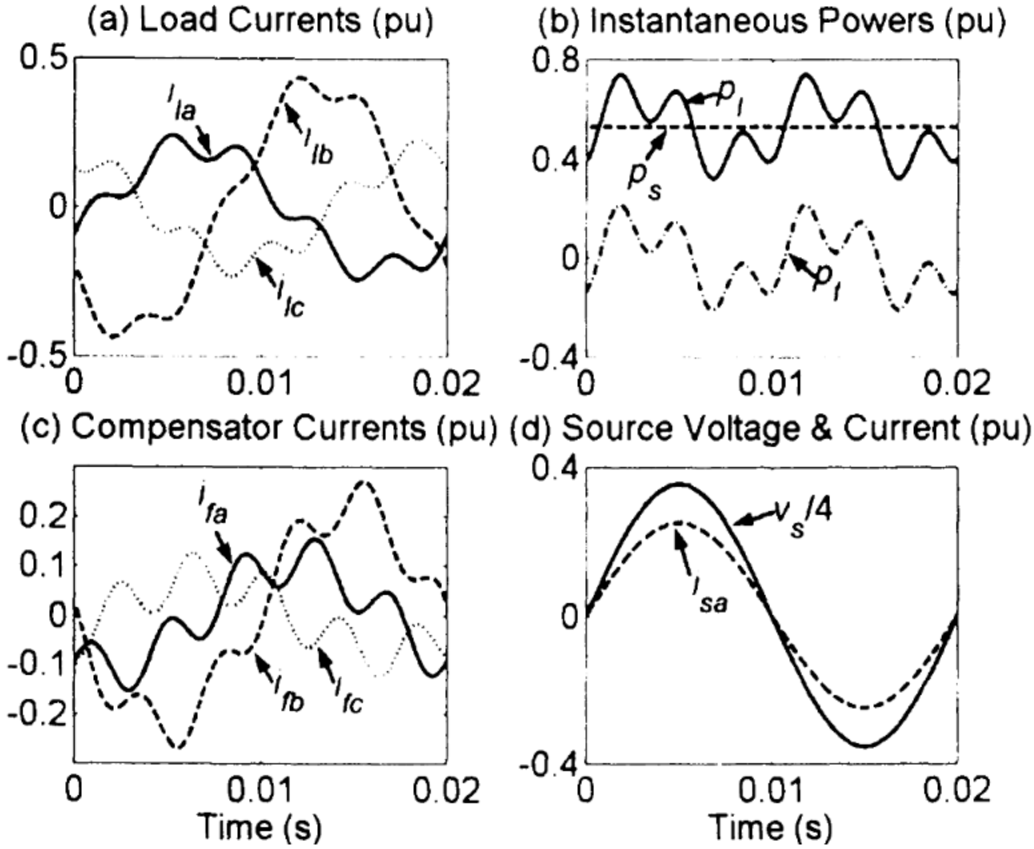


Figure . The system performance with the shunt compensator of Example

The compensator structure of Figure can be used in a three-phase system when the load is Y-connected. When used in a three-phase, four-wire distribution system, the compensator balances the supply current thereby eliminating the neutral current. When the same structure is used in a three-phase, three-wire distribution system that supplies a Y-connected load, the link between the supply neutral (*N*) and the load neutral (*n*) is not present. However, the connection $n' - n$ is still important as this provides a path for the zero-sequence current to flow when the load is unbalanced.

The compensator structure of a three-phase, three-wire (3p3w) system supplying a Δ-connected load is shown in Figure . Like in the case of a Y-connected load, the compensator, represented by three current sources, are connected in parallel with the load. The only difference being that in the previous case, the compensator branches were connected between line and neutral and in this case they are connected between two lines.

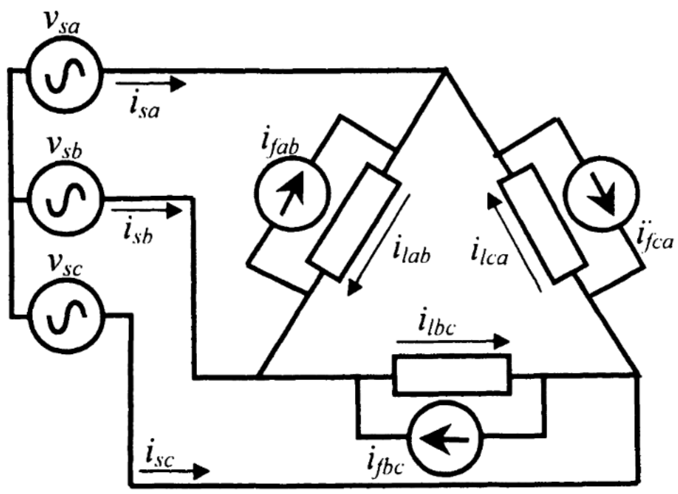


Figure Schematic diagram of a shunt compensator for 3p3w distribution system that is supplying a Δ-connected load

The first step in shunt compensation, as illustrated in Example , is to generate a set of compensator currents i_{fa}, i_{fb} and i_{fc}. In actual practice the compensator is not made of three ideal current sources, but of a power electronic circuit that injects these currents in the distribution system. We shall therefore call these the reference currents of the compensator.

In Example we generated the reference current by characterizing the load completely and extracting the component to be compensated. This however, is not desirable and may not even be possible as the load may change frequently. It is therefore imperative that the compensator reference currents be generated based on measurements of real-time quantities like voltages, currents and power. Again, as the compensator currents are instantaneous quantities, it will be desirable to generate them on an instant by instant basis. Below we present various techniques that can be used for the generation of the three-phase reference currents of the compensator.

INSTANTANEOUS PQ THEORY

3. WITH SUITABLE EQUATIONS EXPLAIN GENERATING REFERENCE CURRENTS USING INSTANTANEOUS PQ THEORY.

Hirofumi Akagi and his coworkers have described an instantaneous method of generating reference currents for shunt compensator in
Since then various interpretations of this method have been presented
This method is applicable to a three-phase, four-wire system. To begin with, we transform the three-phase voltages from *a-b-c* frame to *α-β-0* frame and vice versa using the following power invariant transformation

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix}$$

We can also use the same transform matrix for transforming currents. The instantaneous three-phase power is then given by

$$p_{3\phi} = v_a i_a + v_b i_b + v_c i_c = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 = p + p_0$$

where p is the total instantaneous real power in the three phase wires and $p_0 = v_0 i_0$ is the instantaneous power in the zero-sequence network. Let us define the following variable

$$q = v_\alpha i_\beta - v_\beta i_\alpha = \frac{1}{\sqrt{3}}\{i_a(v_c - v_b) + i_b(v_a - v_c) + i_c(v_b - v_a)\}$$

We now investigate the fundamental frequency equivalent of the variable q through the following example.

Example : Let us consider the following balanced three-phase voltages and currents

$$\begin{aligned} v_a &= V_m \sin\omega t & i_a &= I_m \sin(\omega t - \phi) \\ v_b &= V_m \sin(\omega t - 120^0), & i_b &= I_m \sin(\omega t - 120^0 - \phi) \\ v_c &= V_m \sin(\omega t + 120^0) & i_c &= I_m \sin(\omega t + 120^0 - \phi) \end{aligned}$$

We can then write

$$\begin{aligned} v_a - v_b &= \sqrt{3} V_m \sin(\omega t + 30^\circ) \\ v_b - v_c &= \sqrt{3} V_m \sin(\omega t - 90^0) \\ v_c - v_a &= \sqrt{3} V_m \sin(\omega t + 150^0) \end{aligned}$$

Using the above relations we get

$$i_a(v_b - v_c) = -\sqrt{3}V_m I_m\{\cos\omega t\sin(\omega t - \phi)\}$$
$$= -\frac{\sqrt{3}}{2}V_m I_m\{\sin(2\omega t - \phi) - \sin\phi\}$$
$$i_b(v_c - v_a) = -\sqrt{3}V_m I_m\{\cos(\omega t - 120^\circ)\sin(\omega t - 120^\circ - \phi)\}$$
$$= -\frac{\sqrt{3}}{2}V_m I_m\{\sin(2\omega t - 240^\circ - \phi) - \sin\phi\}$$
$$i_c(v_a - v_b) = -\sqrt{3}V_m I_m\{\cos(\omega t + 120^\circ)\sin(\omega t + 120^\circ - \phi)\}$$
$$= -\frac{\sqrt{3}}{2}V_m I_m\{\sin(2\omega t + 240^\circ - \phi) - \sin\phi\}$$

Adding the above three terms together we get

$$i_a(v_b - v_c) + i_b(v_c - v_a) + i_c(v_a - v_b) = \frac{3\sqrt{3}}{2}V_m I_m\sin\phi = \sqrt{3}\,Q = -\sqrt{3}\,q$$

where Q is the reactive power required by the circuit.

ΔΔΔ

We thus see that the quantity q given in equn. is the reactive power absorbed by a circuit when both voltages and currents contain only the fundamental frequency. However, this quantity can be used in a much broader context when either voltages or currents or both have many frequency components. Akagi et al called this term the instantaneous imaginary power [7]. We can write from equn.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

This is equivalent to writing

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix}$$

$$= \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \left\{ \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ q \end{bmatrix} \right\} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix}$$

The following components of current can then be defined from the above equation

α - axis instantaneous active current: $i_{\alpha p} = \dfrac{v_\alpha}{v_\alpha^2 + v_\beta^2} p$

α - axis instantaneous reactive current: $i_{\alpha q} = -\dfrac{v_\beta}{v_\alpha^2 + v_\beta^2} q$

β - axis instantaneous active current: $i_{\beta p} = \dfrac{v_\beta}{v_\alpha^2 + v_\beta^2} p$

β - axis instantaneous reactive current: $i_{\beta q} = \dfrac{v_\alpha}{v_\alpha^2 + v_\beta^2} q$

Let the instantaneous powers in α-axis and β-axis be denoted respectively by p_α and p_β. We can then write from

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha \\ v_\beta i_\beta \end{bmatrix} = \begin{bmatrix} v_\alpha i_{\alpha p} \\ v_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} v_\alpha i_{\alpha q} \\ v_\beta i_{\beta q} \end{bmatrix} = \begin{bmatrix} p_{\alpha p} \\ p_{\beta p} \end{bmatrix} + \begin{bmatrix} p_{\alpha q} \\ p_{\beta q} \end{bmatrix}$$

We now define the following quantities

α - axis instantaneous active power: $p_{\alpha p} = v_\alpha i_{\alpha p}$

α - axis instantaneous reactive power: $p_{\alpha q} = v_\alpha i_{\alpha q}$

β - axis instantaneous active power: $p_{\beta p} = v_\beta i_{\beta p}$

β - axis instantaneous reactive power: $p_{\beta q} = v_\beta i_{\beta q}$

Let us now expand these expressions

$$p_{\alpha p} = \frac{v_\alpha^2}{v_\alpha^2 + v_\beta^2} p, \; p_{\beta p} = \frac{v_\beta^2}{v_\alpha^2 + v_\beta^2} p$$

Adding the above two expressions we get

$$p = p_{\alpha p} + p_{\beta p}$$

Similarly adding the reactive power components we get

$$p_{\alpha q} + p_{\beta q} = 0$$

We can then conclude the following

- The sum of $p_{\alpha p}$ and $p_{\beta p}$ is equal to the instantaneous real power. Therefore they are referred to as instantaneous active powers.
- The instantaneous powers $p_{\alpha q}$ and $p_{\beta q}$ cancel each other and do not contribute to the real power. They are thus called instantaneous reactive powers.

The instantaneous three-phase power is then given by

$$p_{3\phi} = p_{\alpha p} + p_{\beta p} + p_0$$

Let us consider the following example.

Example : Let the following balanced three-phase voltages

$$v_a = V_m \sin\omega t \, , \; v_b = V_m \sin\left(\omega t - 120^0\right) \text{ and } v_c = V_m \sin\left(\omega t + 120^0\right)$$

be supplying a non-linear load. The load currents contain 3^{rd} and 5^{th} harmonics in addition to the fundamental. These currents are given by

$$i_a = \sum_{n=1,3,5} \frac{I_m}{n} \sin(n\omega t - \phi_n)$$

$$i_b = \sum_{n=1,3,5} \frac{I_m}{n} \sin\{n(\omega t - 120^\circ) - \phi_n\}$$

$$i_c = \sum_{n=1,3,5} \frac{I_m}{n} \sin\{n(\omega t + 120^\circ) - \phi_n\}$$

Transforming the voltages and currents into α-β-0 frame we get

$$v_0 = \frac{1}{\sqrt{3}}\{v_a + v_b + v_c\} = 0$$

$$v_\alpha = \sqrt{\frac{2}{3}}\left\{v_a - \frac{1}{2}v_b - \frac{1}{2}v_c\right\} = \sqrt{\frac{3}{2}}v_a = \sqrt{\frac{3}{2}}V_m \sin\omega t$$

$$v_\beta = \frac{1}{\sqrt{2}}\{v_b - v_c\} = -\frac{2}{\sqrt{2}}V_m \cos\omega t \sin 120^\circ = -\sqrt{\frac{3}{2}}V_m \cos\omega t$$

$$i_0 = \frac{1}{\sqrt{3}}\{i_a + i_b + i_c\} = \frac{I_m}{\sqrt{3}}\sin(3\omega t - \phi_3)$$

$$i_\alpha = \sqrt{\frac{2}{3}}\left\{i_a - \frac{1}{2}i_b - \frac{1}{2}i_c\right\} = \sqrt{\frac{3}{2}}I_m \sin(\omega t - \phi_1) + \sqrt{\frac{3}{2}}\frac{I_m}{5}\sin(5\omega t - \phi_5)$$

$$i_\beta = \frac{1}{\sqrt{2}}\{i_b - i_c\} = -\sqrt{\frac{3}{2}}I_m \cos(\omega t - \phi_1) + \sqrt{\frac{3}{2}}\frac{I_m}{5}\cos(5\omega t - \phi_5)$$

It can be seen from the above expression that the 3rd harmonic current is present only in the zero-sequence. Furthermore, the zero-sequence power is given by $p_0 = v_0 i_0 = 0$. We can then get from (7.10)

$$p = v_\alpha i_\alpha + v_\beta i_\beta = \frac{3}{2}V_m I_m\left\{\cos\phi_1 - \frac{1}{5}\cos(6\omega t - \phi_5)\right\}$$

$$q = v_\alpha i_\beta - v_\beta i_\alpha = -\frac{3}{2}V_m I_m\left\{\sin\phi_1 - \frac{1}{5}\sin(6\omega t - \phi_5)\right\}$$

The above example clearly demonstrates that there are two components of real and reactive power present in a system when the load contains harmonics. We can then write

$$p = p_{av} + p_{osc}$$
$$q = q_{av} + q_{osc}$$

where the subscript *av* indicates the mean or dc value and the subscript *osc* indicates the oscillating component. We have already observed the average (dc) power and the oscillating power in Figure The reactive power will also have two similar components. We shall now discuss the reference current generation scheme for the compensator using the above-mentioned theory.

Refer to the compensator structure shown in Figure Suppose we want to compensate only for the reactive power of the load such that the current drawn from the source is unity power factor. The compensator then must supply the entire reactive power requirement of the load. Let $i_{f\alpha}$ and $i_{f\beta}$ be the α-β components of the compensator and $v_{s\alpha}$ and $v_{s\beta}$ be the α-β components of the source voltage v_s. Note from Figure that the source voltage is applied both across the load and the compensator. Now since the compensator must supply the entire load reactive power and no real power, we can write from

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \frac{1}{v_{s\alpha}^2 + v_{s\beta}^2} \begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} 0 \\ q_l \end{bmatrix}$$

where q_l is the instantaneous imaginary power of the load. A reverse transformation using equnwill yield the compensator currents in *a-b-c* plane. In a similar way we can also compensate for both the imaginary power and the oscillating component of the real power. In that case we can modify

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \frac{1}{v_{s\alpha}^2 + v_{s\beta}^2} \begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix} \begin{bmatrix} p_{losc} \\ q_l \end{bmatrix}$$

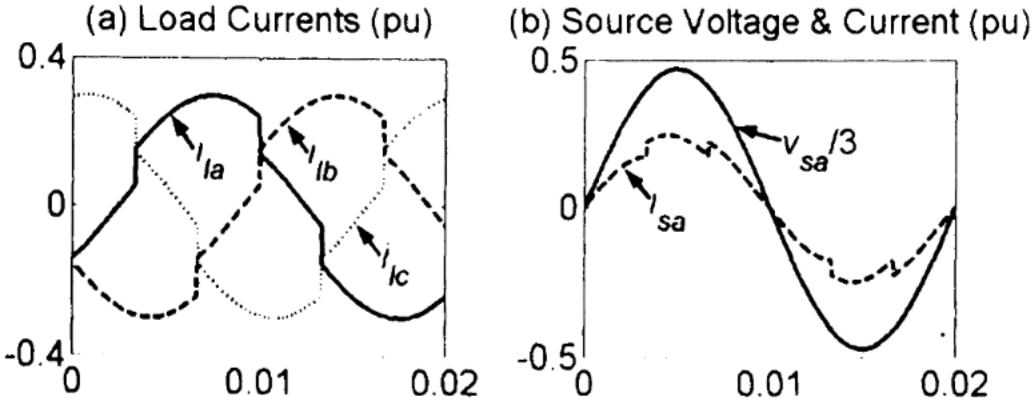
where p_{losc} is the oscillating component of the load power.

Let us now consider the following example on the application of this instantaneous power analysis. Note that in this example and all the subsequent examples of this chapter it is assumed that the compensator is represented by three ideal current sources as shown in Figure for Δ-connected loads). This implies that these current sources inject the exact reference currents obtained through the different algorithms. Practical compensator implementation will be discussed in Chapter 8 where, in particular, it will be shown how the reference currents can be tracked using voltage source inverters.

Example Let a Y-connected balanced RL load be connected to a balanced three-phase supply with an rms value of 1.0 per unit. The instantaneous source voltages and load are given in per unit by

$$v_{sa} = \sqrt{2}\sin\omega t$$
$$v_{sb} = \sqrt{2}\sin\left(\omega t - 120^\circ\right)$$
$$v_{sc} = \sqrt{2}\sin\left(\omega t + 120^\circ\right)$$
$$Z_{la} = Z_{lb} = Z_{lc} = 5.0 + j5.0$$

with $\omega = 100\pi$. In addition to the RL load, the source also supplies a nonlinear load that is drawing square wave current of peak 0.1 per unit. The load currents are shown in Figure (a). Figure (b-d) shows the system plots when only q_l is compensated as per . It is obvious from Figure (b) that the source current is in phase with the source voltage indicating that the entire amount of reactive power is supplied by the compensator. In this figure the source voltage is scaled by a factor of three. The source currents are shown in Figure (c). It can be seen that they are distorted and this is totally undesirable. The instantaneous powers are shown in Figure (d). It can be seen that the compensator power is zero while the load and source powers are equal.



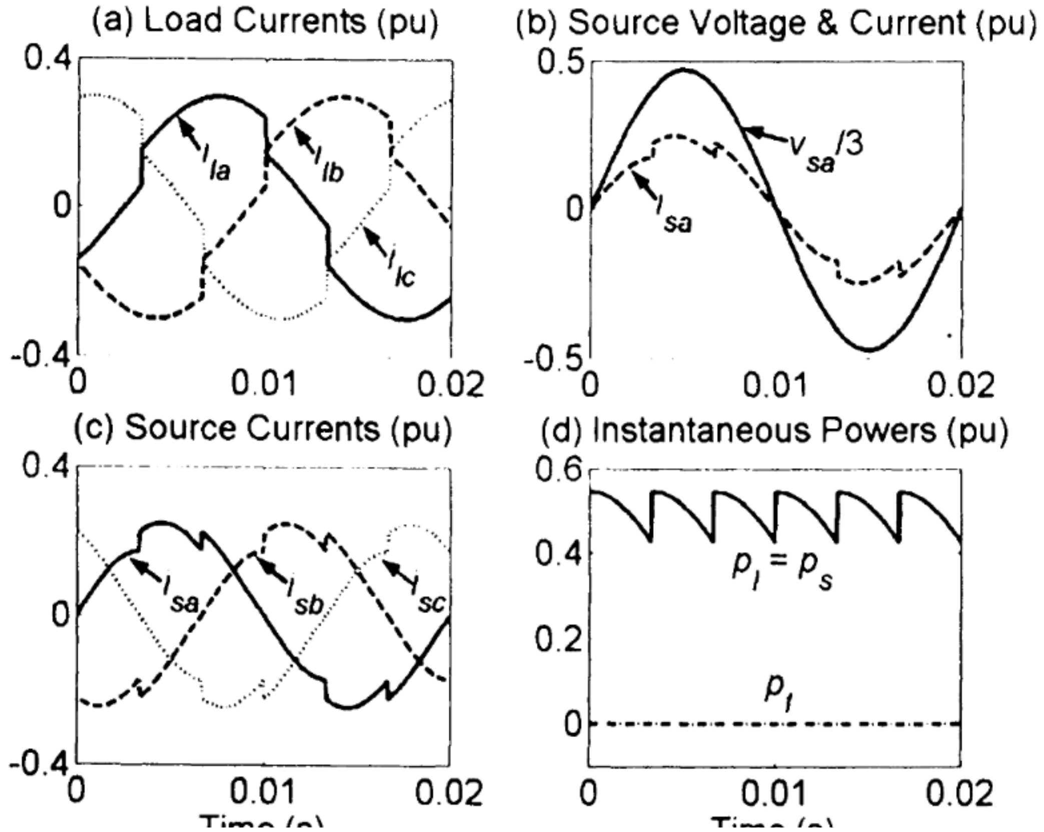


Figure System response with balanced nonlinear load when only q is compensated

We now use the compensation algorithm given in instead. The system plots are shown in Figure . It can be seen that the source currents are all balanced sinusoids and are in phase with the source voltage. The compensator in this case however supplies a zero-mean oscillating power such that the source supplies the average (dc) power required by the load. The compensator currents, shown in Figure (a), are balanced but distorted, as they have to cancel the distortion of the load currents.

In the above example the average power consumed by the load is obtained by a moving average (MA) filter rather than to a low-pass Butterworth filter suggested by Akagi . An MA filter continuously calculates the average over a certain number of past consecutive samples. To illustrate the idea, let us assume that the signal is uniformly sampled with a sampling time of 100 μs. This means that there are 100 samples in a half cycle if the fundamental frequency is 50 Hz. Then, at any given instant, the average of last 100 consecutive samples is taken to produce the power average. Since the fundamental power fluctuates at 100 Hz, the average of any consecutive 100 values corresponds to a full cycle of the fundamental power waveform. Thus the starting point need not be synchronized with the zero crossing of the waveform. This has the advantage that any change in the instantaneous power is reflected in the power average just after half a cycle.

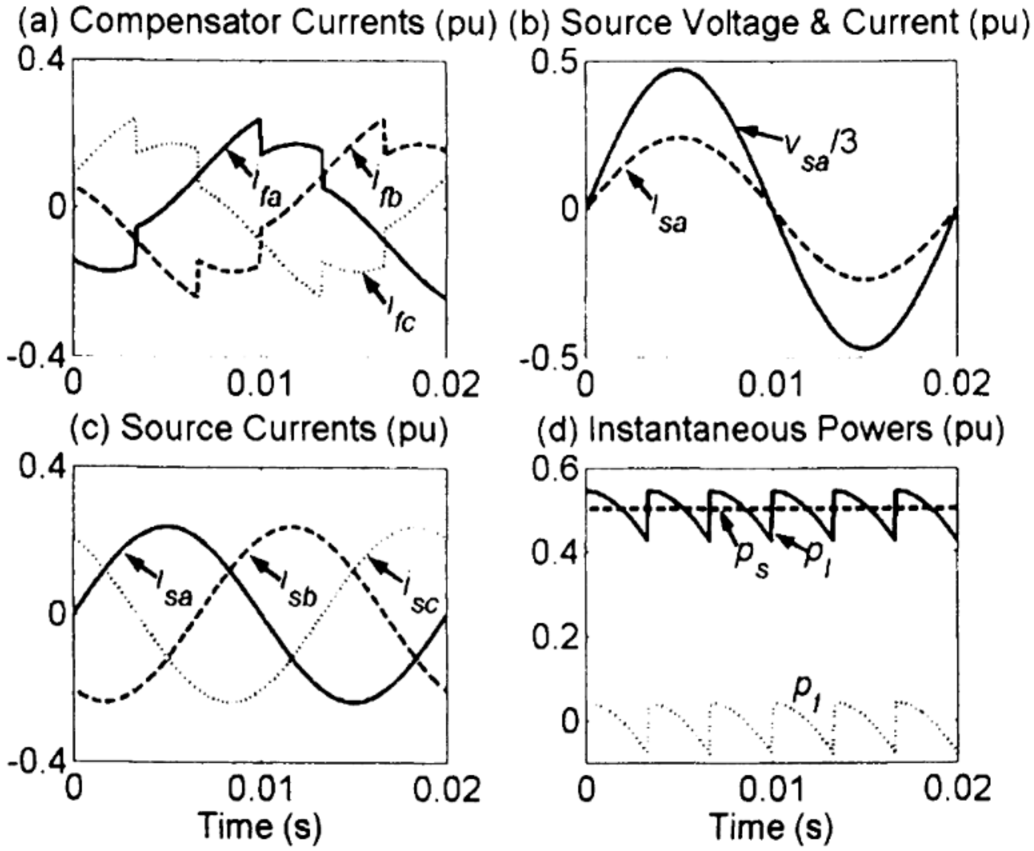


Figure . System response with balanced nonlinear load when both q and p_{losc} are compensated

Example Let us now investigate how this algorithm performs when the load is unbalanced. Let a Y-connected unbalanced RL load be connected to a balanced three-phase supply with an rms voltage of 1.0 per unit. The source voltages are the same as given in Example and the loads are given in per unit by

$$Z_{la} = 5.0 + j5.0,\ Z_{lb} = 5.0 + j1.0 \text{ and } Z_{lc} = 3.0 + j2.0$$

$$Z_{la} = 5.0 + j5.0,\ Z_{lb} = 5.0 + j1.0 \text{ and } Z_{lc} = 3.0 + j2.0$$

In addition three single-phase rectifier loads that are drawing a current of magnitude of 0.1 per unit are connected in parallel with the RL load. The load currents are shown in Figure (a).

We first use the compensation algorithm given in in which both q and p_{losc} are compensated. The system plots are shown in Figure . It is evident from Figure (b) that the source current is not unity power factor. Furthermore, as can be seen from Figure (c), the source currents are neither harmonic-free, nor are they balanced. The reason for this unwanted behavior is the presence of zero-sequence current in the source. This is shown in Figure (d) from which it can be seen that this current contains harmonics as well.

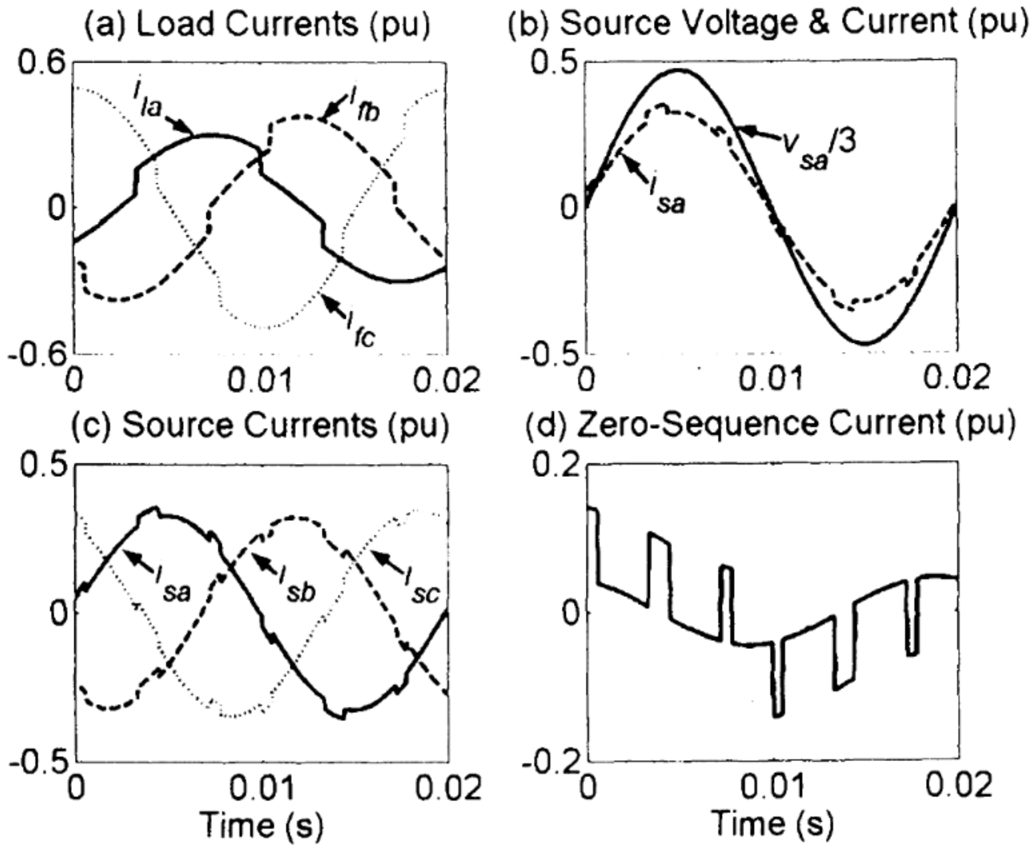


Figure System response with unbalanced nonlinear load when both q and p_{losc} are compensated, but the zero-sequence is not compensated

To correct this unwanted behavior, the compensation algorithm of is used again with the added stipulation that the zero-sequence of the load current be taken into consideration while obtaining the compensator currents in the a-b-c frame. Refer to Figure in which it is shown that the compensator neutral (n') is connected to the load neutral (n). Thus in order to prevent the source from drawing neutral current, the load neutral current must flow through the compensator neutral. Thus, once the compensator currents are obtained in α-β plane using , we generate these currents in the a-b-c frame

$$\begin{bmatrix} i_{fa}^* \\ i_{fb}^* \\ i_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} (i_{la} + i_{lb} + i_{lc})/\sqrt{3} \\ i_{f\alpha} \\ i_{f\beta} \end{bmatrix}$$

where the superscript '$*$' denotes the instantaneous reference values.

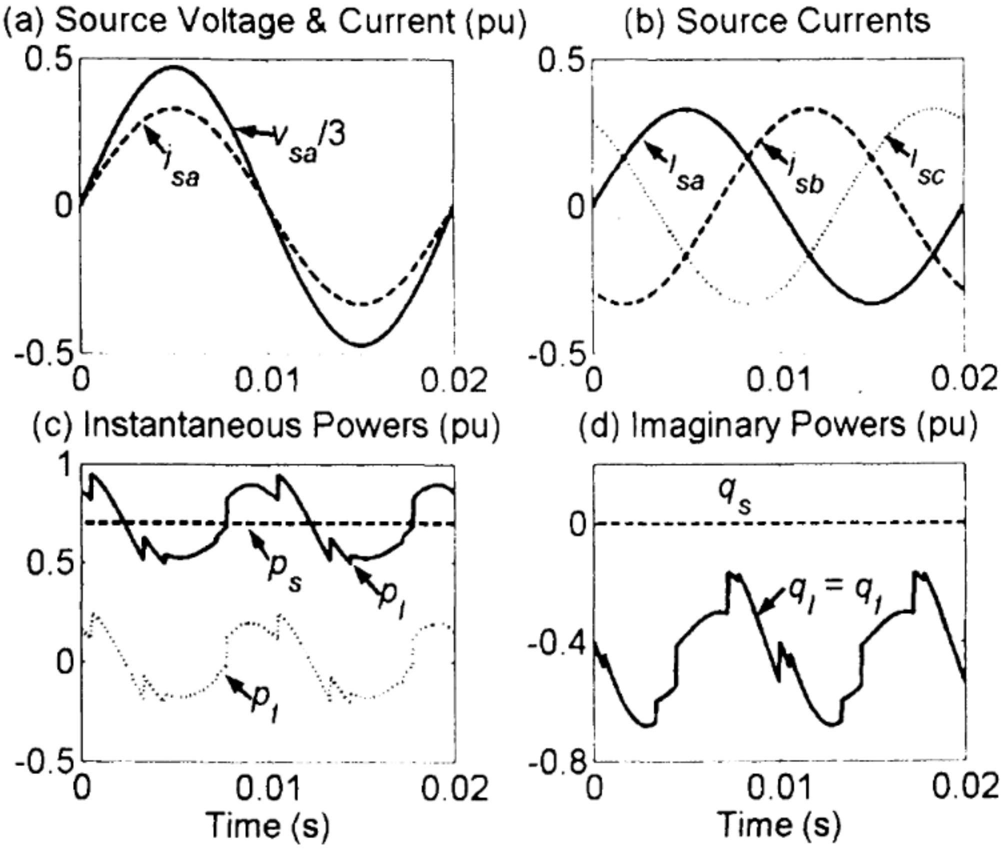


Figure System response with unbalanced nonlinear load when both q and p_{losc} are compensated along with the zero-sequence compensation

It is important to note here that if the compensator neutral is not available, or in other words, we have a three-wire compensator, the source currents cannot be balanced if the distribution system is three-phase, four-wire and the load is Y-connected. On the other hand, if the distribution system contains only three wires, the zero-sequence current will not have a path to flow. This will ensure that the sum of the three source currents is zero and hence the compensator will be able to balance these currents.

4. EXPLAIN GENERATING REFERENCE CURRENTS USING INSTANTANEOUS SYMMETRICAL COMPONENTS THEORY.

Generating Reference Currents using Instantaneous Symmetrical Components

Compensating Star Connected Loads

The objective in either three or four wire system compensation is to provide balanced supply current such that its zero sequence component is zero. We therefore have

$$i_{sa} + i_{sb} + i_{sc} = 0$$

In the method discussed in Section 7.3, there is no direct control over the power factor angle from the source and the algorithm forces the source current to be unity power factor. In the method under consideration, this angle can be set to have any desired value [4]. Let us assume that the source voltages are balanced and are given by

$$v_{sa} = \sin \omega t,\ v_{sb} = \sin\left(\omega t - 120^\circ\right),\ v_{sc} = \sin\left(\omega t + 120^\circ\right)$$

Then from (3.16) we get

$$v_{sa1} = \frac{1}{\sqrt{3}}\left\{v_{sa} + a v_{sb} + a^2 v_{sc}\right\}$$

The angle of the vector is then given by

$$\phi = \angle\left(v_{sa1}\right) = \tan^{-1}\left\{\frac{\frac{\sqrt{3}}{2}v_{sb} - \frac{\sqrt{3}}{2}v_{sc}}{v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc}}\right\} = \tan^{-1}\left\{\frac{\frac{\sqrt{3}}{2}\left(v_{sb} - v_{sc}\right)}{\frac{3}{2}v_{sa}}\right\} \qquad 1)$$

Substituting the values of the instantaneous voltages in 1) we get

$$\phi = \tan^{-1}\left\{\frac{-\cos \omega t}{\sin \omega t}\right\} = \omega t - \frac{\pi}{2} \qquad 2)$$

It can thus be seen from 2) that the angle of the vector v_{sa1} will change linearly as t changes. We can then easily force another vector to follow (or lead) this vector by an arbitrary angle. If we now assume that the phase of the vector i_{sa1} lags that of v_{sa1} by an angle ϕ, we get

$$\angle\left\{v_{sa} + av_{sb} + a^2 v_{sc}\right\} = \angle\left\{i_{sa} + ai_{sb} + a^2 i_{sc}\right\} + \phi \qquad 3)$$

Substituting the values of a and a^2 3) can be expanded as

$$\angle\left\{\left(v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc}\right) + j\frac{\sqrt{3}}{2}\left(v_{sb} - v_{sc}\right)\right\}$$

$$= \angle\left\{\left(i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}\right) + j\frac{\sqrt{3}}{2}\left(i_{sb} - i_{sc}\right)\right\} + \phi$$

Equating the angles, we can write from the above equation

$$\tan^{-1}\left(K_1/K_2\right) = \tan^{-1}\left(K_3/K_4\right) + \phi \qquad 4)$$

where

$$K_1 = \frac{\sqrt{3}}{2}\left(v_{sb} - v_{sc}\right), \quad K_2 = v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc},$$

$$K_3 = \frac{\sqrt{3}}{2}\left(i_{sb} - i_{sc}\right) \text{ and } K_4 = i_{sa} - \frac{i_{sb}}{2} - \frac{i_{sc}}{2}$$

Using the formula

$$\tan(\alpha + \beta) = \frac{\tan\alpha + \tan\beta}{1 - \tan\alpha\tan\beta}$$

4) can be expanded as

$$\frac{K_1}{K_2} = \tan\left\{\tan^{-1}\left(K_3/K_4\right) + \phi\right\} = \frac{K_3/K_4 + \tan\phi}{1 - \left(K_3/K_4\right)\tan\phi}$$

Solving the above equation we get

$$\left(v_{sb} - v_{sc} - 3\beta\, v_{sa}\right) i_{sa} + \left(v_{sc} - v_{sa} - 3\beta\, v_{sb}\right) i_{sb} + \left(v_{sa} - v_{sb} - 3\beta\, v_{sc}\right) i_{sc} = 0 \qquad 5)$$

where

$$\beta \equiv \tan\phi / \sqrt{3}\,. \qquad 6)$$

It is interesting to note the implication of 5). When the power factor angle is assumed to be zero, 5) implies that the instantaneous reactive power supplied by the source is zero. On the other hand, when this angle is non-zero, the source supplies a reactive power that is equal to β times instantaneous power.

As we have seen before that the instantaneous power in a balanced three-phase circuit is constant while for an unbalanced circuit it has a double frequency component in addition the dc value. In addition, the presence of harmonics adds to the oscillating component of the instantaneous power. The objective of the compensator is to supply the oscillating component such that the source supplies the average value of the load power. Therefore we obtain

$$v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} = p_{lav} \qquad 7)$$

where p_{lav} is the average power drawn by the load. Since the harmonic component in the load does not require any real power, the source only supplies the real power required by the load.

Combining 5) and 7) we get

$$\begin{bmatrix} 1 & 1 & 1 \\ v_{sb} - v_{sc} - 3\beta\, v_{sa} & v_{sc} - v_{sa} - 3\beta\, v_{sb} & v_{sa} - v_{sb} - 3\beta\, v_{sc} \\ v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ p_{lav} \end{bmatrix} \qquad 8)$$

Assuming that the current are tracked without error, the KCL at PCC can be written in terms of the reference currents as

$$i_{fk}^{*} = i_{lk} - i_{sk}, \quad k = a, b, c$$

Substituting the above equation in 8) and solving we get

Substituting the above equation in 8) and solving we get

$$\left.\begin{aligned}
i_{fa}^{*} &= i_{la} - \frac{v_{sa} + (v_{sb} - v_{sc})\beta}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}} p_{lav} \\
i_{fb}^{*} &= i_{lb} - \frac{v_{sb} + (v_{sc} - v_{sa})\beta}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}} p_{lav} \\
i_{fc}^{*} &= i_{lc} - \frac{v_{sc} + (v_{sa} - v_{sb})\beta}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}} p_{lav}
\end{aligned}\right\} \qquad 9)$$

Generating Reference Currents when the Source is Unbalanced

5. EXPLAIN GENERATING REFERENCE CURRENTS WHEN THE LOAD IS UNBALANCED.

We have so far assumed that the sources are stiff and balanced. In practice, these assumptions may not true. In this section we investigate the implication of having unbalanced voltage sources. We shall however assume that the voltage sources are undistorted, i.e., at fundamental frequency. Let us begin our discussion with the following example.

Example Let us consider the same load as used in Example The source voltages are unbalanced and are given in per unit by

$$\begin{aligned}
v_{sa} &= \sqrt{2}\sin\omega t \\
v_{sb} &= 0.8 \times \sqrt{2}\sin(\omega t - 120^\circ) \\
v_{sc} &= 1.2 \times \sqrt{2}\sin(\omega t + 120^\circ)
\end{aligned}$$

The source voltage and load currents are shown in Figure (a) and Figure (b) respectively. We use the same algorithm as given by The system plots are shown in Figure From Figure (c) it can be seen that the source currents are both unbalanced and distorted. Furthermore, the real power drawn from the source is not a steady dc value. This can be seen from Figure (d). The imaginary power drawn from the source however remains zero. Thus the compensator supplies the entire imaginary power requirement of the load.

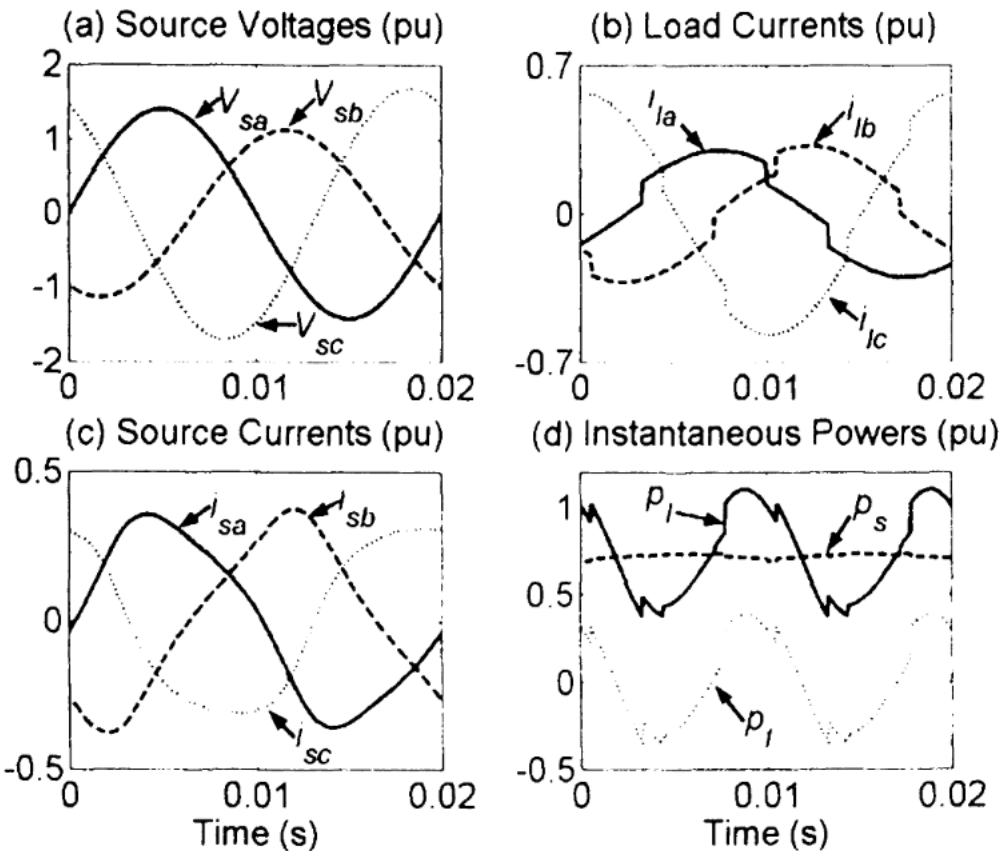


Figure System response with unbalanced nonlinear load and unbalanced source when both q and p_{osc} are compensated along with the zero-sequence compensation

In a similar way, the currents will be distorted when the reference currents are generated based on the algorithm given . It is to be noted that the algorithm given , which assumes a balanced source voltage, cannot be directly used here. These equations can however be easily modified to consider the general case. It can be shown that for unity power factor operation these equations are

$$\left.\begin{aligned} i_{fa}^{*} &= i_{la} - i_{sa} = i_{la} - \frac{v_{sa} - v_0}{\Delta} p_{lav} \\ i_{fb}^{*} &= i_{lb} - i_{sb} = i_{lb} - \frac{v_{sb} - v_0}{\Delta} p_{lav} \\ i_{fc}^{*} &= i_{lc} - i_{sc} = i_{lc} - \frac{v_{sc} - v_0}{\Delta} p_{lav} \end{aligned}\right\}$$

where

$$v_0 = \frac{1}{3} \sum_{k=a,b,c} v_{sk} \quad \text{and} \quad \Delta = \left[\sum_{k=a,b,c} v_{sk}^2 \right] - 3v_0^2$$

Note that when the system is balanced, v_0 will be zero and will be identical to for unity power factor operation.

Using the modified algorithm of it can be shown that the source currents and voltages are in phase. The source currents are however distorted and their magnitudes are not equal. Even though the algorithm can find a solution, the unequal phase currents added up to zero only with severe and unacceptable distortions. Therefore alternate formulations are imperative.

In general, the compensating currents for this problem can be generated to achieve one of the following three objectives

- Equal equivalent resistance in all three phases.
- Equal source current magnitude in all three phases
- Equal sharing of average power by all three phases

The algorithms for generating compensator currents for each of the above cases are discussed below.

Compensating to Equal Resistance

The aim of this scheme is to inject the compensator currents in such a way that the supply sees a balanced resistive load. This means that the ratios of instantaneous source voltage and current in each phase are equal, i.e.,

$$\frac{v_{sa}}{i_{sa}} = \frac{v_{sb}}{i_{sb}} = \frac{v_{sc}}{i_{sc}} = R_{eq}$$

This gives the following two equations

$$v_{sa}i_{sb} - v_{sb}i_{sa} = 0$$

$$v_{sb}i_{sc} - v_{sc}i_{sb} = 0$$

Furthermore, the three-phase average power supplied by the source must be equal to the average power drawn by the load. Since the compensated load is resistive, from this consideration we get

$$|V_{sa}||I_{sa}| + |V_{sb}||I_{sb}| + |V_{sc}||I_{sc}| = p_{lav}$$

where V_{sa} and I_{sa} are respectively the phasor source voltage and current of phase-a. Now if we denote the peak of the phase-a voltage and current by V_{sam} and I_{sam} respectively, we can then write

$$|V_{sa}||I_{sa}| = \frac{V_{sam} I_{sam}}{2} = \frac{V_{sam}^2 I_{sam}}{2V_{sam}} = \frac{V_{sam}^2 i_{sa}}{2v_{sa}}$$

Similar expressions can also be written for the other two phases. We then rewrite

$$\frac{V_{sam}^2}{2v_{sa}} i_{sa} + \frac{V_{sbm}^2}{2v_{sb}} i_{sb} + \frac{V_{scm}^2}{2v_{sc}} i_{sc} = p_{lav}$$

Combining the equaabove equations and rearranging, we get the following expressions for the reference compensator currents

$$\left.\begin{aligned} i_{fa}^* &= i_{la} - i_{sa} = i_{la} - \frac{2v_{sa}}{\Delta_1} p_{lav} \\ i_{fb}^* &= i_{lb} - i_{sb} = i_{lb} - \frac{2v_{sb}}{\Delta_1} p_{lav} \\ i_{fc}^* &= i_{lc} - i_{sc} = i_{lc} - \frac{2v_{sc}}{\Delta_1} p_{lav} \end{aligned}\right\}$$

where

$$\Delta_1 = V_{sam}^2 + V_{sbm}^2 + V_{scm}^2$$

Assuming that the peaks of the source voltages remain constant, the instantaneous compensator reference currents can be computed from

$$\frac{|V_{sa}|^2 + |V_{sb}|^2 + |V_{sc}|^2}{R_{eq}} = p_{lav}$$

Solving the above equation we get

$$R_{eq} = \frac{\Delta_1}{2p_{lav}}$$

Example Let us consider the same system as given in Example The source voltage and load currents are the same as shown in Figure We shall now use the compensator

The system response is shown in Figure It can be seen that the source currents are in phase with the source voltages. Furthermore, the magnitude of the source currents is a fixed proportion (R_{eq}) of the source voltages. The proportionality constant (R_{eq}) in this case has a value of 4.202. This compensation will however not result in balanced source current. As a consequence, the power drawn from the source contains both its ac and dc components and oscillates at 100 Hz. The compensator however supplies a zero mean oscillating power as evident from Figure

Compensating to Equal Source Currents

Let us consider the general case in which both the magnitudes and phase angles of the supply voltage are unbalanced. The supply voltage is given by

$$
\begin{aligned}
v_{sa} &= V_{sam} \sin \omega t \\
v_{sb} &= V_{sbm} \sin(\omega t - 2\pi/3 + \theta_b) \\
v_{sc} &= V_{scm} \sin(\omega t + 2\pi/3 + \theta_c)
\end{aligned}
$$

the magnitudes V_{sam}, V_{sbm} and V_{scm} are unequal. The phase angles θ_b and θ_c contribute to the phase unbalance. Let us define a set of fictitious set of voltages v'_{sa}, v'_{sb} and v'_{sc} as

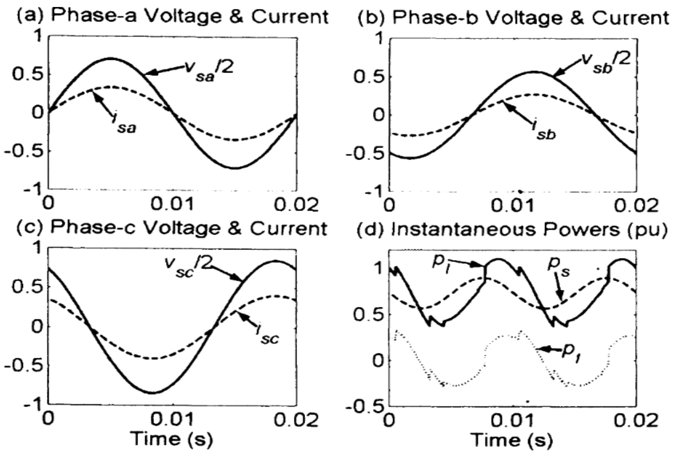


Figure . System response when compensated to equal resistance

$$
\begin{aligned}
v'_{sa} &= V'_{sm} \sin \omega t \\
v'_{sb} &= V'_{sm} \sin(\omega t - 2\pi/3) \\
v'_{sc} &= V'_{sm} \sin(\omega t + 2\pi/3)
\end{aligned}
$$

$$V'_{sm} = \frac{1}{3}\left(v_{sa} + v_{sb}\alpha_b + v_{sc}\alpha_c\right)$$

where

$$\alpha_b = \frac{\cos(\phi + \theta_b)}{\cos\phi} \text{ and } \alpha_c = \frac{\cos(\phi + \theta_c)}{\cos\phi}$$

$$\left.\begin{aligned} i^*_{fa} &= i_{la} - \frac{1}{\Delta_2}\left(p_s v'_{sa} + q_{sb} v'_{sc} - q_{sc} v'_{sb}\right) \\ i^*_{fb} &= i_{lb} - \frac{1}{\Delta_2}\left(p_s v'_{sb} + q_{sc} v'_{sa} - q_{sa} v'_{sc}\right) \\ i^*_{fc} &= i_{lc} - \frac{1}{\Delta_2}\left(p_s v'_{sc} + q_{sa} v'_{sb} - q_{sb} v'_{sa}\right) \end{aligned}\right\}$$

where

$$\Delta_2 = V'^2_{sa} + V'^2_{sb} + V'^2_{sc}$$

Compensating to Equal Average Power

In this case, the source voltages are assumed to be same as those given in and the source currents are given by

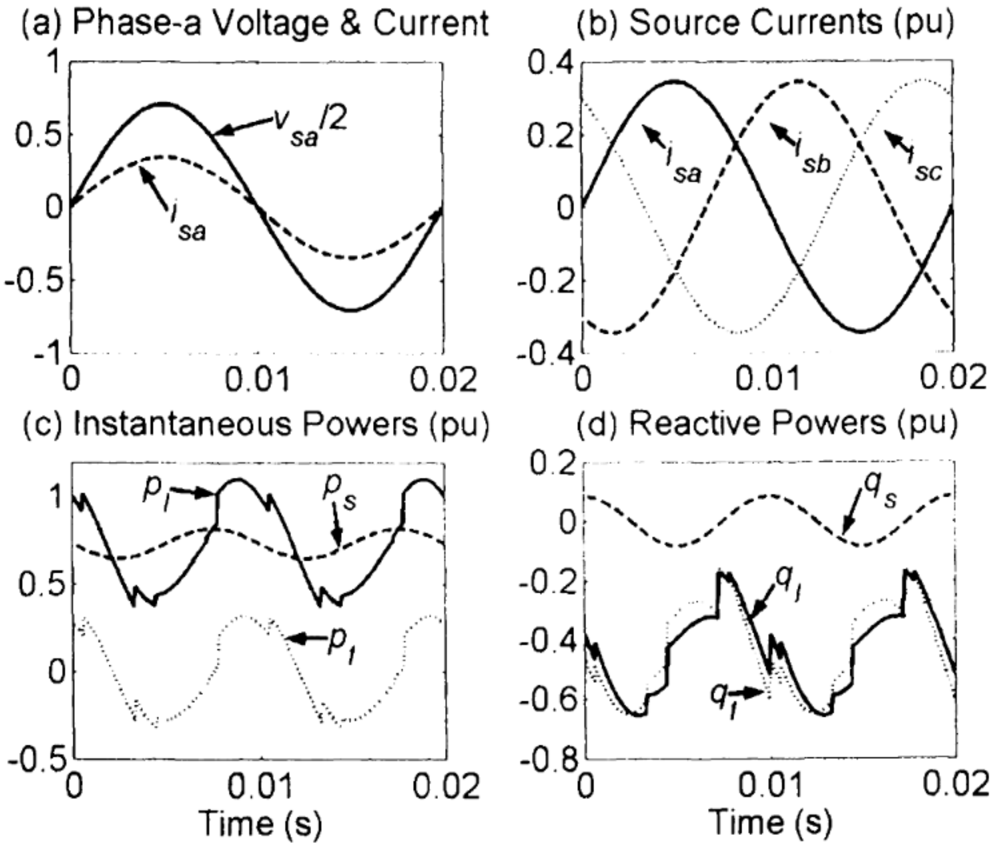
$$\begin{aligned} i_{sa} &= I_{sam} \sin \omega t \\ i_{sb} &= I_{sbm} \sin\left(\omega t - 2\pi/3 + \theta_b\right) \\ i_{sc} &= I_{scm} \sin\left(\omega t + 2\pi/3 + \theta_c\right) \end{aligned}$$

$$p_{sa} = \frac{V_{sam} I_{sam}}{2}\left(1 - \cos 2\omega t\right)$$

$$\frac{V_{sam}I_{sam}}{2} = \frac{V_{sbm}I_{sbm}}{2} = \frac{V_{scm}I_{scm}}{2} = \frac{p_{lav}}{3}$$

The phase-a source current is then given by

$$i_{sa} = I_{sam}\sin\omega t = \frac{2p_{lav}}{3} \times \frac{v_{sa}}{V_{sam}^2}$$



$$\left.\begin{aligned} i_{fa} &= i_{la} - i_{sa} = i_{la} - \frac{2v_{sa}}{3V_{sam}^2}p_{lav} \\ i_{fb} &= i_{lb} - i_{sb} = i_{lb} - \frac{2v_{sb}}{3V_{sbm}^2}p_{lav} \\ i_{fc} &= i_{lc} - i_{sc} = i_{lc} - \frac{2v_{sc}}{3V_{scm}^2}p_{lav} \end{aligned}\right\}$$

It is to be noted that only when $\theta_b = \theta_c = 0$,

Realization and Control of DSTATCOM

6. DISCUSS DSTATCOM IN A VOLTAGE CONTROLLED MODE.

DSTATCOM IN A VOLTAGE CONTROLLED MODE.

In a distribution system there may be several compensating devices of different kinds. However, in a radial distribution system, the voltage of a particular bus can be distorted or unbalanced if the loads in any part of the system are nonlinear or unbalanced. The customers connected to that bus would be supplied by a set of unbalanced and distorted voltages, even when their loads are not contributing to the bus voltage pollution. Therefore a DSTATCOM can be used at this bus to reduce harmonics and balance the bus voltages.

Consider the three-phase, four-wire radial system shown in Figure 8.19. Let us assume that we would like to correct the voltage of Bus-3. The single-phase Thevenin equivalent of the system is the same as that shown in Figure 8.11 (b). In this v_s, R and L constitute the Thevenin equivalent looking towards left into the network, while the equivalent load is the impedance looking towards right into the network, at Bus-3. We now have to use the DSTATCOM in the voltage control mode at Bus-3. Below we present two different control schemes of DSTATCOM in voltage control mode.

7. EXPLAIN STATE FEEDBACK CONTROL OF DSTATCOM IN VOLTAGE CONTROLLED MODE.

For the state feedback control of the DSTATCOM operating as a voltage regulator we need to specify the following references with respect to Figure 8.10: terminal voltage v_t, injected current i_f, current through the filter capacitor i_{cf} and load current i_l. Of these, the load current is load dependent that may change at any time. Just as we have done in Examples 8.5 and 8.6, we have eliminated the load current from the feedback signal.

We can choose an arbitrary magnitude for the reference signal of v_t. For simplicity, let us denote this magnitude by $|V_t^*|$. The instantaneous phase-a terminal reference voltage is then given by $v_{ta}^* = |V_t^*|\sin(\omega t + \phi_t)$. Since we require a balanced voltage at the terminal, the reference voltage for the other two phases can be obtained by phase shifting this waveform by 120°. However, the angle of the reference signal must be chosen such that the real power drawn by the DSTATCOM is zero in the steady state. To facilitate this, we use the following feedback signal [10]

$$\phi_t(k+1) = \phi_t(k) + C_P p_{fav}$$

where C_P is a gain, p_{fav} is the average of the shunt power and k is the discrete-time index. Once ϕ_t is obtained from , the reference voltages for the three phases are calculated. The instantaneous three-phase reference voltages for the terminal can then be generated with respect to any phase locked point that provides the reference time setting. Once this voltage reference is generated, the corresponding current through the filter-capacitor can be generated as follows. Since the reference voltage for phase-a is $|V_t^*|\sin(\omega t + \phi_t)$, the reference current for this phase is then given by $|V_t^*|\omega C_f \cos(\omega t + \phi_t)$.

To generate i_f, it is to be noted that $i_l = i_s + i_f$. Hence the reference for i_f could be the instantaneous difference between these two currents. However, in order to prevent distortion creeping in, it is desirable to generate this reference using the fundamental value of the source current, i.e.,

$$i_f^* = i_l - i_s^{fund}$$

7. EXPLAIN OUTPUT FEEDBACK CONTROL OF DSTATCOM IN VOLTAGE CONTROLLED MODE.

The state feedback controller presented above assumes that the system parameters are known. However as we have mentioned before, the feeder parameters are at best the Thevenin equivalent of the upstream distribution system. Since the Thevenin equivalent can change at any time depending on the load, it is desirable that these parameters are not used in the voltage controller design. Below we present a voltage control technique that only requires the timing information from the source v_s for synchronization.

Consider the network shown in Figure 8.30. In this u is the switching variable that can take on values ± 1 corresponding to the states of the inverter. To derive a control law, we assume for the time being that u is equal to a continuous signal u_c. We shall derive the state space equation for the part system enclosed in the dotted path in Figure Let us define the following state and input vectors

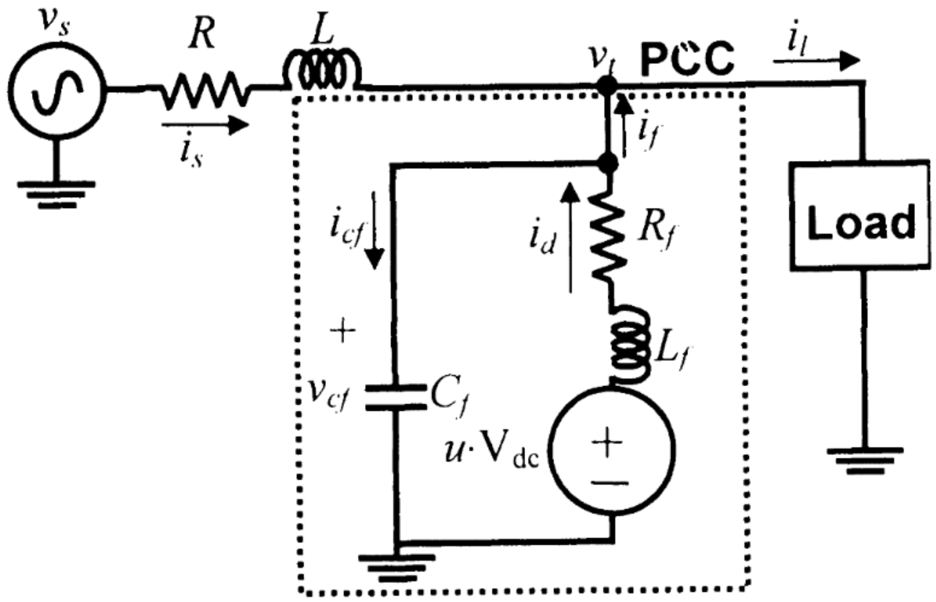


Figure . Equivalent circuit of voltage compensated distribution system

$$x^T = \begin{bmatrix} v_t & i_d \end{bmatrix} \quad z^T = \begin{bmatrix} u_c & i_f \end{bmatrix}$$

The state space equation of the system is then given by

$$\dot{x} = \begin{bmatrix} 0 & 1/C_f \\ -1/L_f & -R_f/L_f \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ V_{dc}/L_f & 0 \end{bmatrix} z$$
$$= Ax + Bz$$

The continuos-time state equation is then discretized as

$$x(k+1) = \phi\, x(k) + \theta\, z(k)$$

where k is the k^{th} sampling instant and the matrices ϕ and θ, for a sampling time of ΔT, is given as

$$\phi = e^{A\Delta T} \text{ and } \theta = \int_0^{\Delta T} e^{A\tau} B d\tau$$

Let us define the elements of the matrices given in as follows

$$\phi = \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} \text{and } \theta = \begin{bmatrix} \theta_{11} & \theta_{12} \\ \theta_{21} & \theta_{22} \end{bmatrix}$$

We can then write from (

$$v_t(k+1) = \phi_{11} v_t(k) + \phi_{12} i_d(k) + \theta_{11} u_c(k) + \theta_{12} i_f(k)$$

We shall now design a deadbeat controller discussed For a reference voltage of v_t^*, the following cost function is chosen

$$J = \left\{ v_t(k+1) - v_t^*(k+1) \right\}^2$$

The minimization of this function results in the following control input

$$u_c(k) = \frac{v_t^*(k+1) - \phi_{11} v_t(k) - \phi_{12} i_d(k) - \theta_{12} i_f(k)}{\theta_{11}}$$

Once u_c is obtained the control input u is obtained in the hysteresis band

UNIT 5
SERIES COMPENSATION OF POWER DISTRIBUTION SYSTEM

Rectifier supported DVR – DC Capacitor supported DVR – DVR Structure – Voltage Restoration – Series Active Filter – Unified Power Quality Conditioner.

PART-A

1.What is series compensation of power distribution system?

Series compensation is the method of improving the system voltage by connecting a capacitor in series with the transmission line. In series compensation, reactive power is inserted in series with the transmission line for improving the impedance of the system.

2.What is the formula for series compensation?

of the series capacitor and X is the total reactance of the line at the fundamental power system frequency f. Since the degree of series compensation k = Xc/X is usually in the 25 to 75% range, the electrical resonant frequency fe; is less than the power frequency f, i.e., fe is a sub harmonic frequency.

3. What is series compensation?

Series compensation is the method of improving the system voltage by connecting a capacitor in series with the transmission line. In series compensation, reactive power is inserted in series with the transmission line for improving the impedance of the system. It improves the power transfer capability of the line.

4. What is an example of series compensation?

Series compensation is most effective on the higher-voltage transmission lines (230 kV and above) because they have relatively high ratios of series X to series R; typically 7 to 20 or so. For example, the typical 345 kV line has an X/R ratio of about 10 and a 500 kV line has an X/R of about 18

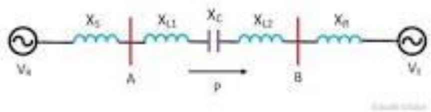
5. What is the main objective of series compensation?

Series compensation is basically a powerful tool to improve the performance of EHV lines. It consists of capacitors connected in series with the line at suitable locations. relationship characterizing the power transmission over a single line.

6.What is series and shunt compensation in power system?

Series compensation modifies the reactance parameter of the transmission or distribution system, while shunt compensation changes the equivalent load impedance.

7.What is series compensation advantages?



Series compensation has several advantages like it increases transmission capacity, improve system stability, control voltage regulation and ensure proper load division among parallel feeders. These advantages are discussed below. Thus, the power transfer is doubled by 50 % compensation.

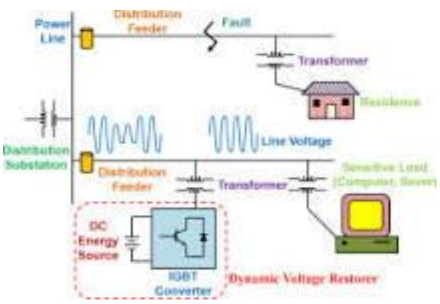
8. What is series compensation disadvantages?

Series compensation is effective only during heavy loads. During light load conditions shunt compensation has to be provided. 2. Whenever an outage occurs on a line with series compensation, the series compensation has to be removed.

9.What is DVR in battery charger?

Dynamic voltage restoration (DVR) is a method of overcoming voltage sags and swells that occur in electrical power distribution. These are a problem because spikes consume power and sags reduce efficiency of some devices.

10.What is a dynamic voltage restorer?



Dynamic voltage restorers (DVR) are complicated static devices which work by adding the 'missing' voltage during a voltage sag. Basically this means that the device injects voltage into the system in order to bring the voltage back up to the level required by the load.

11. What is the application of DVR?

DVR can also be used as active filter for isolating harmonics current from source side to load side. In this operation IGBT or IGCT is used with it. Voltage source converter used is of 3 phase 3wire or 3phase 4 wire. The passive filter is connected on converter side or transformer side.

12. What is a DVR in power system?

DVR is implemented as a voltage source inverter which injects 3-phase voltage into the grid in order to keep load side voltage within prescribed limits. Normally, DVRs are installed in the distribution system between the power supply and a critical load feeder at a point of common coupling (PCC)

13.Why do we use dynamic voltage restorer?

Dynamic Voltage Restorer (DVR) is a series connected power electronics based custom power device that is used to improve voltage disturbances in low voltage electrical power distribution network. Power quality requirement is one of the most important concerns for power system.

14.How does DVR help in power quality?

DVR is a power electronics-based power quality compensation system that is connected in series with the grid. DVR provides effective protection by preventing the voltage quality events occurring in the grid from being seen on the load side with its high-performance voltage compensation ability.

15.What is DVR control?

The DVR is a power electronic based device that provides three-phase controllable voltage output, whose voltage vector-magnitude and angle-adds to the supply voltage during sag event, to restore the load voltage to pre-sag conditions. And when voltage swell occurs DVR injects 180° out of phase voltage into the line.

16. What is the structure of DVR?

The DVR consists of DC power sources, an IGBT converter, and an injection transformer that is connected in series with the power line and the sensitive load. The DC power sources that can be used are batteries, supercapacitors, superconducting magnetic storage units, and flywheels.

17.What is DVR in VFD?

DVR (Dynamic Voltage Restorer) The basic principle of the dynamic voltage restorer is to inject a voltage of required magnitude and frequency, so that it can restore the load side voltage to the desired amplitude and waveform even when the source voltage is unbalanced or distorted.

18.What is DVR circuit?

Dynamic voltage restorer (DVR) is a reliable power electronic offsetting device which when engaged in the power system is effectual in the operation of compensating voltage sag/swell.

19. What is the basic principle of voltage restoration?

The basic principle of dynamic voltage restoration is to inject a voltage of the magnitude and frequency necessary to restore the load side voltage to the desired amplitude and waveform, even when the source voltage is unbalanced or distorted.

20.What is voltage mitigation?

Basically this means that the device injects voltage into the system in order to bring the voltage back up to the level required by the load. ü Injection of voltage is achieved by a switching system coupled with a transformer which is connected in series with the load.

21.What are the operation modes of DVR?

The DVR operates in three modes which are the protection mode, the standby mode, and the injection mode. In this mode of operation, DVR is protected from the high current on the load-side that exceeds an acceptable limit. This high current caused by faults on the load-side can damage the DVR.

22. Why DVR is used in power quality improvement?

Series active power filter also known as dynamic voltage restorer (DVR) is a voltage source device that injects compensation voltage in the distribution line to regulate the voltage level to protect sensitive load from power quality issues such as voltage sag and swell

23. How do you reduce voltage leakage?(OR)

How do you stop leakage current?

Separate circuits in RCD protected/nonprotected areas.

Separate filtered and unfiltered cables.
Starting up the frequency inverter in steps.
Placing the frequency inverter close to the motor (short motor cables)
Overvoltage protection to protect against voltage spikes.

24. What is series active filter?

Series active filters are operated mainly as a voltage regulator and harmonic isolator between a nonlinear load and the utility grid. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply.

25. What is the primary function of the series active power filter?

A series active filter is used to eliminate the voltage harmonics produced by the matrix converter. When the load is sensitive and critical, a series converter is used to regulate line voltage for the load. It cancels out any line voltage distortions such as voltage harmonics, sag, swell, and voltage unbalance.

26. How many types of active filters are there?

Filters can be active or passive, and the four main types of filters are low-pass, high-pass, band-pass, and notch/band-reject (though there are also all-pass filters).

27. What are the applications of active power filter?

Active power filters can be used to filter out harmonics in the power system which are significantly below the switching frequency of the filter. The active power filters are used to filter out both higher and lower order harmonics in the power system.

28. Is Butterworth filter active or passive?

A Butterworth Filter is a type of Active Filter, where the frequency response of the across its pass band is relatively flat. Because of this frequenct response, Butterworth Filters are also known as Maximally Flat Filters or Flat-Flat Filters.

29. What is first order active filter?

A first-order active low pass filter is a simplistic filter that is composed of only one reactive component Capacitor accompanying with an active component Op-Amp. A resistor is utilized with the capacitor or inductor to form RC or RL low pass filter respectively.

30. Why Butterworth filter is used?

Butterworth filters are used in control systems because they do not have peaking. The requirement to eliminate all peaking from a filter is conservative. Allowing some peaking may be beneficial because it allows equivalent attenuation with less phase lag in the lower frequencies

31. What is UPQC?

UPQC is a multifunction power conditioner that can be used to compensate various voltage disturbances of the power supply, to correct voltage fluctuation, and to prevent the harmonic load current from entering the power system.

32. What is difference between Upqc and Upfc?

A UPQC is employed in a power transmission system to perform shunt and series compensation at the same time. A power distribution system may contain unbalance, distortion and even dc components. Therefore a UPQC operate, better than a UPFC, with all these aspects in order to provide shunt or series compensation.

33. What is the principle of UPQC?

UPQC provides the VAR requirement of the load, so that the supply voltage and current are always in phase; therefore, no additional power factor correction equipment is required. UPQC maintains load end voltage at the rated value even in the presence of supply voltage sag.

35. What is the difference between DVR and UPQC?

DVR is a single device to protect a specific load or a feeder. Instead Open UPQC is a distributed solution and combination of series (DVR) and parallel (UPS like or STATCOM) devices distributed inside the installed network. Open UPQC can improve Power Quality of an area.

36. What is the use of power conditioner?

Also known as a line conditioner, it protects equipment from power surges, helps to correct voltage and waveform distortions, and removes external electrical noise (i.e. frequency and electromagnetic interference) caused by devices such as radios and motors.

37. What are the modes of UPQC?

UPQC can work in zero active power consumption mode, active power absorption mode and active power delivering mode. The series active power filter (APF) part of UPQC works in active power delivering mode and absorption mode during voltage sag and swell condition, respectively.

38.Who proposed the UPFC?

UPFC proposed by Dr. Gyugyi in 1991 is the most versatile and powerful device that can provide effective means of controlling the power flow and improving the stability of a power network.

39. How is power quality improvement by using UPQC?

UPQC alleviates the voltage and current based distortions concurrently as well as independently. UPQC improves power quality by compensating both harmonics and load current which thereby makes source current and load voltage sinusoidal at the required voltage level.

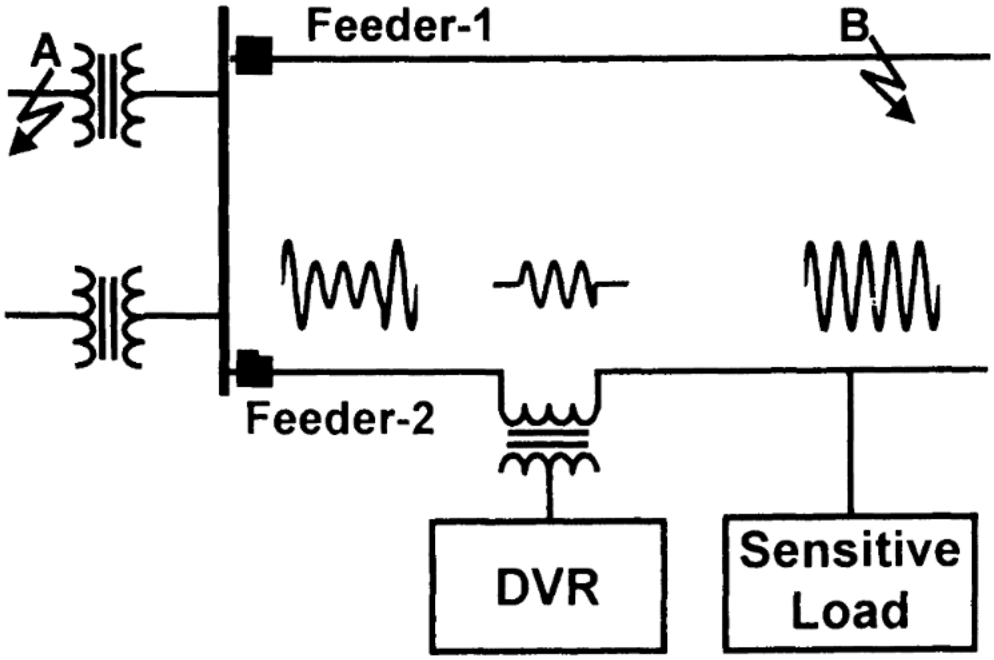
PART-B

SERIES COMPENSATION OF POWER SYSTEM

1.**Write Short Notes on Series compensation of power system.**

A power electronic converter based series compensator that can protect critical loads from all supply side disturbances other than outages is called a dynamic voltage restorer (DVR). This device employs IGBT solid-state power-electronic switches in a pulse-width modulated (PWM) inverter structure. The DVR is capable of generating or absorbing independently controllable real and reactive power at its ac output terminal. Like in a DSTATCOM, the DVR is made of a solid-state dc to ac switching power converter that injects a set of three-phase ac output voltages in series and synchronism with the distribution feeder voltages. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the real and reactive power exchange between the DVR and the distribution system. The dc input terminal of a DVR is connected to an energy source or an energy storage device of appropriate capacity. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components. The real power exchanged at the DVR output ac terminals is provided by the DVR input dc terminal by an external energy source or energy storage system.

A typical DVR connection is shown in Figure It is connected in series with the distribution feeder that supplies a sensitive load. For a fault clearing or switching at point A of the incoming feeder or fault in the distribution feeder-1, the voltage at feeder-2 will sag. Without the presence of the DVR, this will trip the sensitive load causing a loss of production. The DVR can protect the sensitive load by inserting voltages of controllable amplitude, phase angle and frequency (fundamental and harmonic) into the distribution feeder via a series insertion transformer as shown in Figure 9.1. It is however to be mentioned that the rating of a DVR is not unlimited. Thus a DVR can only supply partial power to the load during very large variations (sags or swells) in the source voltage. As we shall demonstrate in this chapter that during steady state operations, the DVR can compensate for the inductive drop in the line by inserting a voltage in quadrature with the feeder current. During this phase, the dc storage need not supply any real power except for the losses in the converter. The DVR can also limit a fault current by injecting a leading voltage in quadrature with the fault current thereby increasing the effective fault impedance of the distribution feeder.



DVR connection for voltage sag correction of sensitive loads

In August 1996, Westinghouse Electric Corporation installed world's first DVR in Duke Power Company's 12.47 kV substation in Anderson, South Carolina. This was installed to provide protection to an automated rug manufacturing plant. Prior to this connection, the DVR was first installed at the Waltz Mill test facility near Pittsburgh for full power tests. The test results are discussed in [1]. The next commissioning of a DVR was done by Westinghouse in February 1997 in Powercor's 22 kV distribution system at

Stanhope, Victoria, Australia. This was done to protect a diary milk processing plant. The saving that may result from the installation of this DVR is estimated at over $100,000 per year [2]. In the next phase of development, DVRs that can be mounted on an overhead platform supported by two poles were fabricated. The first ever DVR that is mounted on a platform was installed to protect Northern Lights Community College and several other smaller loads in Dawson Creek, British Columbia, Canada [3].

In this chapter we shall present two different structures of the DVR. These are shown in Figure In the structure of Figure (a), the dc bus of the VSI realizing the DVR is supplied from the feeder through a rectifier. Therefore the DVR can absorb real power from the feeder through the dc bus. This is not possible for the structure of Figure (b) in which the DVR is supplied by a dc storage capacitor. Therefore the DVR in this structure must operate in the mode in which it will have no real power exchange with the ac system in the steady state.

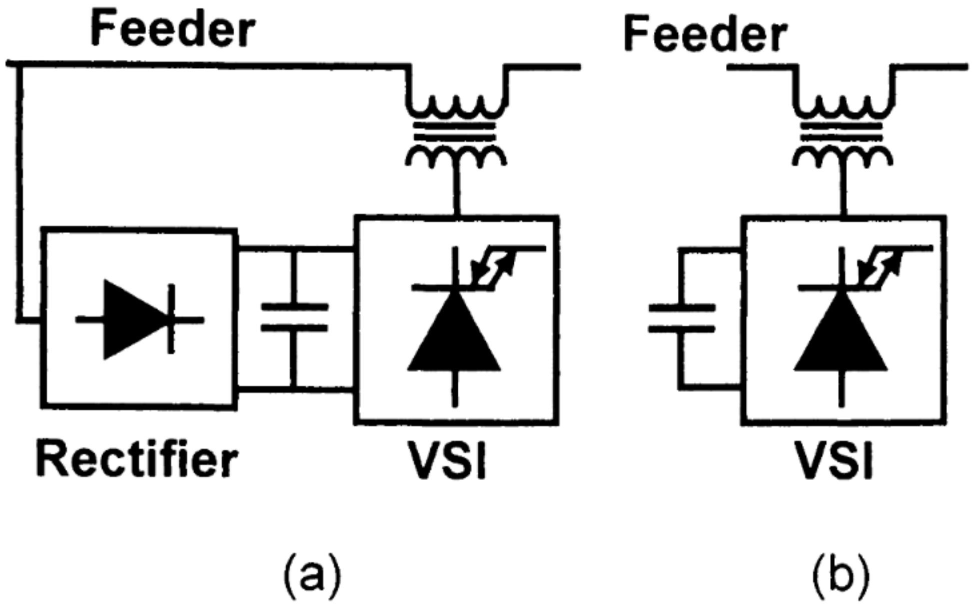


Figure Two possible structures of DVR

In addition to voltage compensation through DVR, a hybrid structure of series active and shunt passive filter has been proposed for harmonic neutralization of nonlinear loads. We shall discuss this method at the end of the chapter.

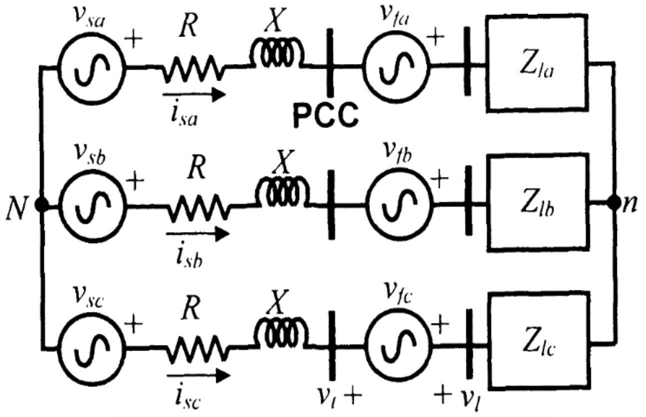
RECTIFIER SUPPORTED DVR

2. Explain Rectified Supported DVR.

Let us first consider the DVR structure shown in Figure (a). Let us consider the simplified distribution system shown in Figure . It is assumed that the system is compensated by an ideal series compensator. We can then define the following components of the distribution system.

- Ideal Series Compensator: represented by the instantaneous voltage sources v_{fa}, v_{fb} and v_{fc}.
- Supply Voltages: represented by the instantaneous voltage sources v_{sa}, v_{sb} and v_{sc}.
- Load Voltages: represented by the instantaneous voltages v_{la}, v_{lb} and v_{lc}.
- Terminal (PCC) Voltages: represented by the instantaneous voltages v_{ta}, v_{tb} and v_{tc}.
- Line Currents: represented by i_{sa}, i_{sb} and i_{sc}. Note that these currents will also flow through the load and therefore we might also call them load currents.
- Sensitive Loads: represented by the impedances Z_{la}, Z_{lb} and Z_{lc}. It is assumed that these loads are balanced, i.e, $Z_{la} = Z_{lb} = Z_{lc}$.

The series compensator is connected between a terminal bus on the left and a load bus on the right. The instantaneous voltages of the terminal (PCC) and load buses are denoted by v_t and v_l respectively with subscripts a, b and c denoting the phases with which they are associated. The voltage sources are connected to the series compensator terminals by a feeder with an impedance of $R + jX$. In this study we assume that the balanced loads are of RL type, given by $Z_{la} = Z_{lb} = Z_{lc} = R_l + jX_l$. It is to be noted that the phase angle ϕ_l between the load terminal voltage v_l and the line current i_s depends on the load impedance and is independent of the line impedance or the series compensator voltage.



From Figure we observe that

$$v_l = v_t + v_f \tag{1}$$

It is desired that the DVR regulates the load voltage. The reference voltage of the DVR (v_f^*) is then given by [4]

$$v_f^* = v_l^* - v_t \tag{2}$$

where v_l^* is the desired load voltage. Theoretically we can choose v_l^* to have any arbitrary magnitude and angle. Let us now consider the following example.

Example : Let us assume that a load is supplied by a balanced source with a peak voltage of √2 per unit. Let the feeder and load impedances in per unit be

$$R + jX = 0.05 + j0.3 \text{ and } R_l + jX_l = 2 + j1.5$$

The DVR will be connected at the end of the first half cycle (0.01 s). We desire that the peak of the load voltage be √2 per unit.

The results are shown in Figure in which the reference load voltage has an angle of – 20° in Case-1, while it has an angle of + 20° in Case-2. These reference angles are measured with respect to the source voltage and all quantities in Figure are given in per unit. It can be observed from Figure (a) and (c) that the load voltage becomes the desired voltage as soon as the DVR is connected. However to understand the behavior of the instantaneous powers shown in Figure (b) and (d), let us for the moment assume that the dc bus of the DVR is supplied by an ideal dc source that injects or absorbs any amount of power. Then for Case-1, part of power demanded by the load (p_l) is supplied by the terminal (p_t) and the other part comes from the compensator (p_f). The behavior in Case-2 however is different. In this case the terminal supplies more power than demanded by the load. Therefore the excess power is returned to the dc source connected to the DVR.

In actual situation when the dc bus of the DVR is supplied by the terminal through the rectifier shown in Figure (a), the reverse power flow may damage the rectifier unit. We must therefore always ensure that the phase angle of the desired load bus voltage is less than that of the terminal voltage.

To alleviate the problem of reverse power flow we must compute the phase angle of the positive sequence of the terminal voltage (V_{t1}) and make the reference load voltage (v_l^*) to lag this voltage by a small amount. To accomplish this we shall use the on-line fundamental symmetrical component extraction algorithm given in Section The positive sequence extraction is used because a disturbance in the supply side creates a temporary unbalance in the system. The idea is illustrated in the following example.

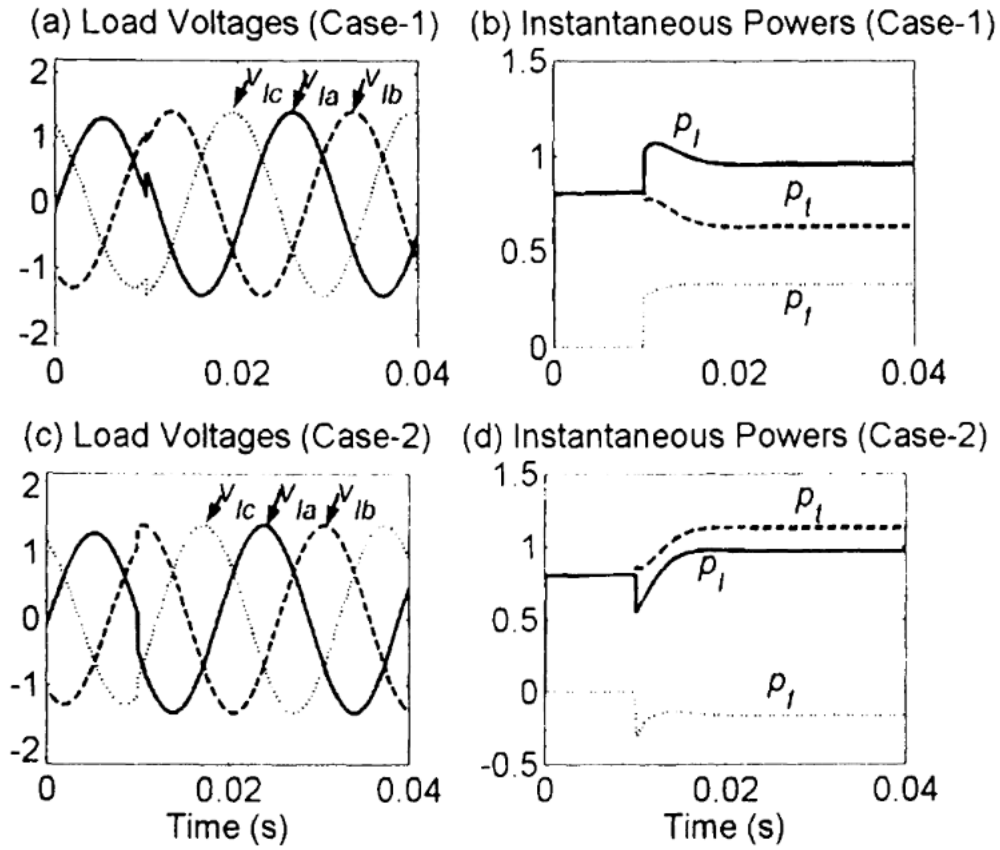


Figure Performance of rectifier supported DVR for two different phase angles: Case-1 when load voltage lags the source voltage by 20° and Case-2 when it leads by 20°

Example Let us consider the same system as given in Example We desire that the reference load voltage has a magnitude of √2 per unit while its phase angle lags that of the phase angle of the positive sequence of the terminal voltage by 5°. The compensator is connected at the end of the first half cycle. Further after two cycles (0.04 s) a voltage disturbance is created in the source voltage that lasts for about one and a half cycle. During the disturbance, the voltages of phases-a and b sag to 75% and 80% of the nominal values respectively, while that of the phase-c rises to 120% of the nominal value. We have not introduced any change in the phase angles of these voltages. The results are shown in Figure It can be seen that the load voltages are held constant during the disturbance. Also during the voltage disturbance, the terminal voltages are unbalanced and as a consequence the DVR voltages are also unbalanced. Therefore both the instantaneous powers supplied by the terminal and the DVR oscillate at 100 Hz. However there is no reverse power flow through the DVR. Since the load voltage is held balanced and loads are balanced, the load power remains constant except for minor disturbances at the beginning and end of the voltage sag/swell.

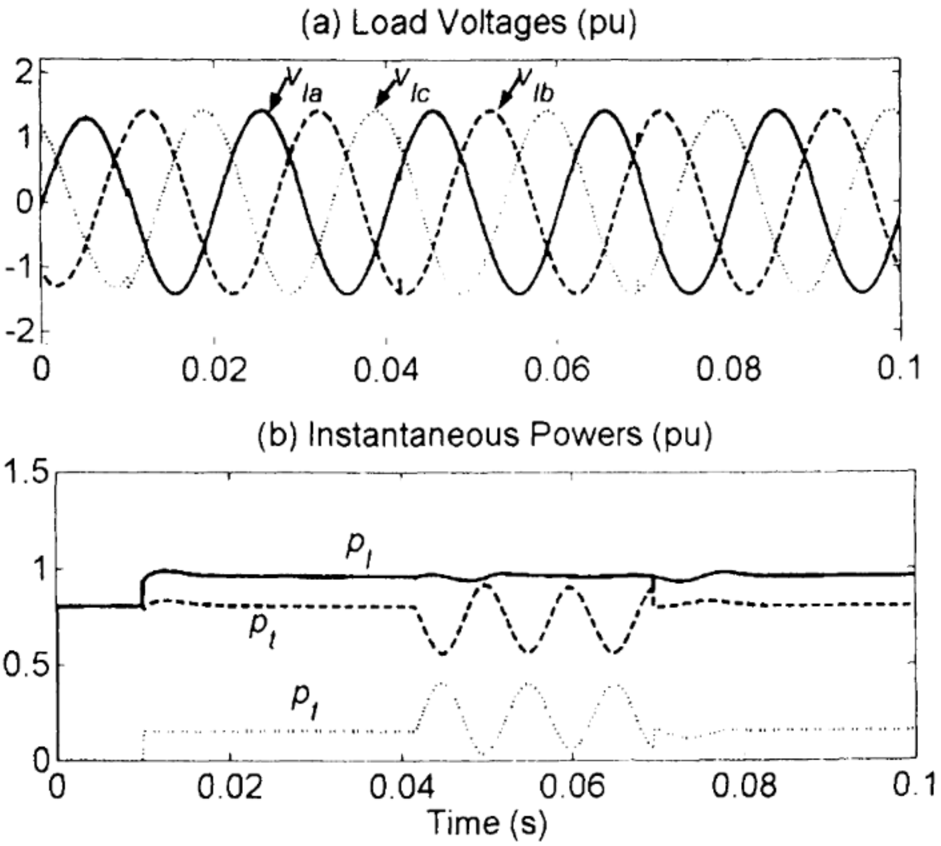


Figure Performance of rectifier supported, phase angle controlled DVR during voltage sag/swell

To investigate the performance of the DVR during the load change we have assumed that the load current has reduced suddenly such that load impedance is three times the value given in Example The results are shown in Figure in which the load reduction takes place when the system is in the steady state. It can be seen that no transient is observed in the load voltages. Further there is a reduction in all the three powers indicating that load demand has reduced. However even during this load reduction, the flow of power through the DVR remains in the positive direction.

In addition to the power flow consideration, the rating of the DVR also plays an important role in voltage correction. Figure depicts the per unit voltage to be injected by the DVR for four different symmetrical sags in the source voltage. Since the sag is symmetric, only phase-a voltage of the DVR is shown in this figure, as the DVR will inject a balanced voltage. It can be seen as the sag magnitude increases, the peak of the injected voltage increases. In fact for a sag in which the peak of the source voltage reduces to 50% its nominal value, the peak voltage to be injected is 0.85 per unit, i.e., the voltage has an rms value 0.6 per unit. This will obviously increase the rating of the device. Therefore the device rating and the maximum available compensation achievable are important issues.

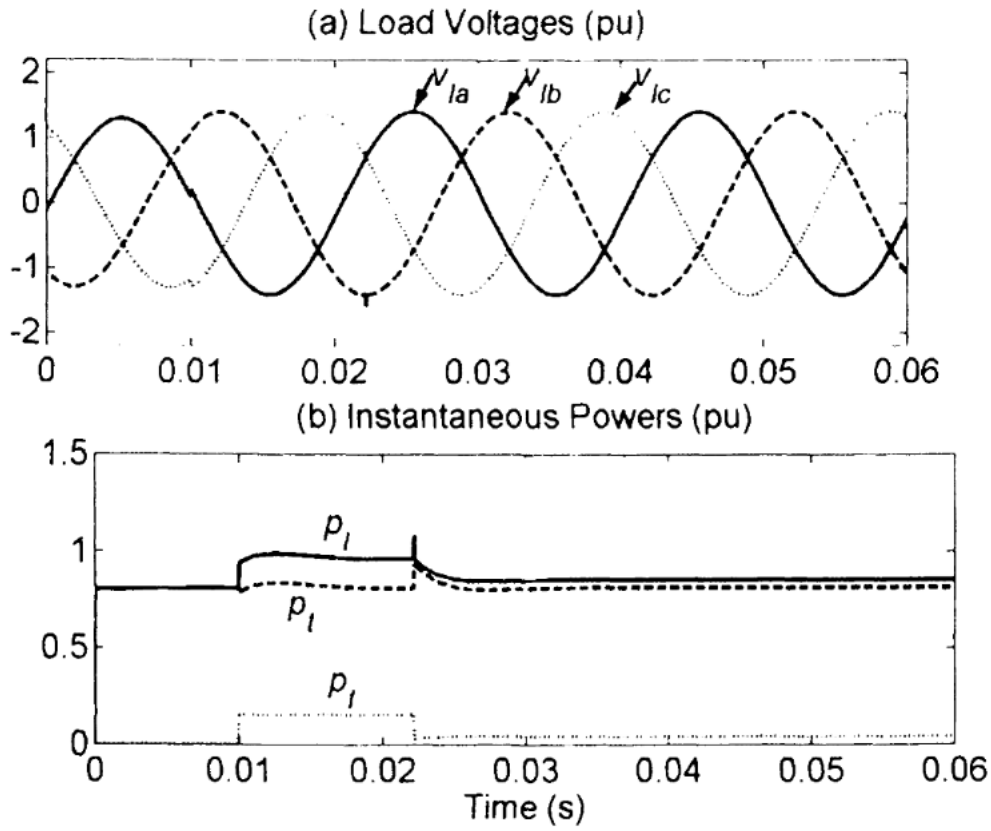


Figure Performance of rectifier supported, phase angle controlled DVR during load reduction

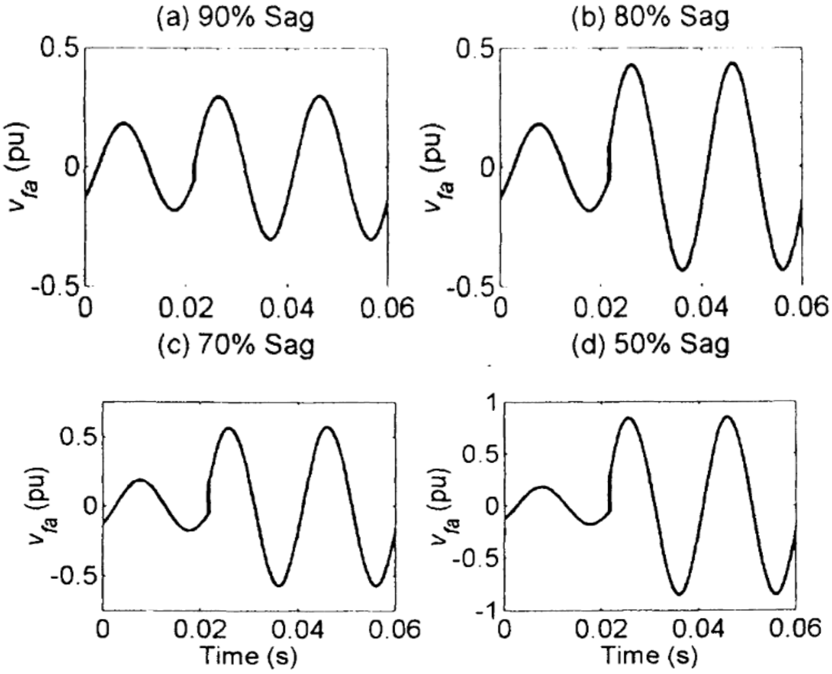


Figure DVR voltage injection requirements for different voltage sags

DC CAPACITOR SUPPORTED DVR

4. With neat diagram explain DC capacitor supported DVR.

In this section we shall consider the DVR structure shown in Figure (b). It will be demonstrated that this series compensator can not only act as a voltage restorer but also as a voltage regulator by pure series reactive injection. This implies that the DVR does not absorb or supply any real power in the steady state. Let us first develop the analytical aspects and illustrate these by examples of the simplified distribution system shown in Figure

Fundamental Frequency Series Compensator Characteristics

First we shall present the sinusoidal steady state analysis of a series compensator connected power system. In the analysis presented below we assume that the magnitude of the source voltage is V per unit and we want to regulate the magnitude of the load voltage to V per unit by injecting a voltage from the series compensator. We stipulate the following condition on the compensator

– ***Condition-1***: The series compensator need not supply any real power in the steady state. This implies that the phase angle difference between series compensator voltage phasor and line current phasor must be $\pi/2$ in the steady state.

Under this condition, we can divide the operation of the series compensator into three different cases depending on the feeder and load impedances. These are discussed below.

Case 1: When the Line Resistance is Negligible, i.e., $R = 0$: The phasor diagram for this case is shown in Figure . The only way the load and source voltage magnitudes can be equal is when the series compensator completely compensates for the reactive drop in the feeder. This will force the source and load voltages to be in phase.

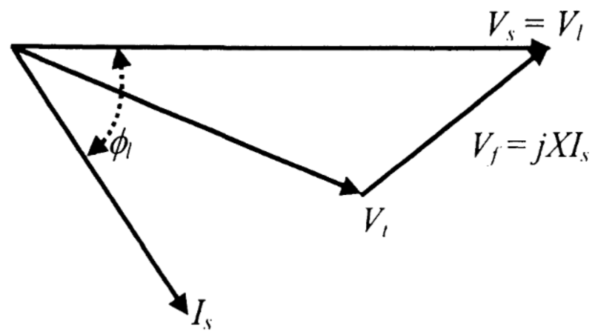


Figure . Phasor diagram for Case-1

Case-2: When the load is resistive, i.e., $X_l = 0$: The phasor diagram for this case is shown in Figure It can be seen that the magnitude of the source and load voltages will never be equal in this case unless the condition that the series compensator must not supply (or absorb) real power is relaxed.

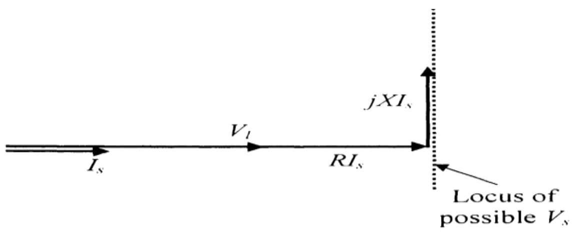


Figure . Phasor diagram for Case-2

Case-3: This is the most general case in which the load current lags the load voltage and the feeder resistance is not neglected. To draw a phasor diagram, we assume that the load voltage is fixed at V per unit and the source voltage is allowed to vary. Since the primary target is to make the magnitudes of V_l and V_s equal, the locus of desirable V_s is the semicircle as shown in Figures

Figure shows the limiting behavior. Let us assume that the resistive drop (RI_s) in the feeder is greater than the length SP. Since the series compensator must inject voltage in quadrature with the load current, it will not be possible to get the source voltage to be equal to V per unit. Even though the source voltage can be fixed anywhere along the line NM, the maximum of $|V_l|/|V_s|$ is obtained when the source voltage is equal to OM. On the other hand, if the RI_s drop is exactly equal to SP, the load and source voltages can be made equal by aligning the source voltage with the line current. The magnitude of the source voltage is then equal to OQ.

Let us again consider the limiting case shown in Figure in which we assume that the magnitude of the source voltage (OM) is equal to 1.0 per unit and that of the load voltage is V per unit. We then have the distance $OT = V\cos\phi_l$. Hence the distance MT will be equal to $1 - V\cos\phi_l$. Therefore we can write $RI_s = 1 - V\cos\phi_l$.

Now suppose the RI_s drop is less than the limiting value (i.e., SP in Figure The series compensator must then compensate the entire reactive drop in the feeder and provide additional injection such that the magnitude of the source voltage becomes V per unit. It can be seen from Figure that there are two possible intersection points with the semicircle – one at A and the other at B. This implies that two possible values of series compensator voltage can be obtained for this case. In the first case the source voltage will be along OA, while in the other case it will be along OB. It is needless to say that the best choice is the A intersection requiring much smaller voltage injection from the series compensator.

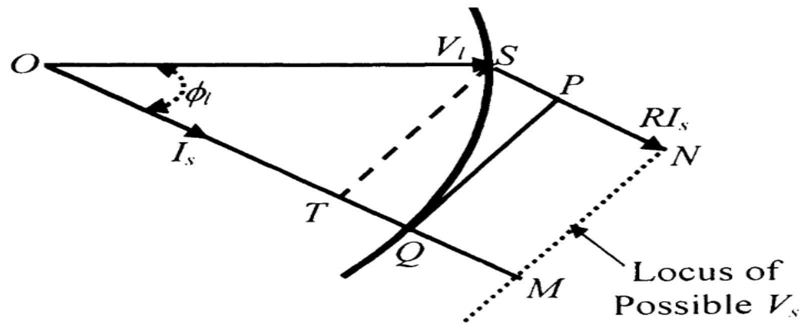


Figure Phasor diagram of the limiting condition for Case-3

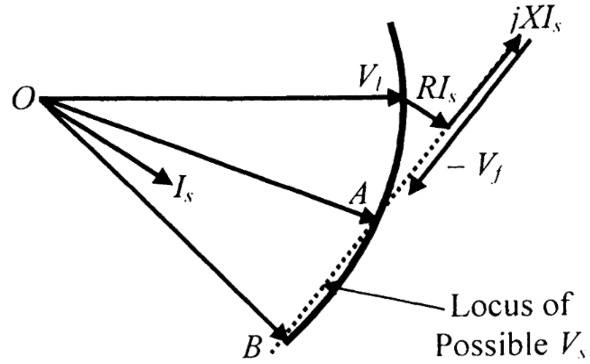


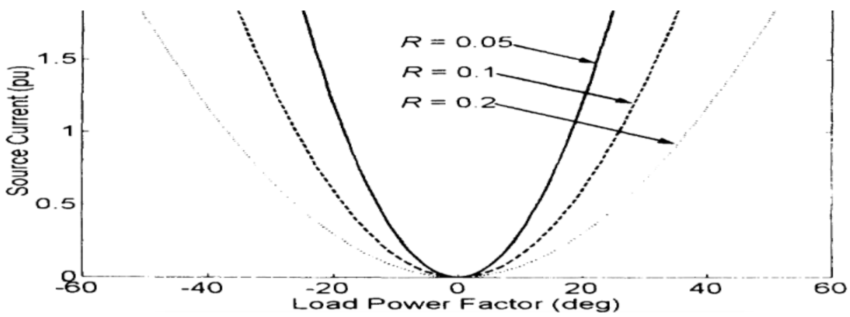
Figure Phasor diagram showing multiple solutions for Case-3

To obtain a valid solution we require that

$$RI_s \leq 1 - V\cos\phi_l \quad \Rightarrow \quad I_s \leq \frac{1 - V\cos\phi_l}{R}$$

The changes in the source current with the changes in the load power factor angle are shown in Figure for different values of the line resistance and $V = 1.0$ per unit. From this it can be seen that as the line resistance increases, the current drawing capacity of load that has to be compensated decreases. This implies that if the load requires more current than is permissible, the series compensator will not be able to regulate the load voltage to 1.0 per unit.

Alternatively, we can also regulate the load voltage to a value that is other than 1.0 per unit. Figure shows the system load current characteristics for different values of V. It can be seen that as the requested load voltage V decreases, the maximum current drawing capacity of the load increases. At the same time, a restriction is also put on the minimum current that can be drawn by the load. Similarly, as V increases, the current drawing capacity of the load decreases. Clearly, even for zero load current, a voltage of 1.05 per unit cannot be achieved for low power factor angles.



Compensatable source current versus power factor, source and load voltages equal: a range of feeder resistance

5. Elaborate the transient operation of series compensator when the supply is balanced .

– ***Condition-2***: The positive sequence of the series compensator power must remain zero in the steady state. Since the reference load voltages and hence load currents are balanced, this implies that the phase angle difference between the positive sequence of the series compensator voltage phasor and the line current phasor must be $\pi/2$ in the steady state.

In the presence of unbalance or harmonics this condition stipulates that the instantaneous series compensator power will have a zero mean, but will also contain a periodic term. We now divide the series compensator terminal voltage as

$$v_t = v_{t1} + v_t^{rest}$$

where v_{t1} is the positive sequence component of v_t and v_t^{rest} is the remaining portion containing the influence of unbalance and harmonics. As per condition-2 we can then write

$$V_{f1} = |V_{f1}| e^{j(\angle I_s + 90^\circ)} = |V_{f1}|(a_1 + jb_1)$$

where $a_1 + jb_1$ is a unit phasor at 90° to I_s. We then modify to obtain the magnitude of the fundamental frequency component of series compensator voltage from the quadratic

$$|V_{f1}|^2 - 2a_1|V_t||V_{f1}| + |V_t|^2 - |V_{t1}|^2 = 0$$

The fundamental component of the series compensator voltage is obtained from the above equation. The instantaneous series compensator voltage is then obtained by solving the following equation after phase locking the fundamental component with the reference point

$$v_f = v_{f1} - v_t^{rest}$$

$$v_f = v_{f1} - v_t^{rest}$$

This will provide for the desired correction of the positive sequence term and will cancel all negative or zero sequence components as well as harmonics.

6. Explain Series Compensator rating for balanced and unbalanced loads.

Series Compensator Rating

Since a series compensator is connected in series with the feeder, the full feeder current flows through it. This current mainly depends on the load voltage and impedance. Thus the power rating of a series compensator will mainly depend on the series compensator voltage. So far in our discussion we have assumed that the series compensator is capable of supplying unlimited amount of voltage. This however may not be feasible. Consider the following example.

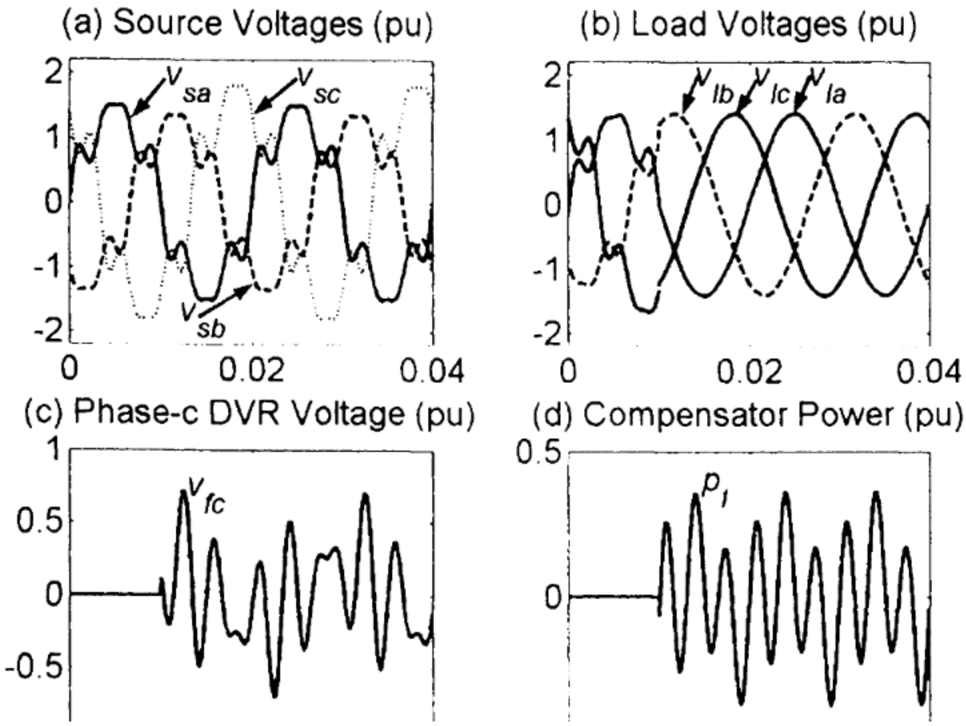


Figure . Performance of series compensator under unbalanced and distorted supply condition

DVR STRUCTURE

7. Discuss with neat diagram the DVR structure.

The examples in the previous sections assume that the series compensator is realized by ideal voltage sources. In this section we shall develop a DVR structure in which the voltage sources are realized by three voltage source inverters (VSIs). This structure is similar to the DSTATCOM structure of Figure In this section we shall study two different filter realizations. One of these two is shown in Figure It can be seen just as in Figure , the three VSIs are connected to a common dc storage capacitor. In this figure each switch represents a power semiconductor device and an anti-parallel diode combination. Each VSI is connected to the network though a transformer and a capacitor filter (C_f). The transformers not only reduce the voltage requirement of the inverters but also provide isolation between the inverters. This prevents the dc storage capacitor from being shorted through switches in different inverters.

In the DVR structure of Figure the capacitor filter is connected across the secondary of the transformer. This prevents switching frequency harmonics from entering the system. The main drawback of the system of Figure is that the direct connection of VSI to the transformer primary results in losses in the transformer. The high frequency flux variation causes significant increase in transformer iron losses. To avoid this, a switch frequency LC filter (L_f–C_f) is placed in the transformer primary as shown in Figure The secondary of the transformer is directly connected to the feeder. This will constrain the switch frequency harmonics to mainly in the primary side of the transformer. Either of the DVR realization can be controlled through output feedback or state feedback We discuss these two realizations below.

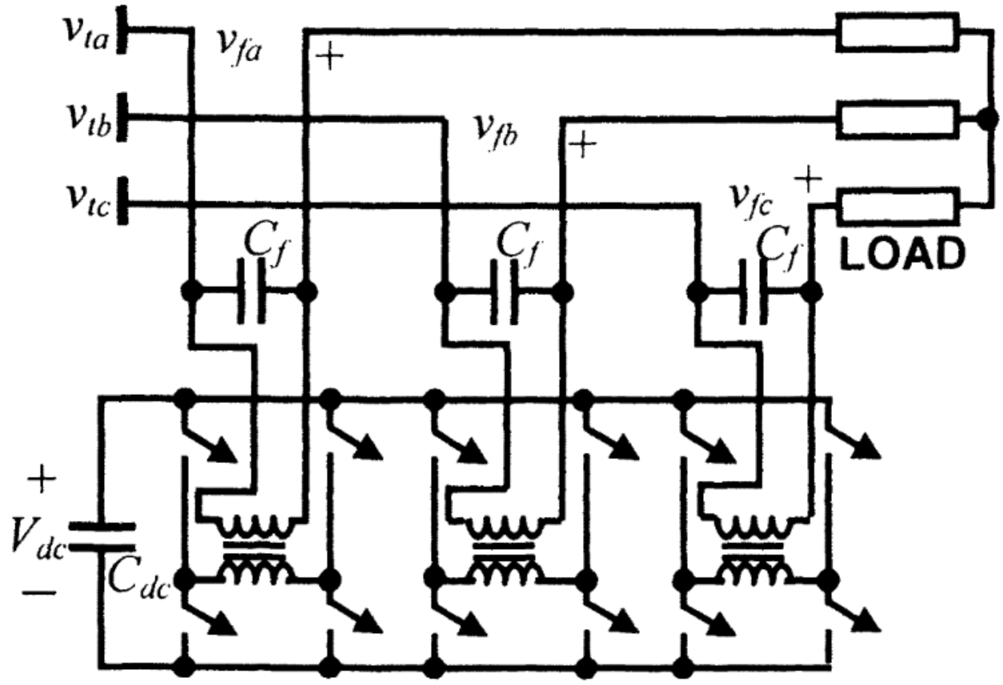


Figure DVR structure with capacitor filter

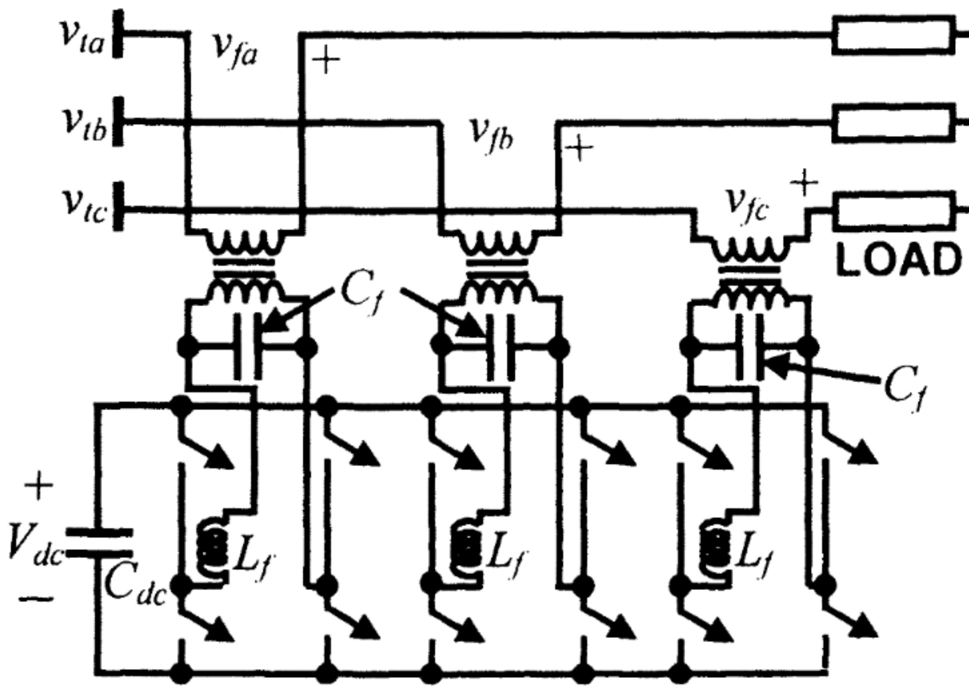


Figure DVR structure with LC filter

at the inverter output terminals, the inductance L_T represents the leakage inductance of each transformer. The switching losses of the inverter and the copper loss of the connecting transformer are modeled by a resistance R_T.

Output Feedback Control of DVR

In this type of control, the square of the error between reference DVR voltage and actual DVR voltage is minimized to obtain a deadbeat control action. The single-phase equivalent circuit of the DVR with capacitor filter is shown in Figure 9.24. Here $u \cdot V_{dc}$ denotes the switched voltage generated

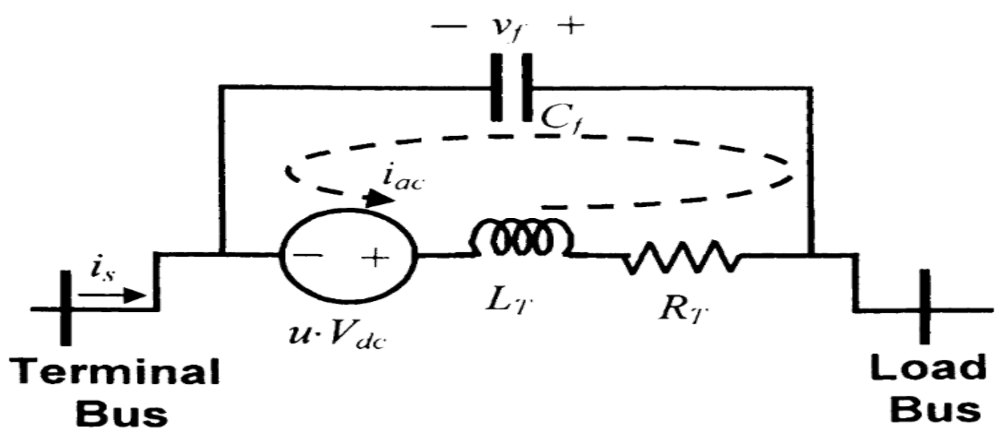


Figure Single phase equivalent circuit of DVR with capacitor filter

We can construct the state space model of the system from the equivalent circuit shown in Figure Let us define a state vector as $x^T = [v_f \ \ i_{ac}]$. We then get the following state space model from Figure 9.24

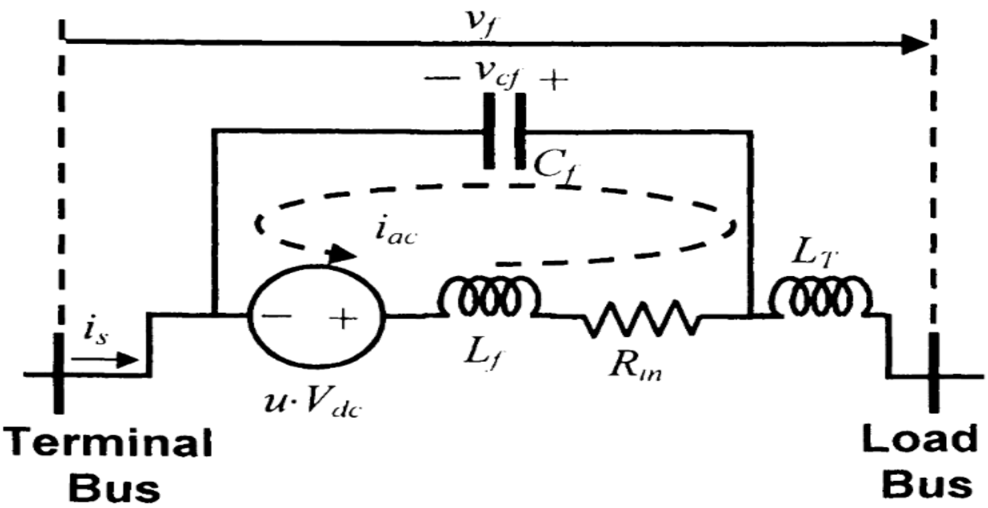
$$\dot{x} = \begin{bmatrix} 0 & 1/C_f \\ -1/L_T & -R_T/L_T \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ V_{dc}/L_T & 0 \end{bmatrix} \begin{bmatrix} u_c \\ i_s \end{bmatrix}$$

The single-phase equivalent circuit of the DVR with the LC filter is shown in Figure In this figure L_T denotes the leakage inductance of each of the transformers and R_{in} denotes the switching losses of each inverter. The copper losses of the transformers are neglected here for simplicity. Note that these losses can be incorporated by a resistor in series with the inductor L_T. Defining a state vector as $x^T = [v_{cf} \ \ i_{ac}]$, we get the following state space model from Figure 9.25

$$\dot{x} = \begin{bmatrix} 0 & 1/C_f \\ -1/L_f & -R_{in}/L_f \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ V_{dc}/L_f & 0 \end{bmatrix} \begin{bmatrix} u_c \\ i_s \end{bmatrix}$$

The DVR voltage is given by

$$v_f = v_{cf} - L_T \frac{di_s}{dt}$$



Single phase equivalent circuit of DVR with LC filter

The state equation is discretized to obtain

$$x(k+1) = Fx(k) + Gu(k)$$

Let us define the output by v_y. It is equal to v_f for and equal to v_{cf} for Defining the elements of matrix F as f_{ij} and the elements of matrix G as g_{ij} we can write

$$v_y(k+1) = f_{11}\, v_y(k) + f_{12}\, i_{ac}(k) + g_{11}\, u_c(k) + g_{12}\, i_s(k)$$

The minimization of the deadbeat performance index results in the following control law

$$u_c(k) = \frac{v_{ref}(k+1) - f_{11}\, v_y(k) - f_{12}\, i_{ac}(k) - g_{12}\, i_s(k)}{g_{11}}$$

where v_{ref} is the instantaneous reference value of the DVR. Once u_c is obtained the control input u is obtained in the hysteresis band control discussed before.

The switching band control scheme can be used only when the control variable $u(k)$ is available. Again obtaining $u(k)$ is dependent on the availability of the reference voltage v_{ref}. The reference voltage for the DVR with the capacitor filter is available in a straightforward manner from since the output for this case is v_f. This however is not true for the DVR with LC filter We have to generate a reference voltage for v_{cf}.

From Figure we can write the phasor fundamental positive sequence component of terminal voltage as

$$V_{t1} = V_l - V_{cf1} + j\omega L_T I_s$$

Since the DVR must inject zero power, the voltage across the filter capacitor can be written as

$$V_{cf} = |V_{cf1}|(a_1 + jb_1)$$

where $a_1 + jb_1$ is a unit vector that leads the line current by 90°. We can then use the following expression for the line current

$$jI_s = |I_s|(a_1 + jb_1)$$

Now defining $X_T = \omega L_T$ can be written as

$$V_{t1} = V_l - \left(\left|V_{cf1}\right| - X_T\left|I_s\right|\right)\left(a_1 + jb_1\right)$$

The above equation results in the following quadratic

$$\left|V_{cf1}\right|^2 - 2\left|V_{cf1}\right|\left(X_T\left|I_s\right| + a_1\left|V_l\right|\right) + \left|V_l\right|^2 - \left|V_{t1}\right|^2 + X_T^2\left|I_s\right|^2 + 2a_1 X_T\left|V_l\right|\left|I_s\right| = 0$$

The DVR voltage must not only supply the instantaneous positive sequence component of v_{cf} but also the harmonic component of v_t. Therefore

$$v_{cf} = v_{cf1} - v_t^{rest}$$

VOLTAGE RESTORATION

8.Write Short notes on voltage restoration.

Voltage Restoration

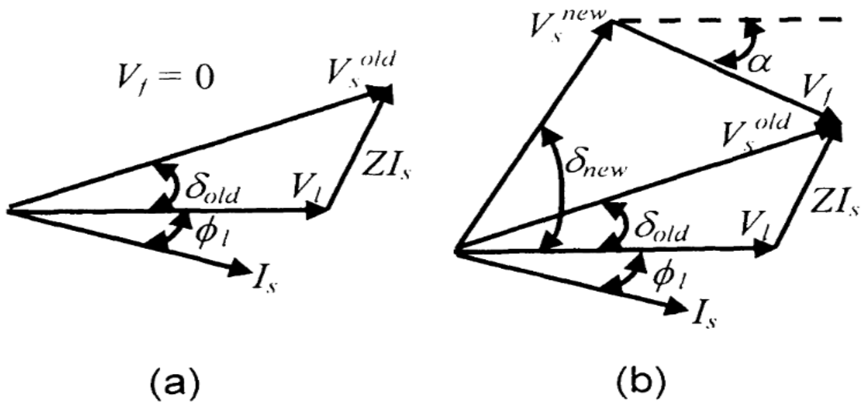
So far our discussion was focused on voltage regulation and restoration using a series compensator that ideally requires no real power in the steady state. In this configuration the series compensator is kept on-line all the time to maintain voltage at the load terminals. It has been shown that the series compensator, which is supplied from a dc storage capacitor, ordinarily needs real power to replenish any losses in the converter circuit. It also needs real power to ride over any transient. However, as we have demonstrated, this power can be drawn from the source through feedback control of capacitor voltage.

The series compensator can also be used in an alternate form in which it comes on line only when there is a voltage sag. Otherwise it stays inactive. Consider the phasor diagram of Figure (a). This represents the steady state operation of the circuit when the series compensator acts as a voltage restorer only. The supply voltage during the steady state operation is V_s^{old} and it leads the load voltage by an angle δ_{old}. Now suppose a fault reduces the supply voltage to V_s^{new} that leads the load voltage by an angle δ_{new}. The series compensator then must inject a voltage such that the vector sum of load voltage and line drop remains unchanged and equal to V_s^{old}. This is shown in Figure (b).

The phasor diagram shown in Figure (a) is only to illustrate the restoration behavior for transient control of sudden voltage dip. Since we can only use the local measurements, neither the source voltage nor the feeder impedance can be used for series compensator control. The voltage restoration function however is very straightforward. The series compensator voltage is obtained from the following equation

$$V_f = V_l^{pf} - V_t$$

where V_l^{pf} is the measured prefaulted voltage at the load terminal. It is to be noted that voltage restoration using implies real power exchange during any transient. A series compensator that is supplied by a dc storage rather than a dc capacitor can easily accomplish that. Dynamic voltage compensation using high speed flywheel energy storage system (FESS) has been reported Alternatively, as we have discussed before, the dc link capacitor can be supplied from a rectifier.



Phasor diagram of series operation: (a) steady state operation and (b) transient voltage restoration

SERIES ACTIVE FILTER

9.Discuss series active filter.

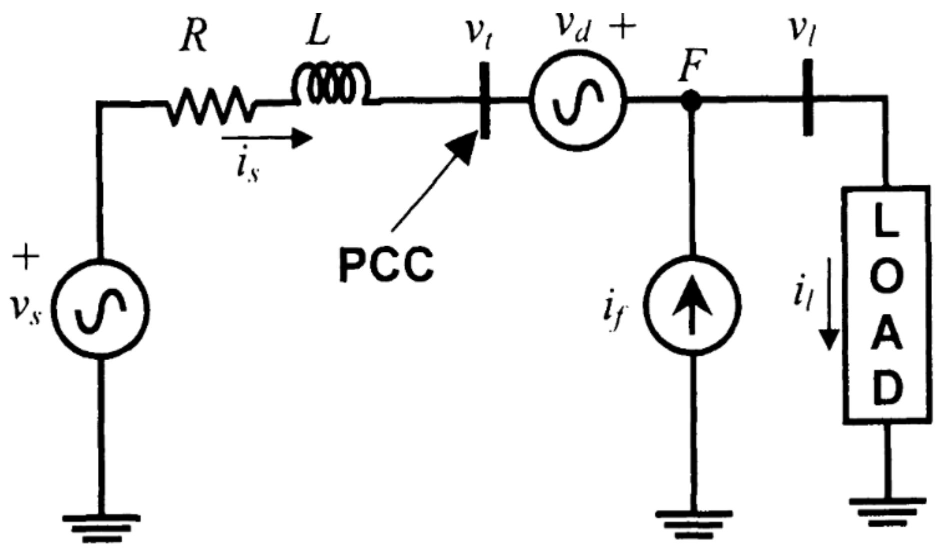
Series Active Filter

A series compensator, which injects a voltage in series, can also act as a series active filter to isolate the source from harmonics generated by loads. Consider the distribution system shown in Figure If the load is unbalanced, then by injecting a voltage in series we shall be able to correct this unbalance at the PCC (terminal bus).

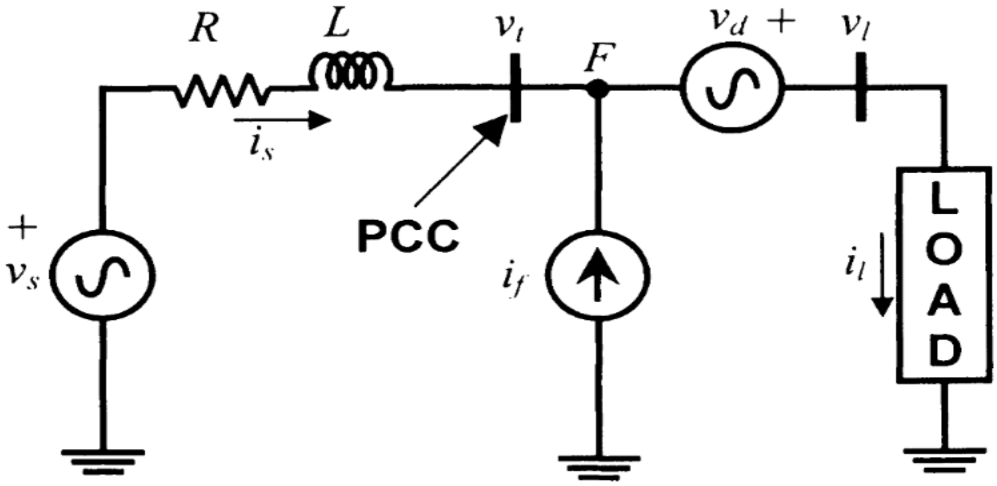
UNIFIED POWER QUALITY CONDITIONER (UPQC)

10. Explain Unified power quality conditioner with neat diagram.

Let us first assume that the combination of an ideal series voltage source and an ideal shunt current source represents the UPQC. There are two possible ways of connecting this device at the point of common coupling (PCC). The single-line diagrams of these two schemes are shown in Figures In these figures the voltage at the PCC is referred to as the terminal voltage v_t. The load voltage, load current and source current are denoted by v_l, i_l and i_s respectively. The voltage and current injected by the UPQC are denoted by v_d and i_f respectively. The source voltage is denoted by v_s, while R and L constitute the feeder impedance. We shall restrict our discussions to three-phase, four-wire systems only.



The right-shunt UPQC compensation configuration



The left-shunt UPQC compensation configuration

- Convert the feeder (source) current (i_s) to balanced sinusoids through the shunt compensator.
- Convert the load voltage (v_l) to balanced sinusoids through the series compensator and also regulate it to a desired value.

This can be achieved by employing either of the two configurations shown in Figures They are termed as right-shunt and left-shunt respectively depending on the placement of the shunt compensator vis-à-vis the series compensator. We shall discuss the characteristics of these two configurations separately.