POWER QUALITY (IIHI)-R19

- **PREPARED BY**

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UNIT - 1

MODULE 1

Power quality phenomenon – Sources and Effects of power quality problems, types of power quality disturbances – Voltage sag (or dip), Swell, Transients, short duration voltage variation, Long duration voltage variation, voltage imbalance, waveform distortion and voltage flicker

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Electric power quality

- *Refers to "maintaining the near sinusoidal waveform of power distribution bus voltages and currents at rated magnitude and frequency*
- Used to express
  - voltage quality
  - current quality
  - reliability of service
  - quality of power supply, etc

Sources of Power quality problems

Primary sources of power distortion are

(1) Non-linear Loads

(2) Power electronic devices

(3) IT and Office Equipment's

(4) Arcing Devices

(5) Load Switching

(6) Large Motor starting

(7) Larger capacitor bank

(8) Electromagnetic radiations and cables

(9) Storm and Environment Related causes

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Sources of Power quality problems

Utility sources

(1) Lightning (2) PF correction equipment

(3) Faults (4) switching

Internal Sources

(1) Individual loads – Lighting, Elevators, Cooler, HVAC

(2) Uninterruptible Power Supplies

(3) Variable Frequency Drives

(4) Battery Chargers

(5) Lighting Ballasts, Electronic Dimming Systems

(6) Arc Welders and other Arc devices

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Effects of Power quality problems

- Equipment failure
- Data corruption
- Overheat
- Unstable distribution system
- Loss of productivity and profitability, Complete shutdown loss of control
- Voltage distortions
- Improper waveshapes
- Loss of system capacity, etc

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Causes and Effects of Common Power quality issues

Problems	Causes	Effects
Harmonics	Electromagnetic interference from appliances, machines, radio and TV broadcasts	Continuous distortion of normal voltage, Random data errors
Voltage Sags/Swells	Major equipment startup or shutdown, Short circuits (faults), undersized electrical wiring, temporary voltage rise or drop	Memory loss, data errors, dim or bright lights, shrinking display screens, equipment shutdown
Interruption	Switching operator, attempting to isolate electrical problem and maintain power to power distribution area	Equipment trips off, programming is lost, disc drive crashes
Flicker	Arc Furnace, voltage fluctuations on utility transmission and distribution systems	Visual irritation, introduction of many harmonic components in the supply power and their associated equipment

Causes and Effects of Common Power quality issues

Problems	Causes	Effects
Transients	Lightning, turning major equipment on or off, utility switching	Tripping, processing errors, data loss, burned circuit boards
Electrical Noise	Arc welders, SMPS, fault clearing devices, ground not isolated	Data corruption, erroneous command functions, improper wave shapes, etc.
Stable AC from DC source	DC power plant available, remote areas	Unavailable AC power
Emergency power source transfer	Back-up generator start-up, power interruption transfer of utility source	System crash, System lock-up, power supply damage, lost data, complete shutdown loss of control
Distribution system and power quality	Lack of understanding of system problems or coordination	Unstable distribution system, lost productivity and profitability
High energy cost/Power factor correction	Need for energy savings and pay back for equipment investment	Lost profits increased cost

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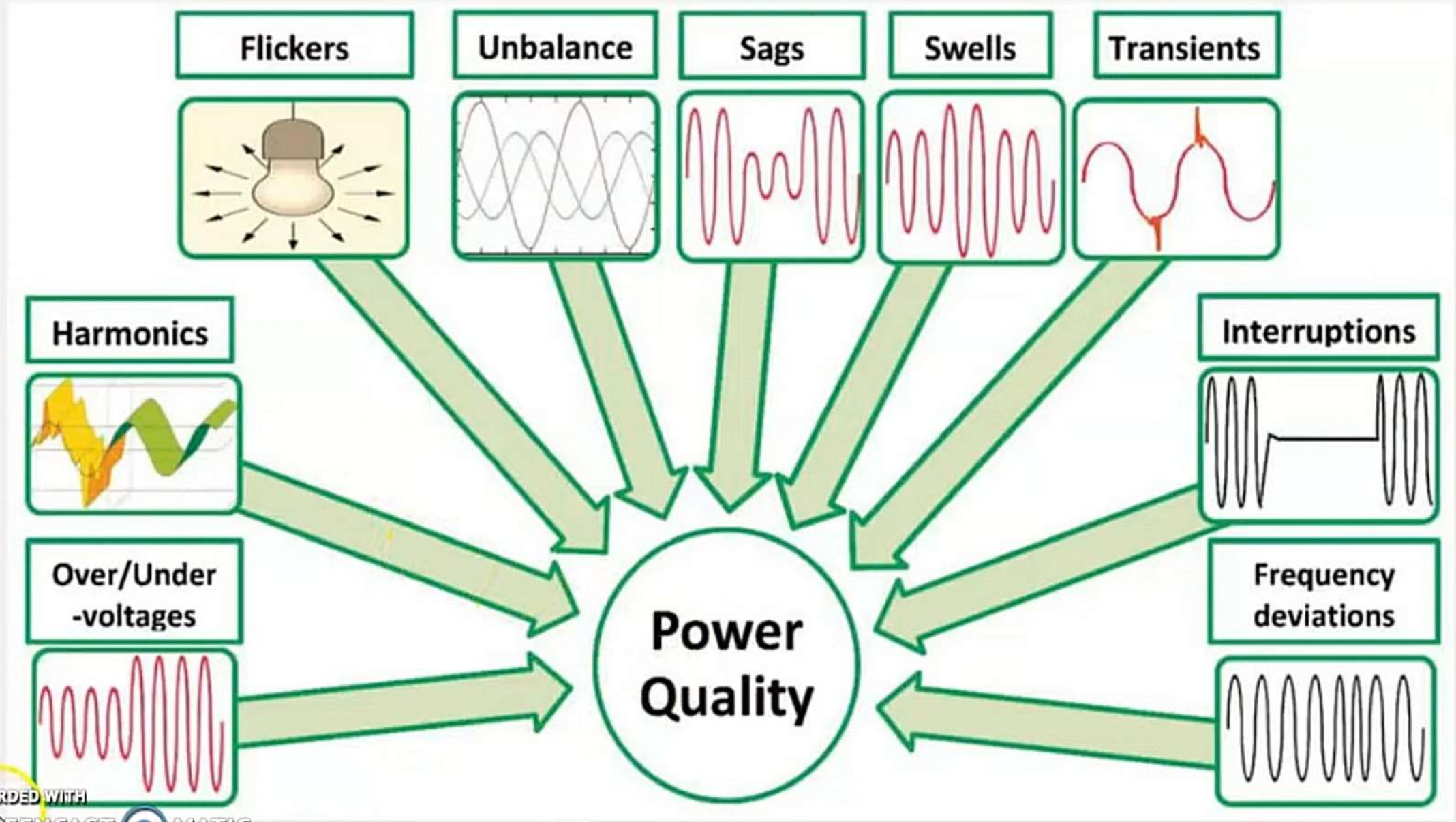
Types of Power Quality disturbances



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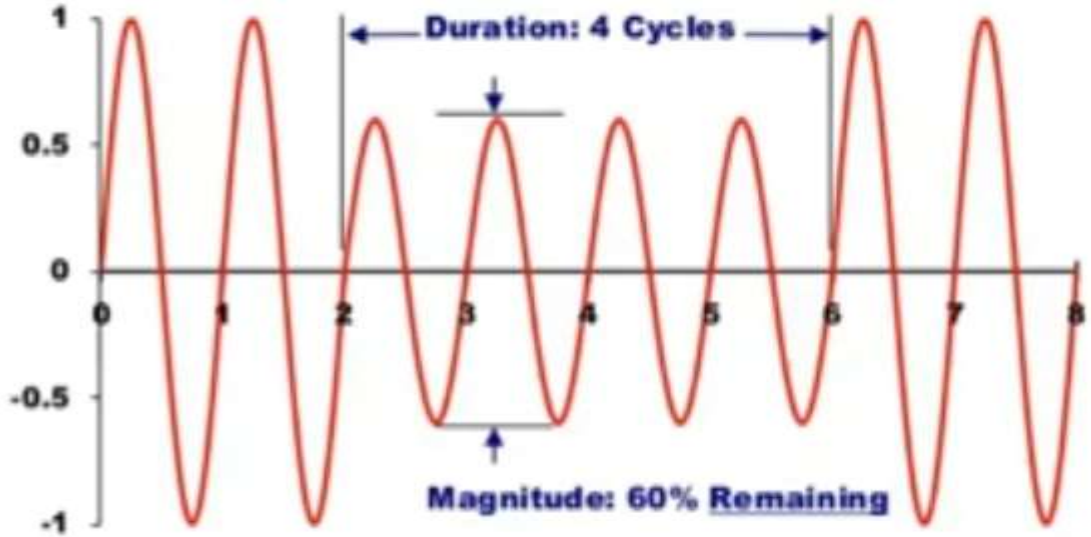
Voltage sag (dip)

- It is a short duration disturbance
- A reduction in RMS voltage over a range of 0.1-0.9pu for a duration greater than 0.5cycles but less than 60sec

Causes for voltage sags

- Energisation of heavy loads
- Starting of large induction motor
- Single line-to-ground faults
- Line-line and symmetrical faults
- Load transferring from one power source to another

- Sag - RMS voltage reduction between 1/2 cycle - 60 sec
- Magnitude and Duration



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Effects of sag

- Voltage instability because of reduction of bus voltage for short duration
- Malfunctions of electrical low-voltage devices
- Malfunctions of uninterruptible power supply
- Malfunctions of measuring and control equipment
- Interfacing with communication signals
- Cause loss of production in automated process => a voltage sag trip a motor or controller to malfunction i.e, microprocessor based control system

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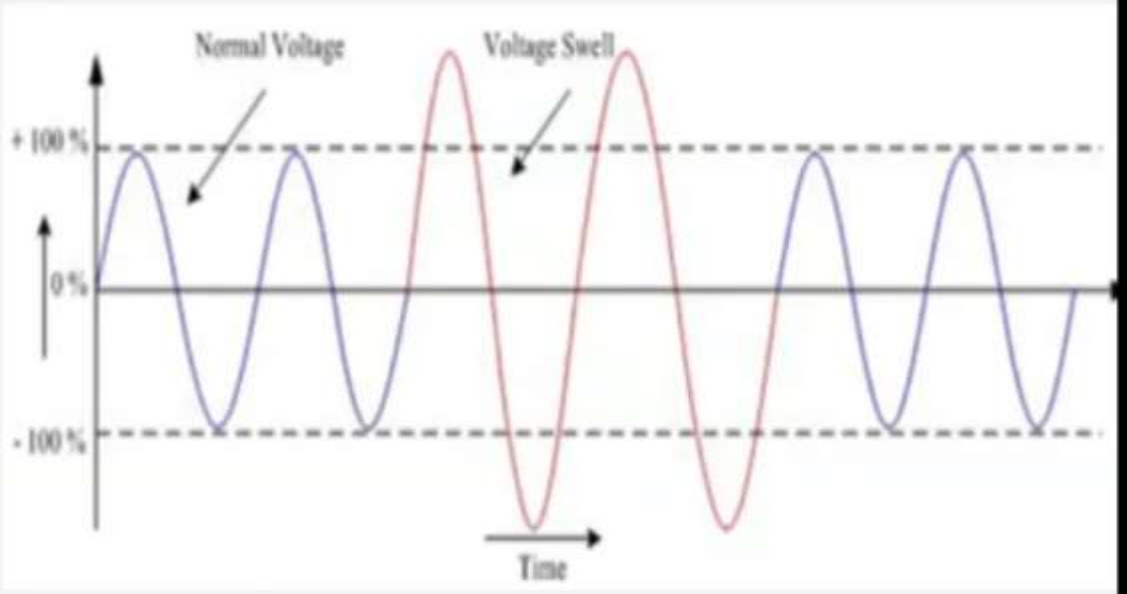
2. Swell

- It is a short duration phenomenon of increase in rms voltage
- Voltage magnitude lies between 1.1 and 1.8pu
- Duration of the event ranges from 0.5cycles to 60 sec



Main causes of swell

- Switching off of a large load
- Energizing a capacitor bank
- Voltage increase of the unfaulted phases during a single line-to-ground fault
- Momentary overvoltage

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Effects of sag

- Voltage instability because of reduction of bus voltage for short duration
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Effects of swell

- Voltage instability because of reduction of bus voltage for short duration
- Malfunctions of electrical low-voltage devices
- Malfunctions of uninterruptible power supply
- Malfunction of measuring and control equipment
- Interfacing with communication signals

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Transients

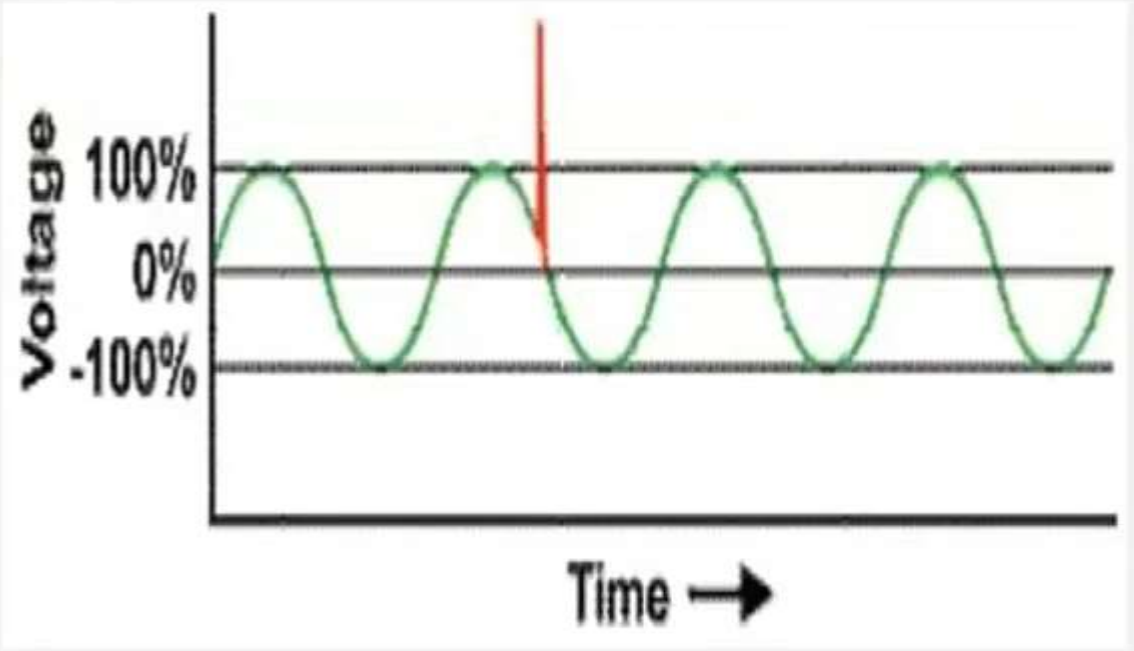
Short duration power system phenomena

They show very high rise of voltage and current in short period of time

Transients may generate in the system or may propagate to the system from other external system

It may be unidirectional or oscillatory in shape

No clear limit for the period of transient



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Transients can be of

(1) Events identified by their fundamental frequency magnitude

(2) Events having significant changes in the fundamental frequency magnitude but of short duration

(3) Events of short duration for which the fundamental frequency magnitude does not offer important information

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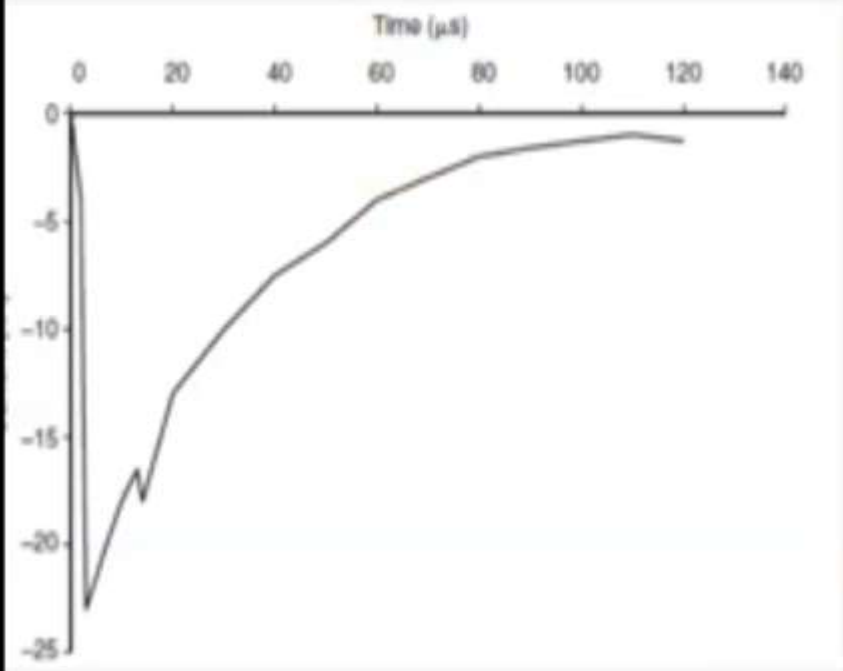
Impulsive transients



Lightning stroke current impulsive transient.

- An impulsive transient is defined as a sudden change in the steady state condition of voltage, current or both, that is unidirectional in polarity either positive or negative.
- Analysis of impulsive transients is done by their rise and decay times.
- Impulsive transients are damped quickly by the resistive circuit elements and do not propagate far from their source. Thus their effects are localized.
- Lightning

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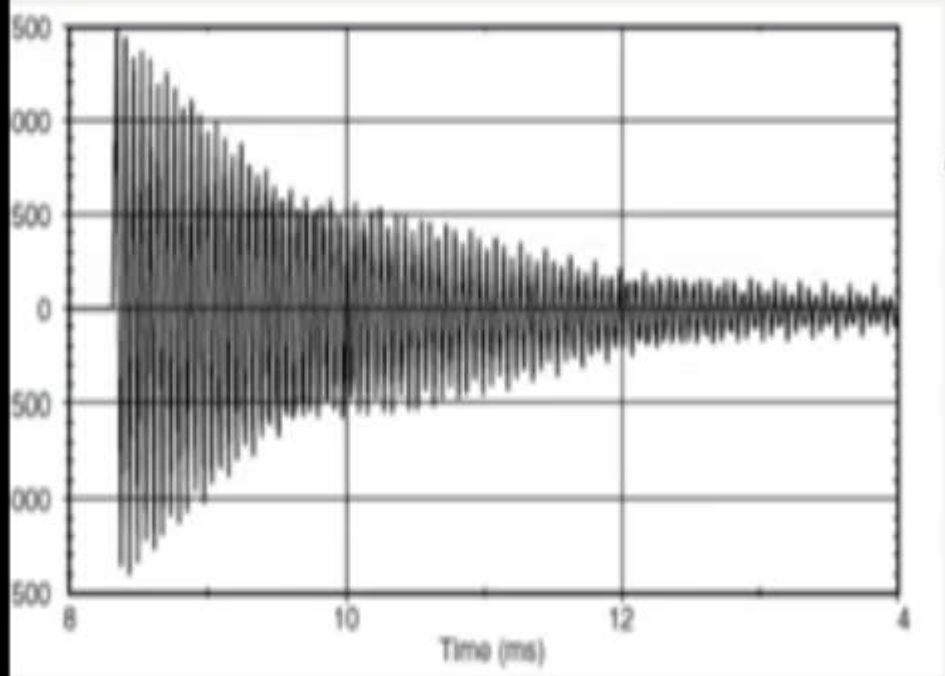
Oscillatory transients



- Oscillatory transient is alternating in nature.
- It shows a damped oscillation with a frequency ranging from a few hundred Hertzs up to several Mega Hertzs.
- Caused by the energizing of a capacitor bank where, frequency of oscillation is mainly determined by the capacitance of the capacitor bank and the short circuit inductance of the circuit feeding the capacitor bank (capacitor energizing).
- Another common cause of oscillatory transient is event of energizing of transmission line.

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Oscillatory transients

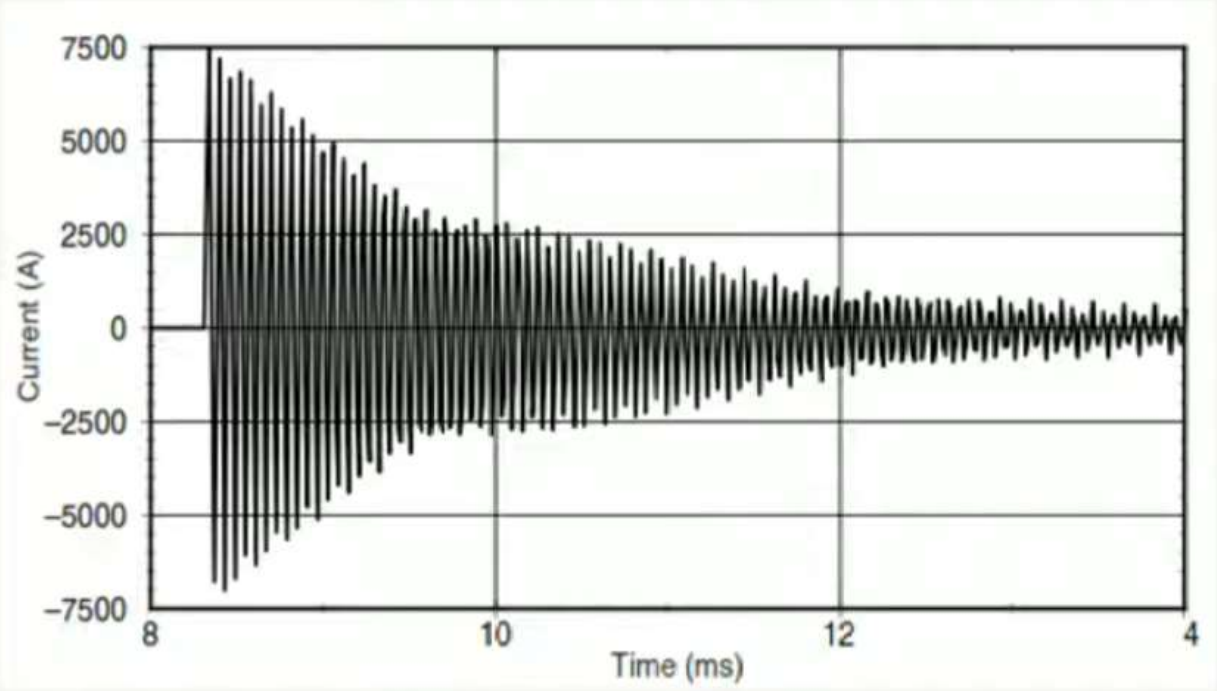
scillatory transient is a sudden, non–power frequency change in the steady-
e condition of voltage, current, or both, that includes both positive and
ative polarity values.

oscillatory transient consists of a voltage or current whose instantaneous
e changes polarity rapidly.

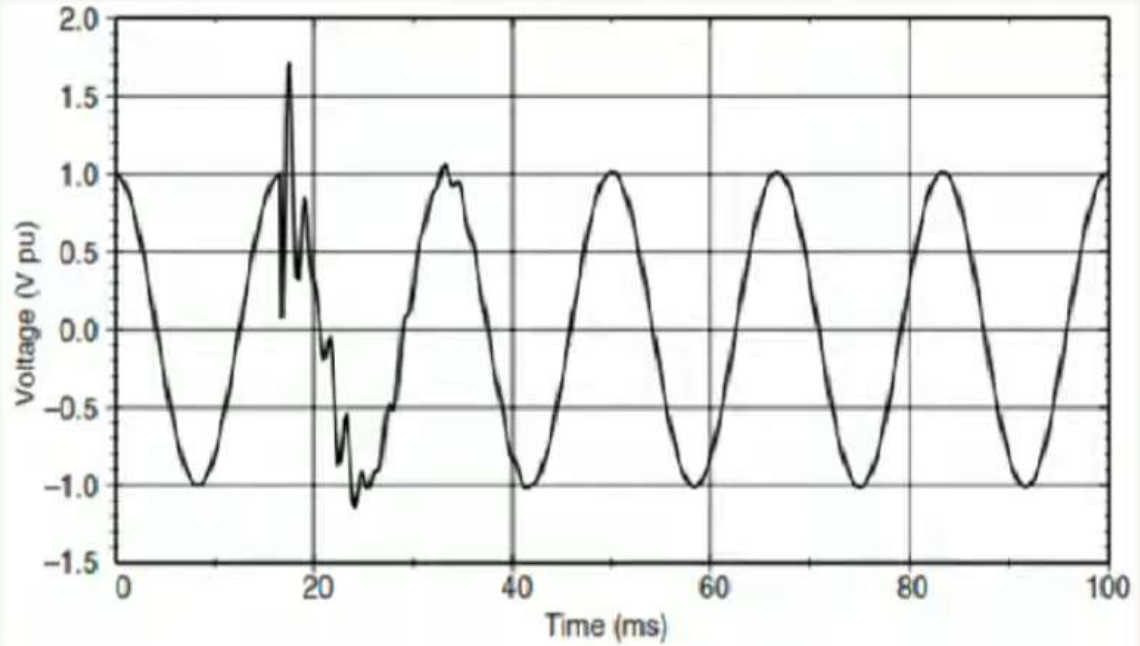
described by its spectral content (predominate frequency), duration, and
nitude.

are high, medium, and low frequency transients.

High Frequency Oscillatory transients



Low Frequency Oscillatory transients



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

Oscillatory transients

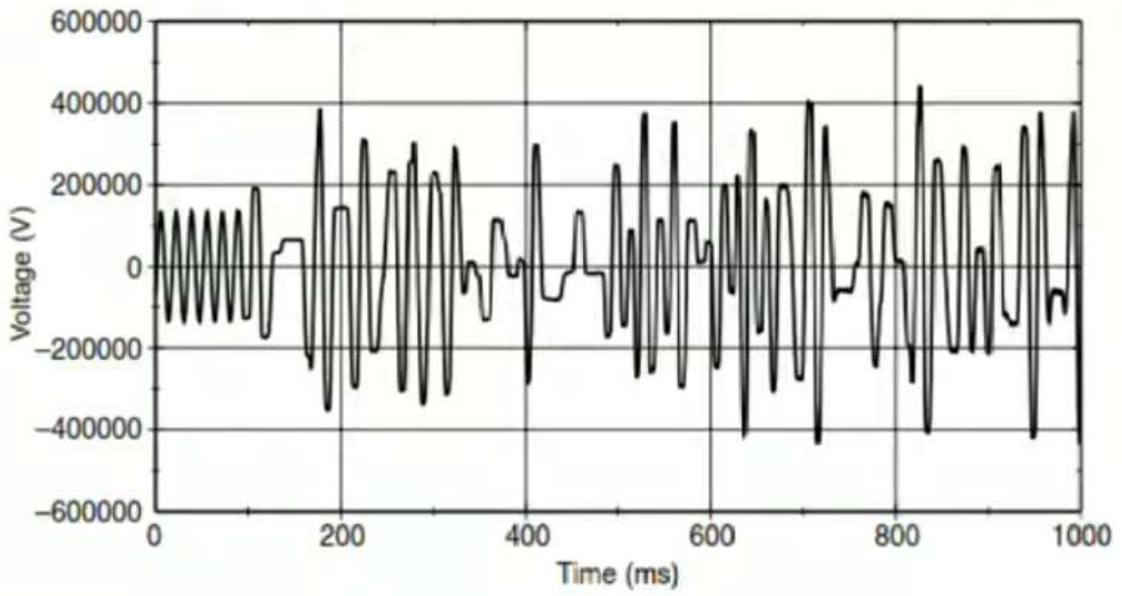
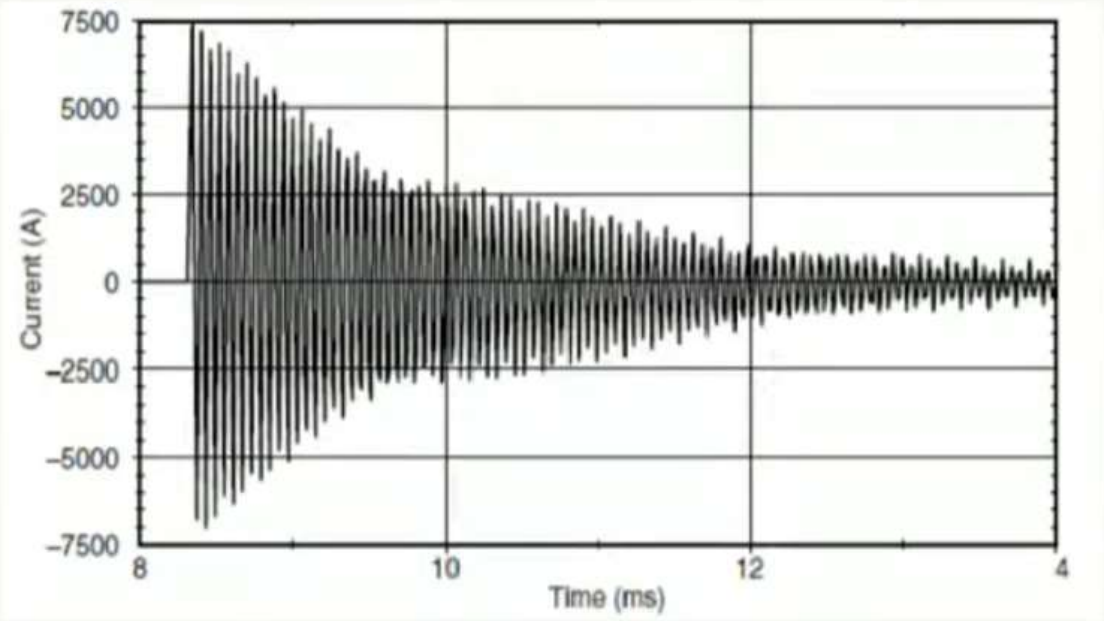


Figure 2.4 Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer.

- Primary frequency component greater than 500 kHz and a typical duration measured in microseconds are considered *high-frequency*
- 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.*

Multiple transients



- Multiple transients are combination of many overlapped transients occurred due to more than one switching action.
- For example, in three phase system, the switching action in the individual phases rarely take place at the same instant. Such events produce multiple transients.
- Current chopping and restrike are other two major causes of multiple transients. .

Effects of transients

- High magnitudes of voltage transients break insulations of the system
- High magnitude of current transients can burn out devices and instruments
- Can cause mal-operation of relays and mal-tripping of CB
- Frequent number of direct or indirect oscillatory transient leads to changes in the magnetic properties of core materials used in electric machines

4. Short duration voltage variation

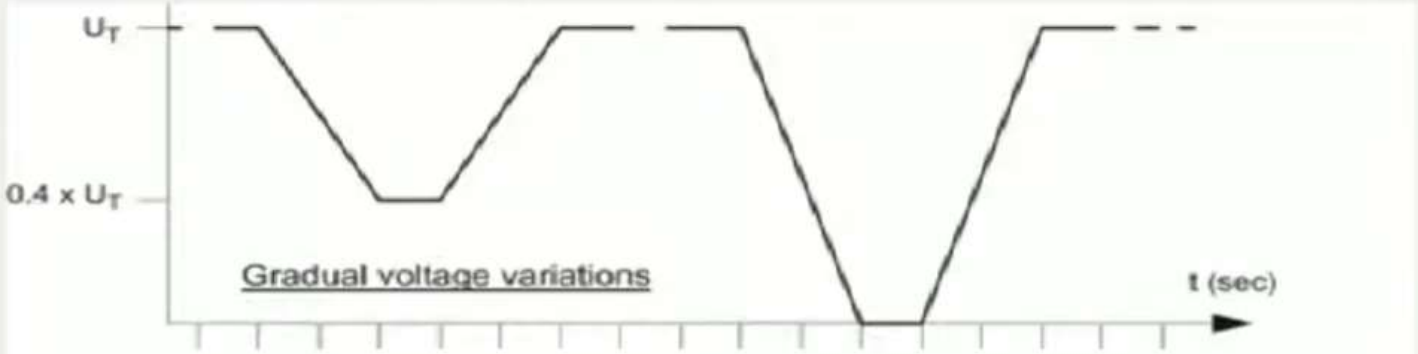
- Short and temporary disturbances occurring in power system

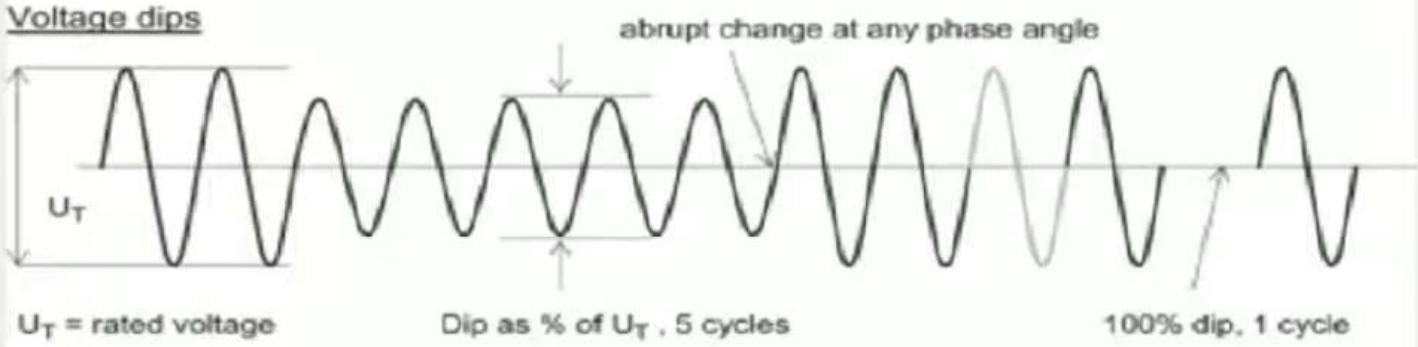
Causes

- Switching on large loads
- Loose connections
- Faults

Types

- Voltage sag
- Voltage swell
- Interruptions





Preferred test level % U_T	Preferred duration # of cycles
0 (interruption) 40 70	0.5, 1, 5, 10, 25, 50

5. Long duration variations

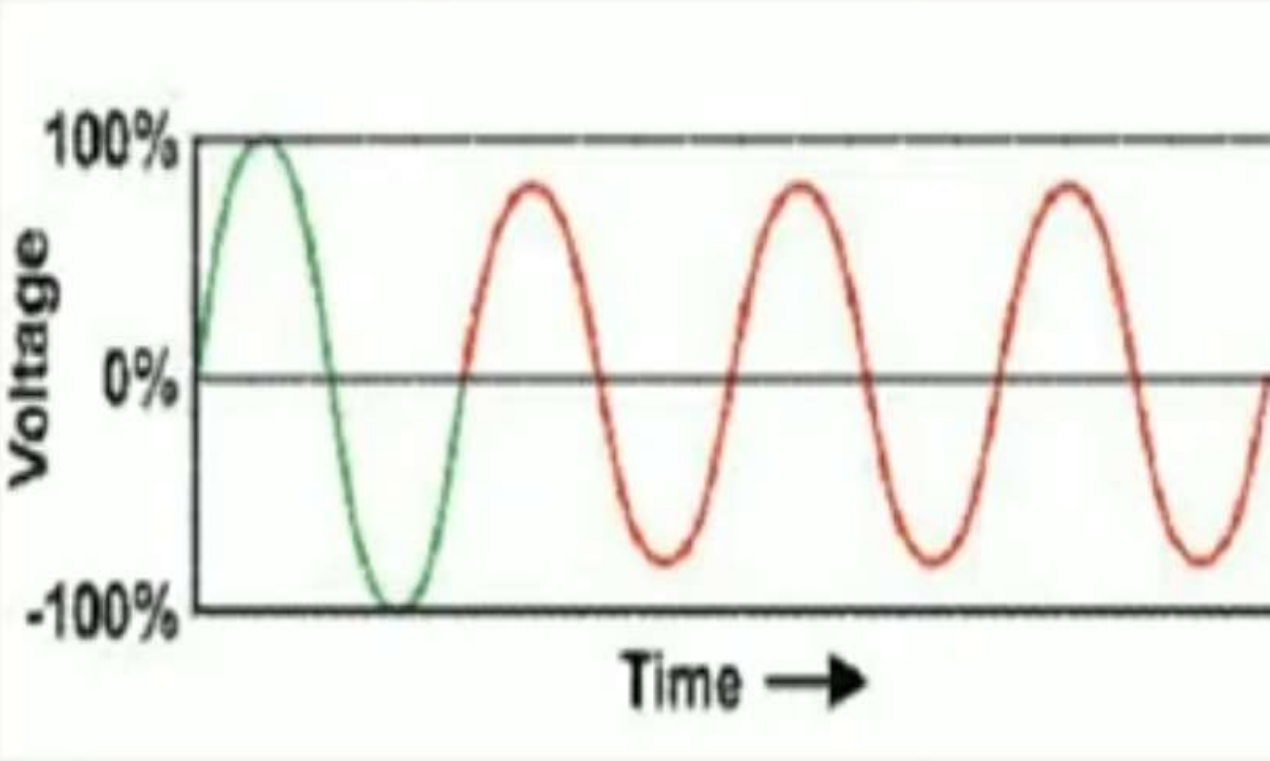
- Encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min
- Voltage variation is considered to be long duration when ANSI limits are exceed for greater than 1 min

Types

- Overvoltage
- Undervoltage
- Sustained interruptions

Under voltage

- The undervoltage is reduction of rms voltage to 0.8–0.9 pu for more than 1 min.
- Normal duration of undervoltage is greater than sag.
- Main causes of undervoltage are overload, less supply capability, fault, etc.
- Load switching on / a capacitor bank switching off



Effects of Undervoltage

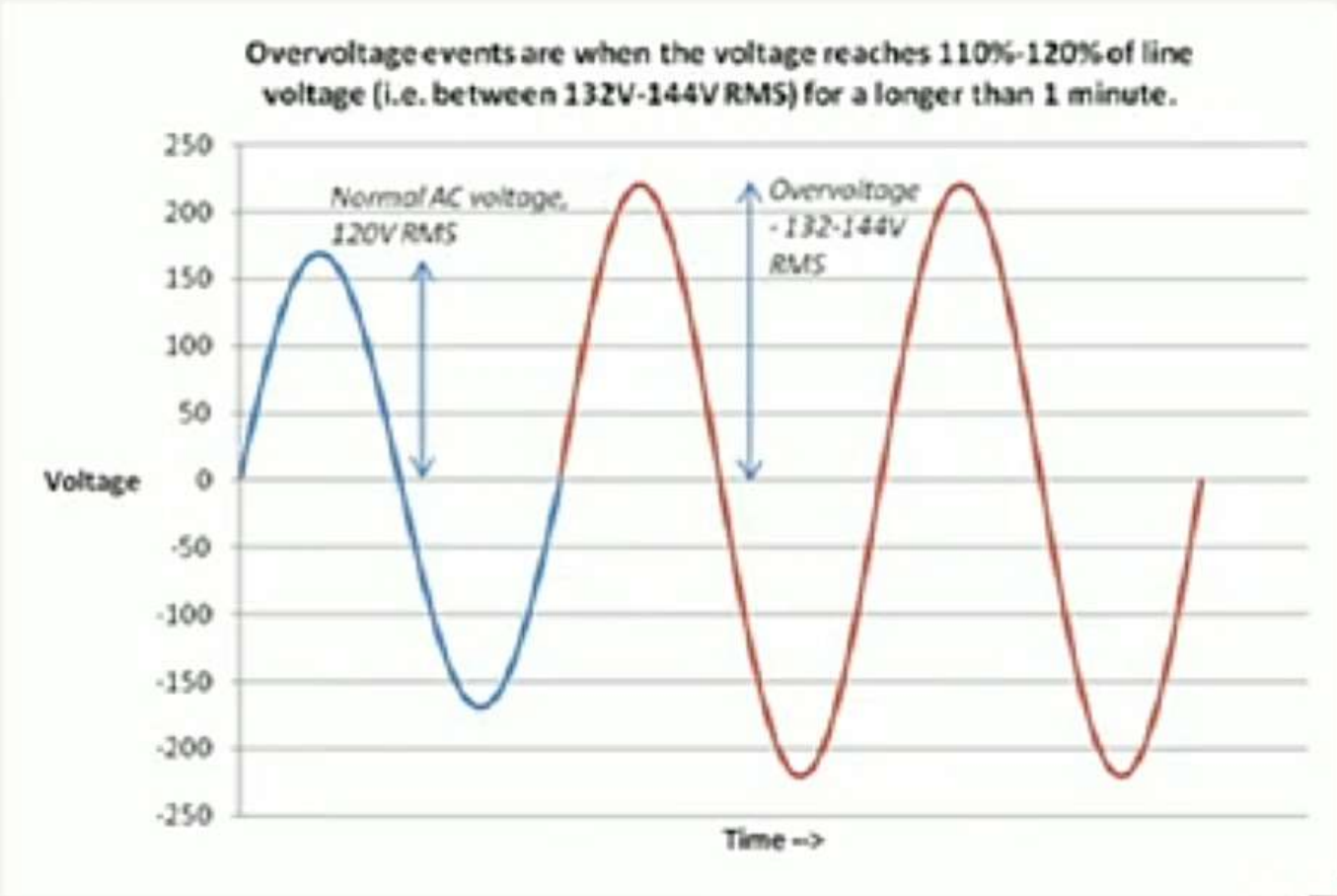
- Undervoltage may cause voltage instability, drawl of high current by motors, high reactive power demand, etc
- Undervoltage increases the operating current causing overheating which will shorten the life of the motor.
- Furthermore, large loads may fail to start if the starting torque is not sufficient due to low voltages.
- These stresses on the motor will eventually lead to mechanical failure.

Undervoltage problems may be alleviated by:

- 1. Reducing the system impedance - increase the size of the transformer, reduce the line length, add series capacitors or increase the size of line conductors.
- 2. Improving the voltage profile - adjust transformers to the correct tap setting (for manual tap changers) or install voltage regulators or automatic on-load tap changers.
- 3. Reducing the line current – de-load the feeder or circuit by transferring some loads to other substations or load centers, add shunt capacitors or static VAR compensators, or upgrade the line to the next voltage level.

Over voltage

- The over voltage is increase of rms voltage to 1.1–1.2 pu for more than 1 min.
- Normal duration of undervoltage is greater than swell.



Causes of Over voltage

There are many reasons for occurring overvoltage in power system as follows:

- Overvoltages generated by an insulation fault
- Ferroresonance
- Faults with the alternator regulator, tap changer transformer, or overcompensation
- Lightning overvoltages
- Switching overvoltages produced by rapid modifications in the network structure

such as opening of protective devices or the switching on of capacitive circuits.

Effects of overvoltage

- Overvoltage may cause over stress on insulation
- Problems of voltage instability
- Demand for reactive power, etc.

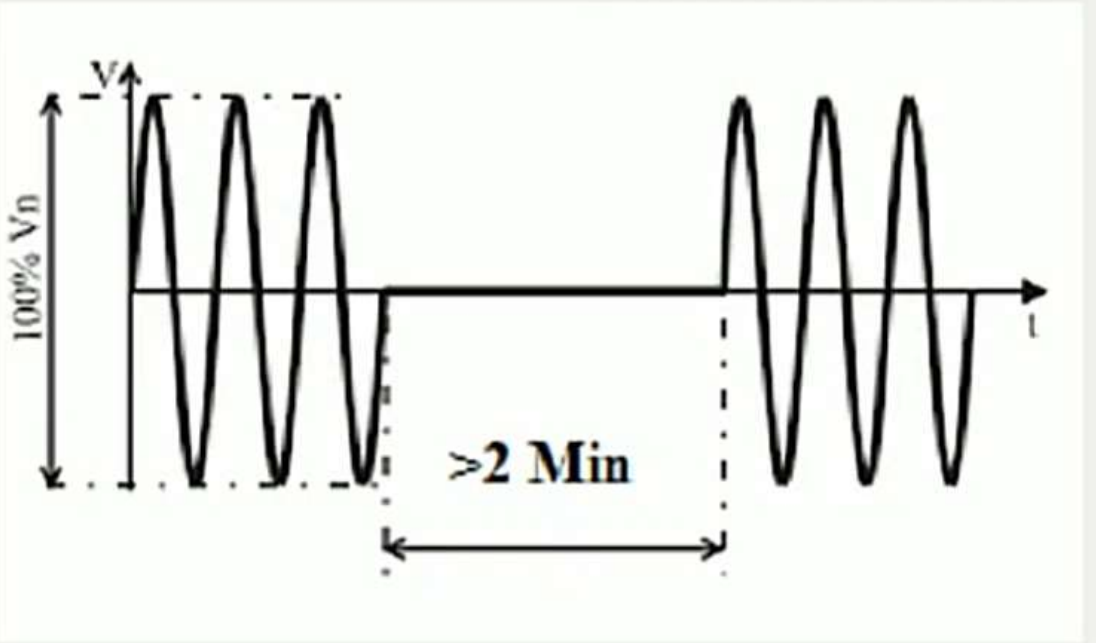
Principles of Overvoltage Protection

The fundamental principles of overvoltage protection of load equipment are

1. Limit the voltage across sensitive insulation.
2. Divert the surge current away from the load.
3. Block the surge current from entering the load.
4. Bond grounds together at the equipment.
5. Reduce, or prevent, surge current from flowing between grounds

Sustained Interruption

- Among all interruption, sustained (or long) interruption is most severe.
- In such interruption voltage drops to zero and it does not return automatically.
- According to the IEC definition, the duration of sustained interruption is more than 3 min; but based on the IEEE definition the duration is more than 2 min.
- Frequency of occurrence and duration of long interruptions are the two main aspects in assessing the ability of a power system to deliver reliable service to customers.



Causes of Sustained interruptions

- Sustained interruptions are usually caused by permanent faults due to storms
- Trees striking lines or poles
- Utility or customer equipment failure in the power system
- Miscoordination of protection devices.
- Consequently, such disturbances would result to a complete shutdown of the customer facility.

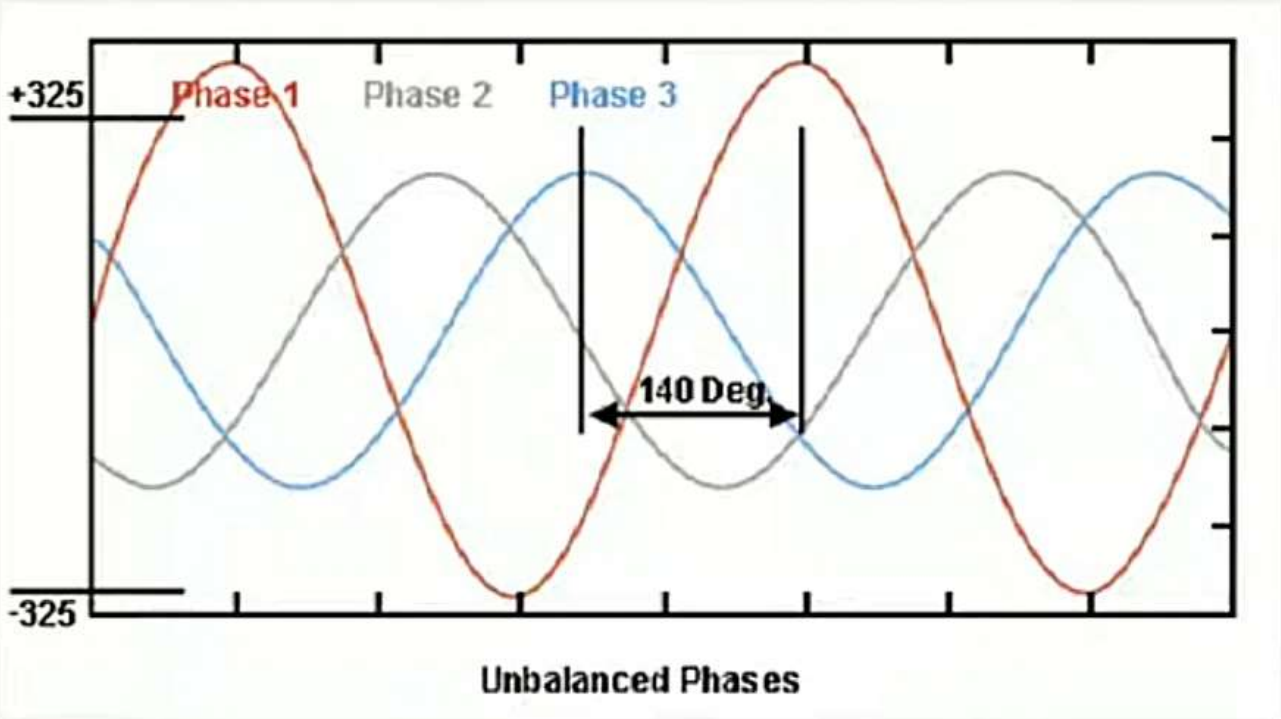
6. Voltage imbalance

$$\text{Voltage unbalance} = \frac{\text{negative or zero sequence component}}{\text{positive sequence component}}$$

- It is a voltage variation in a power system in which the voltage magnitudes or the phase angle differences between them are not equal

Causes

- Due to unequal loads on distribution lines
- Defects in power circuit connection, motor contacts, etc



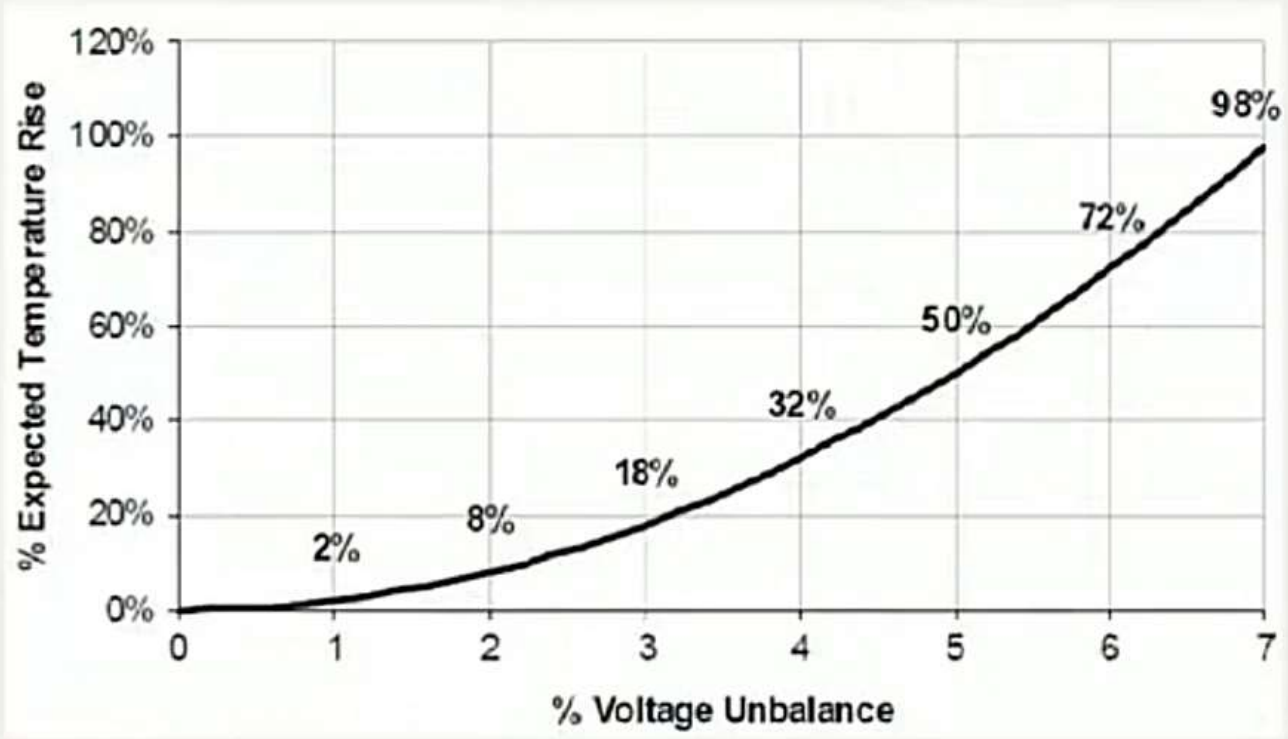
Unbalanced Phases

Causes of Voltage Imbalance

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

Effects

- Motor damage from excessive heat
- Creates current unbalance 6-10 times the magnitude of voltage unbalance
- The graph below shows the relationship between voltage unbalance and temperature rise, which approximately increases by twice the square of the percent of voltage unbalance.



Formula of Voltage Imbalance

- $$\text{Voltage unbalance} = \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}}$$
-

Example:
Assume the following phase-to-phase voltage readings of 226, 231, and 233.

Average Voltage = (226 + 232 + 235) / 3
Average Voltage = 230 V
Maximum Deviation from Average Voltage = 231 - 226 = 5 V

Voltage Unbalance = 5 / 231

Voltage Unbalance = 0.0216 or 2.16%

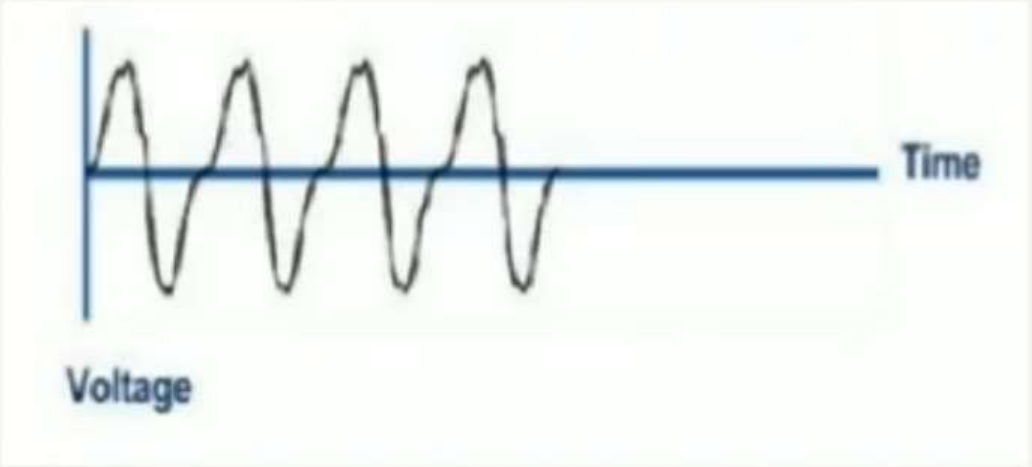
Mitigation of Voltage Imbalance

- For the utility, it is just a matter of repairing malfunctioning equipment or redistributing loads to reduce the unbalance.
- For the end-users, proper testing and communication with the utility would help locate and resolve the problems.

7. Waveform distortion

- Steady-state deviation from a ideal sine wave of power frequency principally characterized by the spectral content of the deviation
- **5 types of waveform distortion**

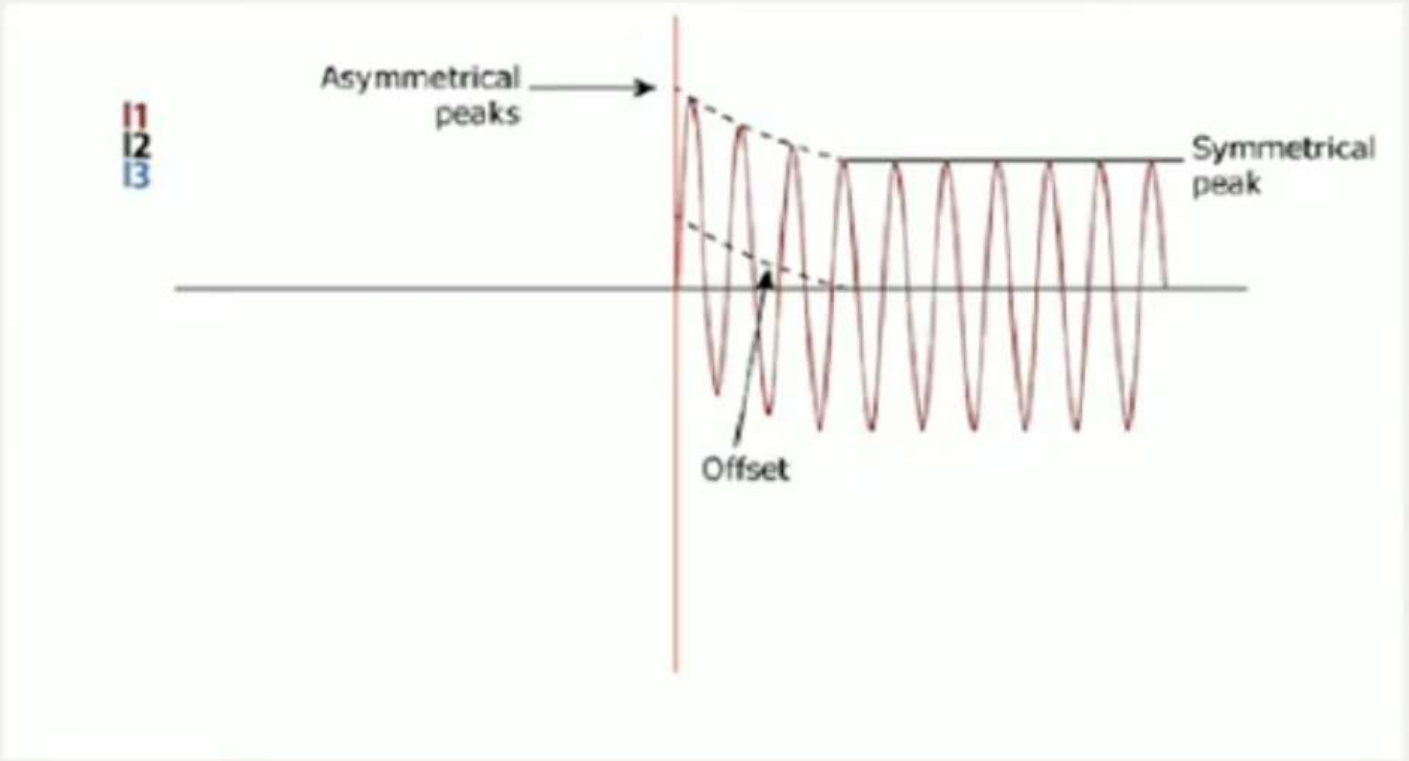
1. DC offset
2. Harmonics
3. Inter-Harmonics
4. Notching
5. Noise



DC Offset

DC offset is the presence of a DC current and/or voltage component in an AC system.

Expansion of ac wave by Fourier series is used for analysis of DC offset.



DC Offset

Main causes of DC offset in power systems are:

- Operation of rectifiers and other electronic switching devices,

The main effects of DC offset in alternating networks are:

- half-cycle saturation of transformer core
- generation of even harmonics in addition to odd harmonics
- additional heating in appliances which may lead to a decrease of the lifetime of transformers, rotating machines, and electromagnetic devices
- Electrolytic erosion of grounding electrodes and other connectors.

Harmonics

- Deviation of voltage and current waveforms from the ideal pure sinusoidal waveforms of fundamental frequency
- A pure polyphase system is expected to have pure sinusoidal alternating current and voltage waveforms of single frequency.
- Real situation deviates from this purity. Real voltage and current waveforms are distorted.
- Normally they are called non sinusoidal waveforms.
- Non-sinusoidal waveform is formed with the combination of many sine waves of different frequencies.
- Thus actual power system signals have fundamental component as well as harmonic components.

Harmonics

- Let 'f' be the fundamental frequency in current waveforms, then fundamental component of current will be

$$i_1 = I_1 sin2\pi ft$$

  - Waveforms in a non-sinusoidal wave having frequencies other than fundamental frequency are called harmonics.

$$i_n = I_n sin2\pi nft$$

n will be 1, 2, 3, ..., etc.

  - Odd Harmonic – n= 3,5, 7...
  - Even Harmonics – 2,4,6...

Harmonics

- Non-sinusoidal wave is constituted by the combination of odd-even harmonic components as well as fundamental component. Thus, mathematically, it can be expressed as,

A non sinusoidal wave may be expressed in terms of harmonics as

$$i = \sum_{n=1,2,3,4,\ldots} i_n = \sum_{n=1,2,3,4,\ldots} I_n \sin 2\pi nft$$

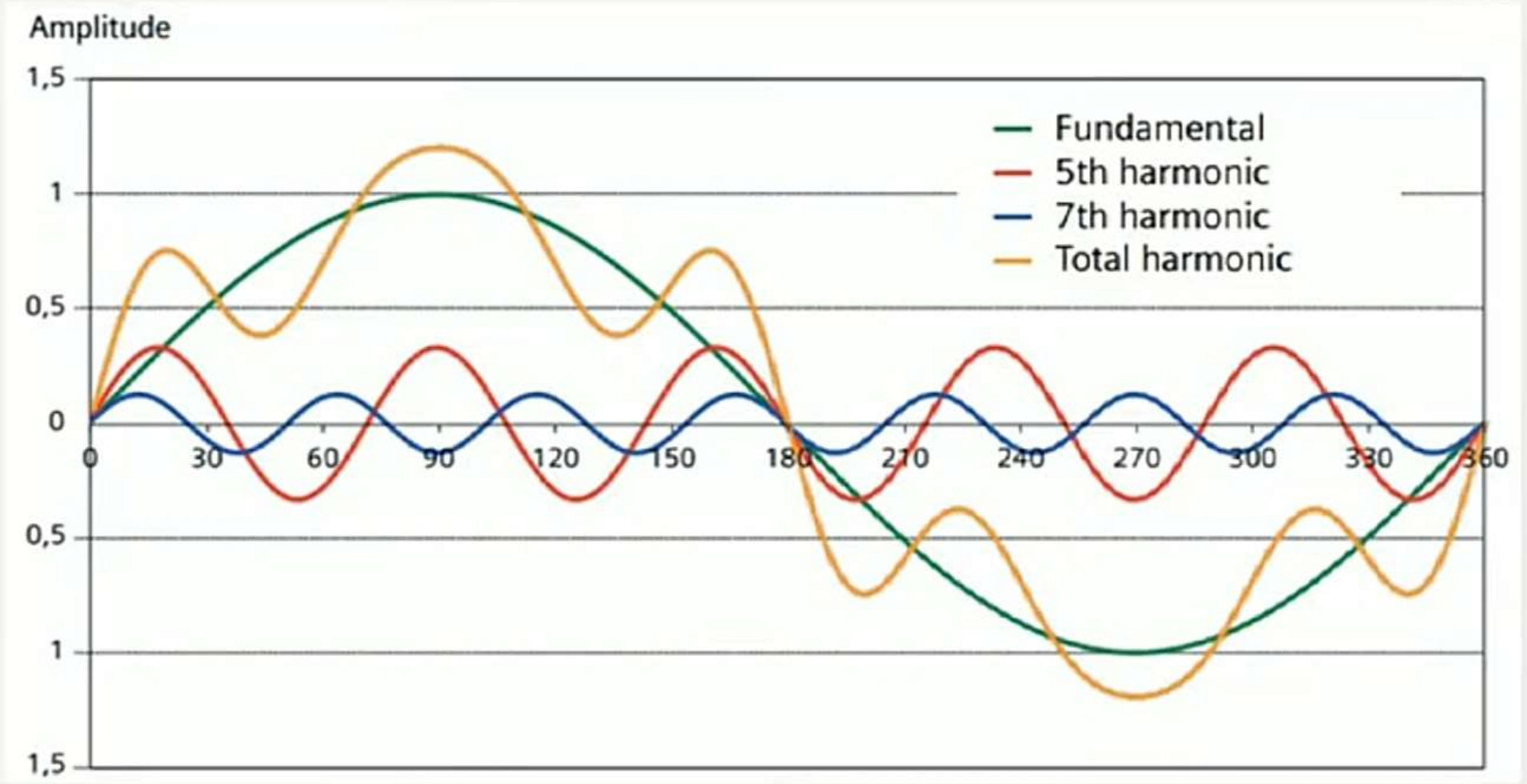
$$= I_1 \sin 2\pi ft + I_2 \sin 4\pi ft + I_3 \sin 6\pi nft + I_4 \sin 8\pi nft$$

$$+ I_5 \sin 10\pi nft + \cdots\cdots\cdots\cdots\cdots$$

$$= I_1 \sin 2\pi f_1 ft + I_2 \sin 2\pi f_2 t + I_3 \sin 2\pi f_3 t + I_4 \sin 2\pi f_4 t$$

$$+ I_5 \sin 2\pi f_5 t \cdots\cdots\cdots\cdots\cdots$$

Harmonics


Amplitude
1,5
1
0,5
0
0,5
1
1,5
0
30
60
90
120
150
180
210
240
270
300
330
360
Fundamental
5th harmonic
7th harmonic
Total harmonic

Inter Harmonics and Sub Harmonics

- **Inter Harmonics** Often in non sinusoidal waveform there are harmonics having frequencies which are greater than fundamental but not integer multiple of fundamental frequency. These are known as inter-harmonics. Mathematically,

$$i_n = I_n sin 2\pi nft$$

Where n>1 but not an integer. n=1.2, 1.3, 1.4 etc

- **Sub Harmonic**

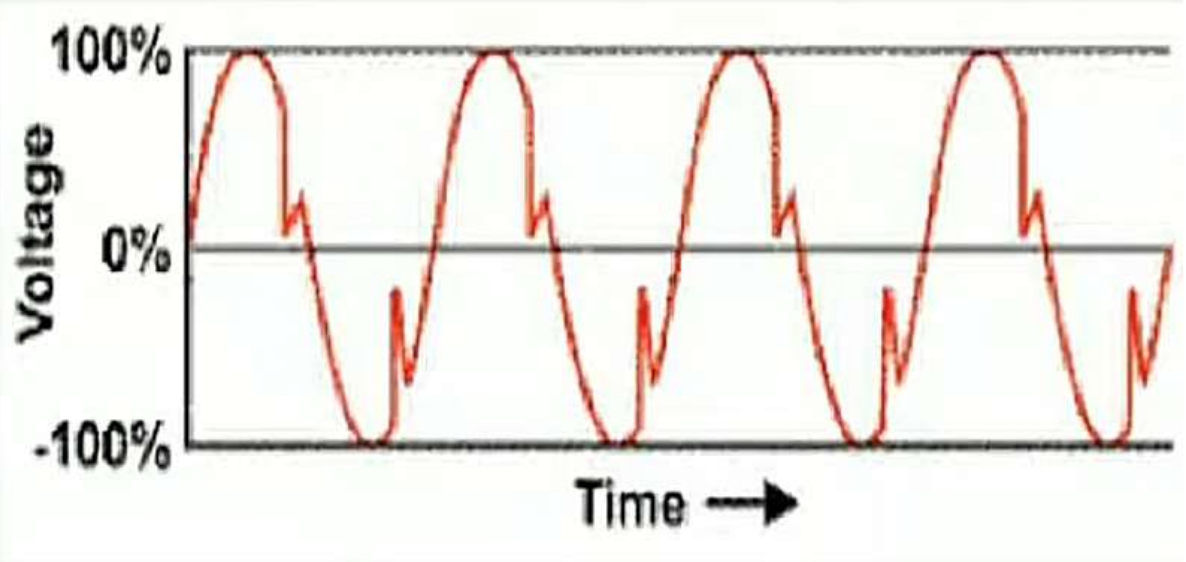
There are harmonics having frequencies which are smaller than fundamental frequency. These are known as sub-harmonics. Mathematically,

$$i_n = I_n sin 2\pi nft$$

Where n<1 eg. . n=0.2, 0.3, 0.4 etc

Notching

- Voltage Notching is described by IEEE as a recurring power quality disturbance due to the normal operation of power electronic devices (i.e. rectifier), when current is commutated from one phase to another.
- In addition, voltage notching characterizes an unusual case that falls between harmonics and transients.
- This is because notching takes place in steady-state, thus, it can be distinguished by the harmonic spectrum of the affected voltage.
- On the other hand, the components of the frequency related to voltage notching are somewhat high and may not be promptly categorized with a measurement device commonly employed for harmonic analysis.



Causes of Notching

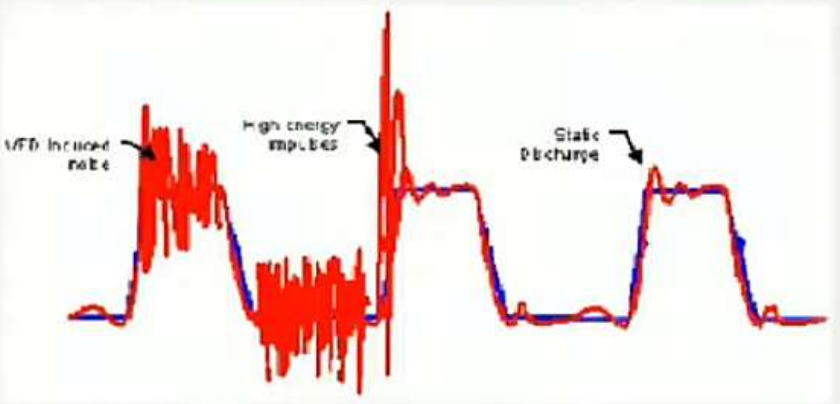
- Voltage Notching is primarily caused by three-phase rectifiers or converters that generate continuous DC current.
- As mentioned, the voltage notches happen when the current commutates from one phase to another. Subsequently, a momentary short circuit between two phases will occur during this period.
- Moreover, the depth of the notch at any point in the system is influenced by the source inductance, the isolating inductance between the rectifier/converter, as well as the point being examined. Consequently, the width of the notch is the commutation angle.

Effects and Solution of Notching

- Voltage Notches introduce harmonic and non-harmonic frequencies that are much higher than those found in higher voltage systems.
- Usually, these frequencies are in the radio frequency range, that cause negative operational effects, such as signal interference introduced into logic and communication circuits.
- Also, when of sufficient power, the voltage notching effect may overload electromagnetic interference filters, and other similar high-frequency sensitive capacitive circuits.
- Furthermore, the solution for voltage notching typically involves isolation of the critical and sensitive equipment from the source (i.e. rectifiers) of the power quality problem.

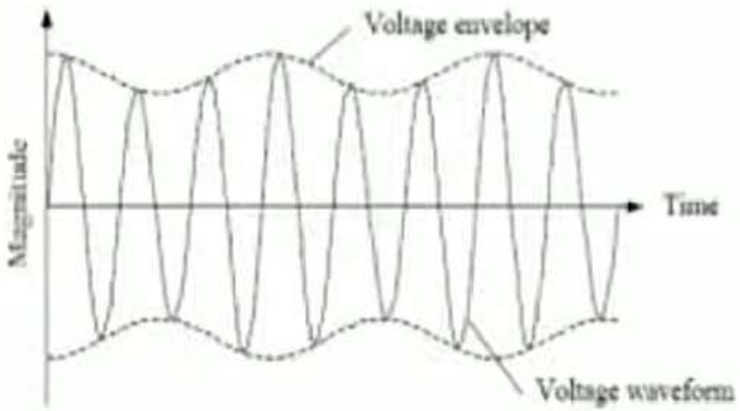
Electric Noise

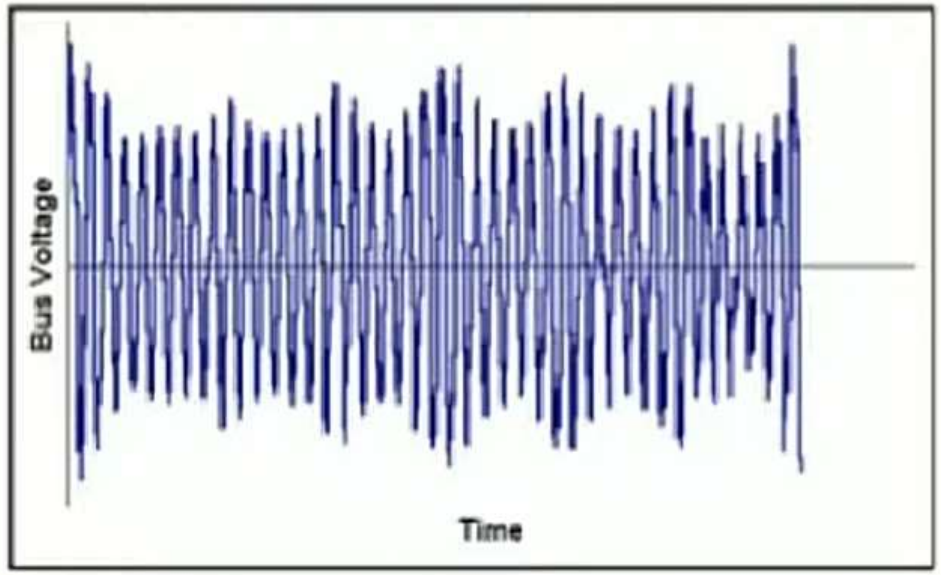
- Electric noise is unwanted electrical signals present in power system having broad-band spectral content lower than 200 kHz superimposed with the power system voltage or current.
- They may be observed in phase conductors, or neutral conductors or signal lines.
- Magnitude of noise is normally very small as compared with power signal.
- However, electric noise creates problems in operation of electronic devices such as microcomputers and programmable controllers.
- Electric noise is mitigated by using filters, line conditioners, and dedicated lines or transformers.



8. Voltage flicker

- Continuous and rapid variations in the load current magnitude which causes voltage variations
- It is a type of voltage fluctuations
- Cause: operation of an arc furnace => voltage fluctuations in utility transmission and distribution systems

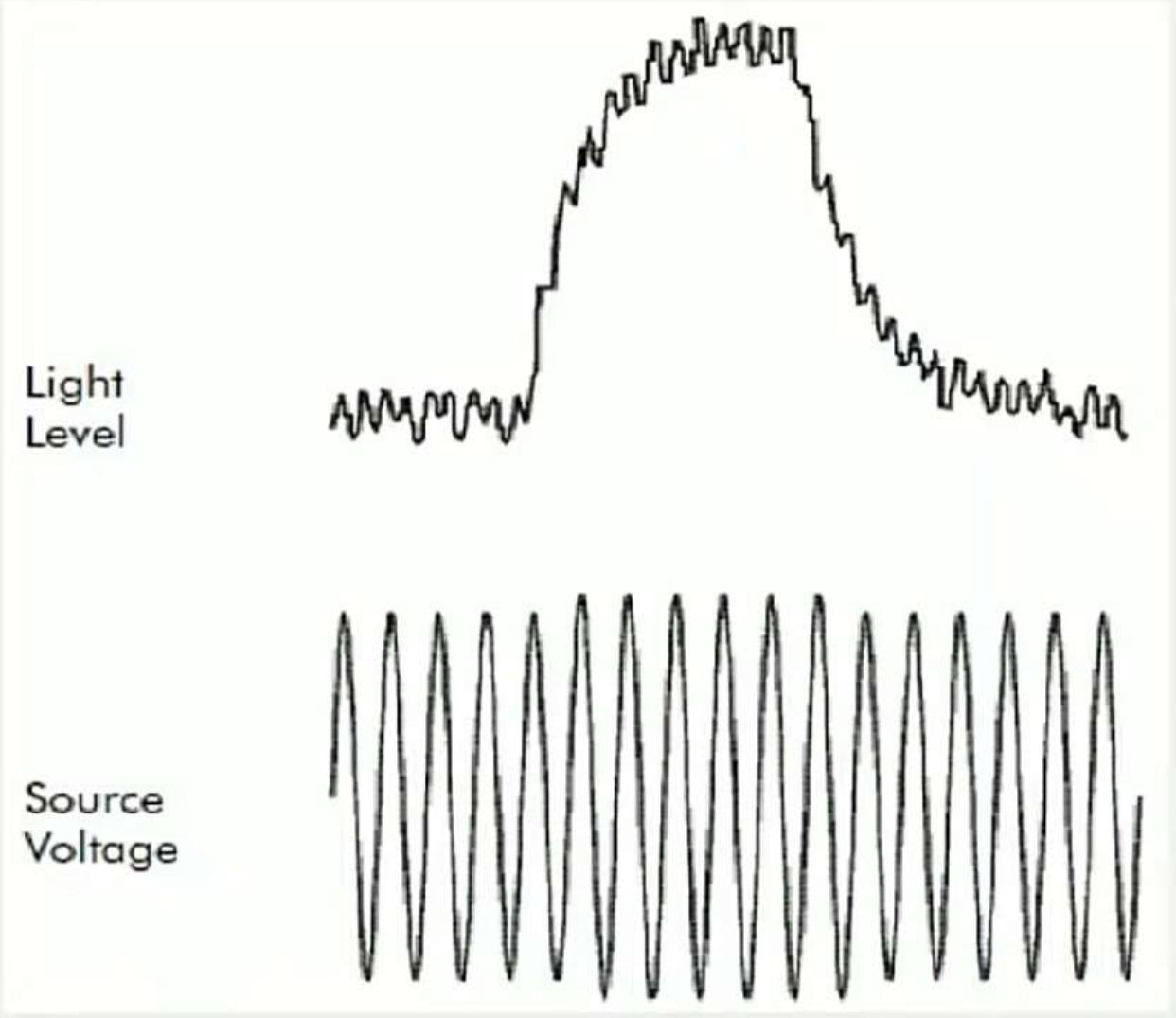




Voltage waveform showing flicker created by an arc furnace

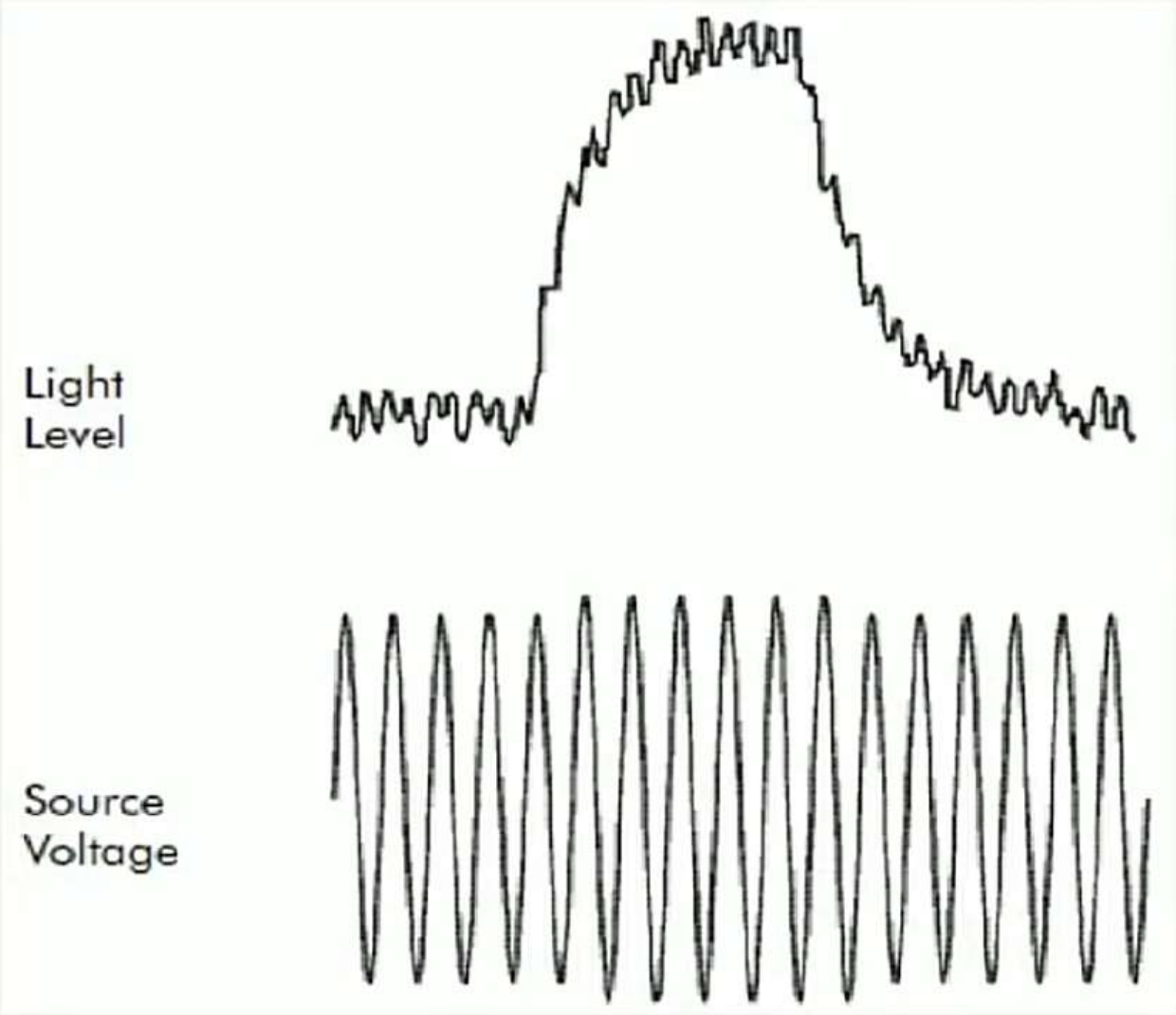
Voltage Flicker

- Voltage Fluctuations are described by IEEE as systematic variations of the voltage waveform envelope, or a series of random voltage changes, the magnitude of which falls between the voltage limits set by ANSI C84.1.
- Generally, the variations range from 0.1% to 7% of nominal voltage with frequencies less than 25 Hz.
- Subsequently, the most important effect of this power quality problem is the variation in the light output of various lighting sources, commonly termed as Flicker.



Voltage Flicker

- In other words, voltage fluctuation is the response of the power system to fast changing loads.
- On the other hand, light flicker is the response of the lighting system to such load variations as observed by the human eye.



Causes of Voltage Flicker

- Equipment or devices that exhibit continuous, rapid load current variations (mainly in the reactive component) can cause voltage fluctuations and light flicker.
- Normally, these loads have a high rate of change of power with respect to the short-circuit capacity at the point of common coupling. Examples of these loads include:
  - Electric arc furnaces
  - Static frequency converters
  - Cycloconverters
  - Rolling mill drives
  - Large motors (starting)

Power quality standards

- Power quality standards are needed in the power quality industry
- Standards allows utilities to provide different levels of power quality service.
- Several national and international organizations have developed power quality standards.
- There are a confusing number of different organizations that set power quality standards.
- The first step in sorting through the confusing number of standards and standards organizations is to examine the primary power quality standards organizations.

Power Quality Standards Organizations

US

- Institute of Electrical and Electronics Engineers (IEEE)
- American National Standards Institute(ANSI),
- National Institute of Standards and Technology (NIST),
- National Fire Protection Association (NFPA),
- National Electrical Manufacturers Association (NEMA)
- Electric Power Research Institute (EPRI), and Underwriters Laboratories (UL)

Outside US

- International Electrotechnical Commission (IEC), Euronorms, and ESKOM for South African standards.

IEEE guide lines, standards and recommended practices

- IEEE power quality standards deal primarily with the power quality limits of disturbances at the point of common coupling (the point where the utility connects to its customer or end user).
- IEEE power quality standards have a great impact in the electrical utility industry but lack official status, while the American National Standards Institute (ANSI) has the official responsibility to adopt standards for the United States.

IEEE guidelines

IEEE 4	Standard techniques for high voltage testing
IEEE 100	Standard dictionary of electrical and electronic engineering
IEEE 120	Master test guide for electrical measurements in power circuits
IEEE 141	Recommended practice for electric power distribution for industrial plants with effect of voltage disturbance on equipment within an industrial area
IEEE 142	Recommended practice for grounding of industrial and commercial power systems
IEEE 281	Standard service conditions for power system communication equipment
IEEE 519	Recommended practice for harmonic control and reactive compensation of static power converters
IEEE 539	Standard definitions of terms relating to corona and field effects of overhead power lines
IEEE 859	Standard terms for reporting and analyzing outage occurrences and outage states of electrical transmission facilities

IEEE Recommended Practice

- The purpose of this recommended practice is to direct users in the proper monitoring and data interpretation of electromagnetic phenomena that cause power quality problems.
- It defines power quality phenomena in order to facilitate communication within the power quality community.
- This document also forms the consensus opinion about safe and acceptable methods for monitoring electric power systems
- It further offers a tutorial on power system disturbances and their common causes.

IEEE Recommended Practice

- IEEE standard 1159-1995 : Recommended Practice for Monitoring Electric Power quality
- IEEE standard 1250-1995: Guide for service to Equipment sensitive to momentary voltage disturbances
- Table : Categories and typical characteristics of power system electromagnetic phenomena

IEEE Recommended Practice

- IEEE standard 1159-1995 : Recommended Practice for Monitoring Electric Power quality
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- Table : Categories and typical characteristics of power system electromagnetic phenomena

IEEE Recommended Practice

- The IEEE 1159.1 Working Group is developing guidelines for instrumentation requirements associated with different types of power quality phenomena.
- These requirements address issues like sampling rate requirements, synchronization, A/D sampling accuracy, and number of cycles to sample.
- The IEEE 1159.2 Working Group is developing guidelines for characterizing different power quality phenomena.
- This includes definition of important characteristics that may relate to the impacts of the power quality variations (such as minimum magnitude, duration, phase shift, and number of phases for voltage sags).

IEEE Recommended Practice

- Standards are very important in the area of power quality monitoring.
- IEEE 1159 is the IEEE Working Group that coordinates the development of power quality monitoring standards.
- The existing IEEE 1159 provides general guidelines and definitions for monitoring power quality, and there are three separate task forces that are working on more specific guidelines and requirements.

UNIT - 2

DSTATCOM

Problems encountered in distribution

- High reactive power burden
- High harmonic currents
- Unbalanced loads
- Excessive neutral currents

Contents

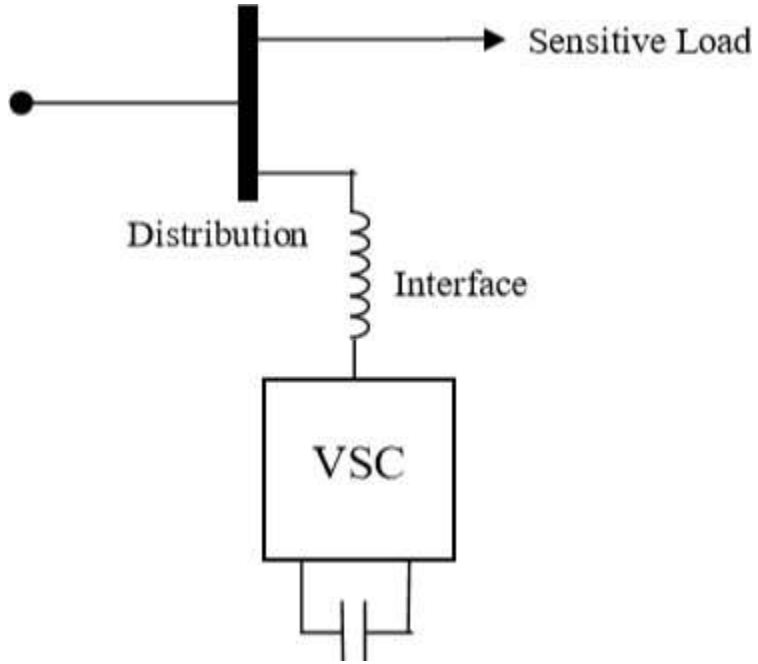
- **Introduction** about **DSTATCOM**
- **Working principle and Operating modes of DSTATCOM**
- **Mathematical modelling of a DSTATCOM**
- **DSTATCOM controller principles**
- **Application** of **DSTATCOM**
- **Advantages of DSTATCOM**

Introduction about DSTATCOM

- One way of increasing the power availability is by reducing the high losses in the existing power transmission and distribution systems.
- In addition, there is a demand for high quality power from customers for custom power devices.
- Compensation for reactive power and unbalance in the power distribution system are key factors in improving the power quality to the end user.
- Excessive reactive power in the system increases feeder losses and reduces the active power flow capability of the distribution system whereas unbalance affects the operation of generators and transformers in the system.
- A Distribution STATic COMpensator (DSTATCOM), a custom power device, connected in shunt with the load, compensates for the reactive power and unbalance caused by various loads in the distribution system.
- The performance of the DSTATCOM depends on the control algorithm used for extracting the reference current components. Here, the working principle of a DSTATCOM is explained and its mathematical model has been derived.
- The control techniques for voltage regulation, power factor improvement and compensation of unbalanced systems, for a DSTATCOM, are described here.

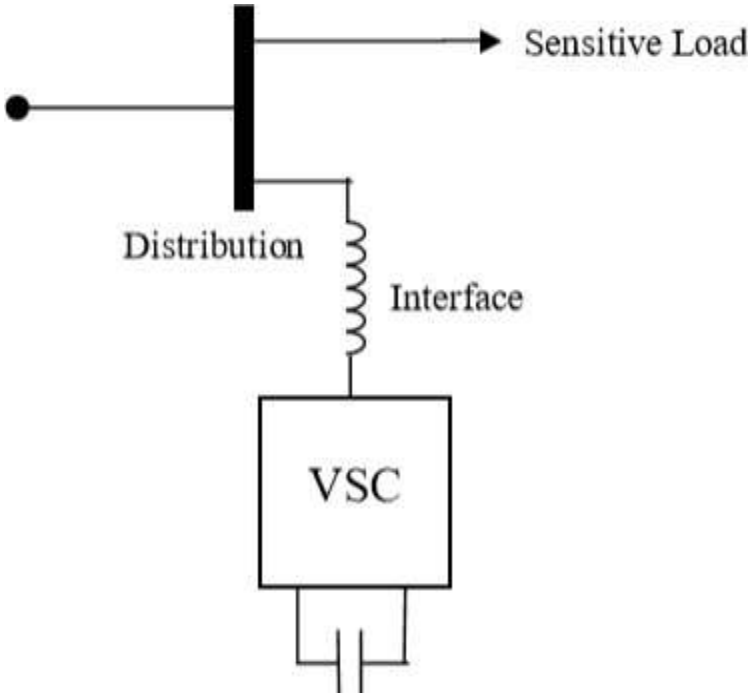
Working Principle of DSTATCOM

- A DSTATCOM is a shunt compensation device that provides an effective solution for reactive power compensation and voltage regulation.
- It comprises of a Voltage Source Converter (VSC), a DC capacitor, a coupling inductor or coupling transformer and a controller.
- The DSTATCOM, connected to the grid through the coupling inductor at the point of common coupling (PCC), is controlled in such a way that it exchanges only reactive power with the grid.
- This is achieved by injecting the current in quadrature with the grid voltage.

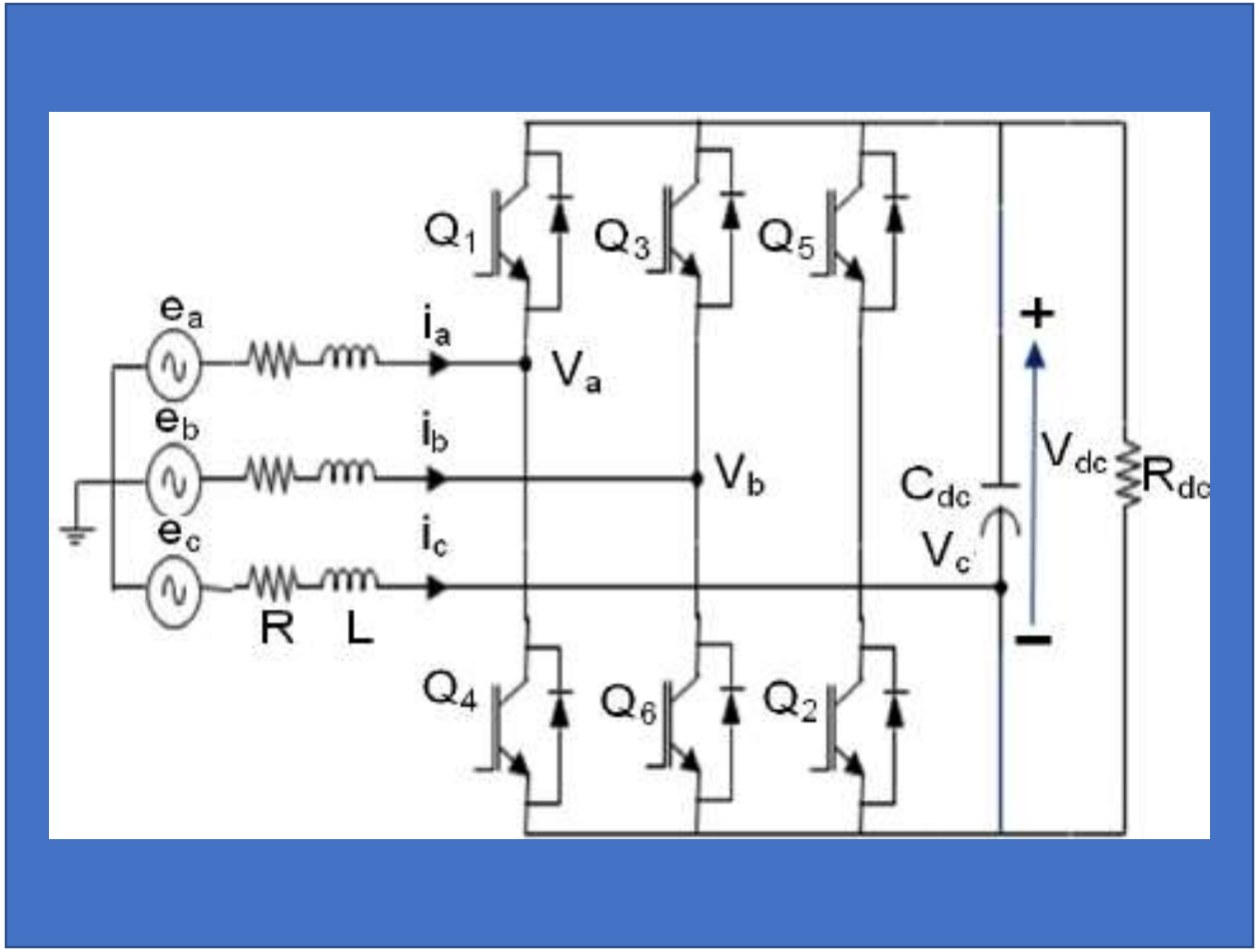


Basic structure of a DSTATCOM

Voltage Source Converter (VSC)

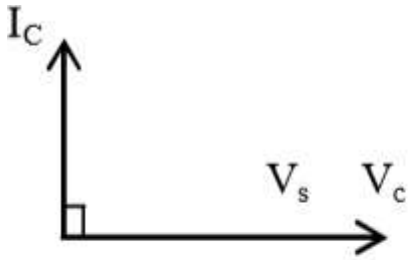


Basic structure of a DSTATCOM

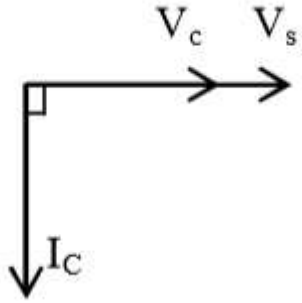


DSTATCOM operating modes

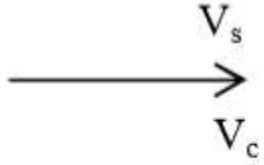
- If the magnitude of the DSTATCOM voltage is greater than the grid voltage (>), the DSTATCOM supplies reactive power to the grid, and the DSTATCOM is operating in the capacitive mode.
- If the grid voltage is greater than the DSTATCOM voltage (>), the DSTATCOM absorbs reactive power from the grid, as shown in Figure, and the DSTATCOM is operating in the inductive mode.
- If the grid voltage and the DSTATCOM voltage are of the same magnitude (=), there is no exchange of reactive power between the grid and the DSTATCOM, as shown in Figure, and the DSTATCOM is operating in the floating state.



Capacitive mode

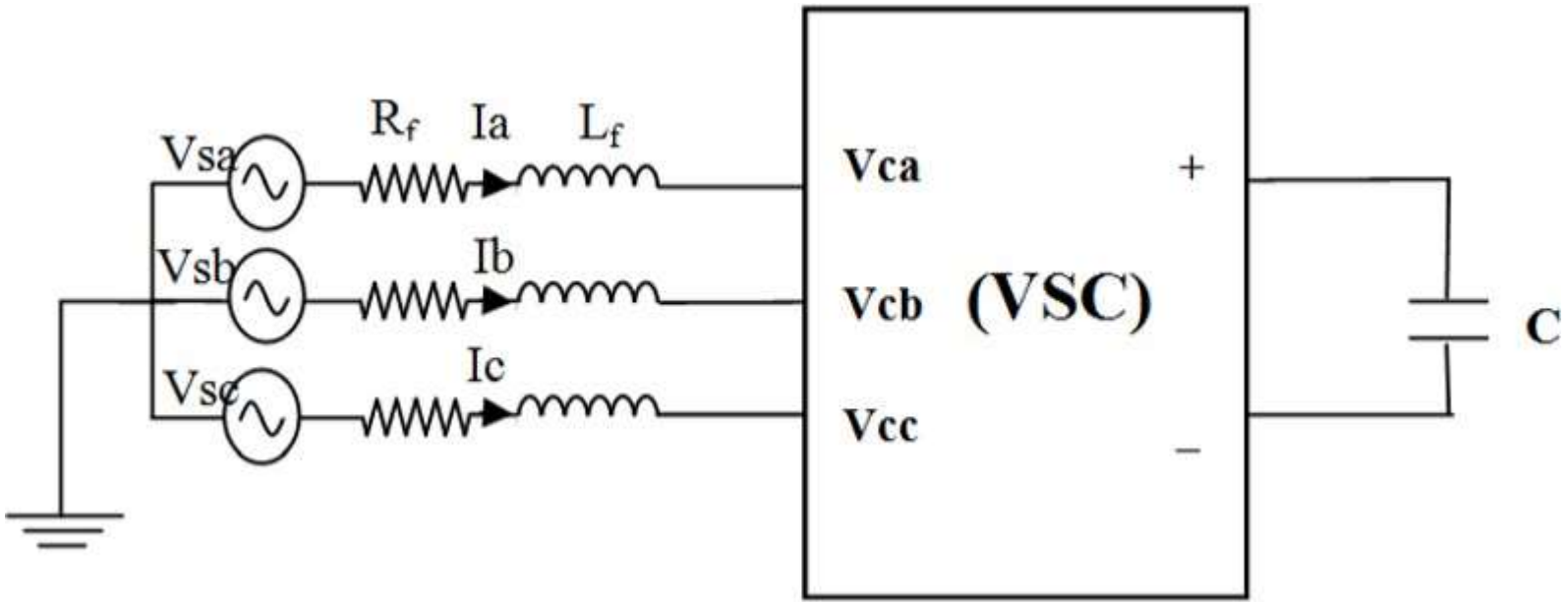


Inductive mode



Floating mode

DSTATCOM operating modes...



Simplified single-line diagram of the DSTATCOM

- DSTATCOM consists of a DC link capacitor, an IGBT based VSC, a filter and a voltage source to represent the grid voltage.
- The DSTATCOM is connected through a filter circuit to the grid at the point of common coupling.

Mathematical modelling of a DSTATCOM

The three-phase instantaneous voltages at the PCC are given by

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin\omega t \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix}$$

The relationship between the PCC voltages, the inverter output voltages and currents are obtained by writing the KVL equation for the single line diagram of DSTATCOM.

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -R_f/L_f & 0 & 0 \\ 0 & -R_f/L_f & 0 \\ 0 & 0 & -R_f/L_f \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L_f} \begin{bmatrix} V_{sa} - V_{ca} \\ V_{sb} - V_{cb} \\ V_{sc} - V_{cc} \end{bmatrix}$$

- Above equations describe the system differential equations in the abc reference frame.
- To control the current injected by the VSC, the transformation of these equations to the synchronous reference frame is required.
- The Park's transformation is used for transforming from the abc reference frame to the synchronous qd0 reference frame.

- As the system is assumed a balanced, only d and q components exist. The transformed results in the dq frame are given by..

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -R_f/L_f & \omega \\ -\omega & -R_f/L_f \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} v_{sd} - v_{cd} \\ v_{sq} + v_{cq} \end{bmatrix}$$

- Neglecting the voltage harmonics produced by the direct and the quadrature axes voltages, we get..

$$v_{cd} = mV_{dc}\cos\alpha$$

$$v_{cq} = mV_{dc}\sin\alpha$$

- According to the power balance theory, the instantaneous power at the AC terminals of the inverter is equal to the instantaneous power at the DC terminals of the inverter. The power balance equation is given as

$$v_{dc}i_{dc} = \frac{3}{2}\left(v_{cd}i_d + v_{cq}i_q\right)$$

- The current in the DC side of the DSTATCOM

$$i_{dc}=\frac{3}{2}m\left(i_d cos\alpha+i_q sin\alpha\right)=C\frac{dV_{dc}}{dt}$$

- The DSTATCOM's state space mathematical model can be written as

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix}=A\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix}-\frac{1}{L_f}\begin{bmatrix} v_{sd} \\ 0 \\ 0 \end{bmatrix}$$

- Where, A is

$$\mathrm{A}=\begin{bmatrix} -R_f/L_f & \omega & -\frac{m}{L_f}cos\alpha \\ -\omega & -R_f/L_f & \frac{m}{L_f}sin\alpha \\ \left(\frac{3}{2}\right)\left(\frac{m}{C}\right)cos\alpha & \left(\frac{3}{2}\right)\left(\frac{m}{C}\right)sin\alpha & 0 \end{bmatrix}$$

- Since the d and q axes are not stationary, they follow the trajectory of the voltage vector.
- The instantaneous active and reactive powers

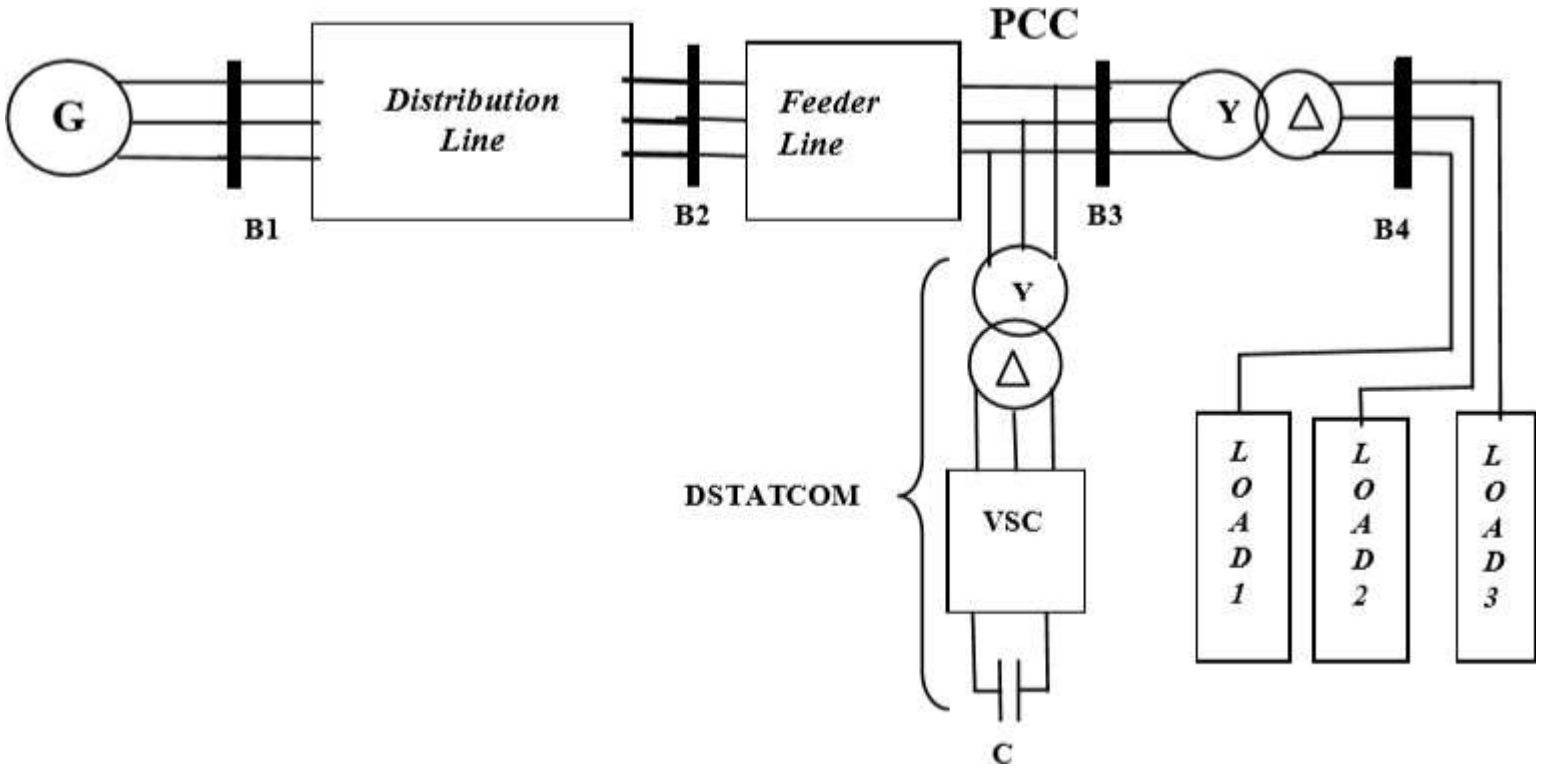
$$p=\frac{3}{2}\left(v_{sd}i_d+v_{sq}i_q\right)=\frac{3}{2}v_{sd}i_d=\frac{3}{2}v_s i_d$$

$$q=\frac{3}{2}\left(v_{sq}i_d-v_{sd}i_q\right)=-\frac{3}{2}v_{sd}i_d=-\frac{3}{2}v_s i_q$$

- By observing, the performance of the DSTATCOM can be controlled by controlling the active and reactive components of currents.
- The control algorithm developed in the synchronous reference frame should control the **d** or the **q** component of the current to attain the control objective.

DSTATCOM controller principle

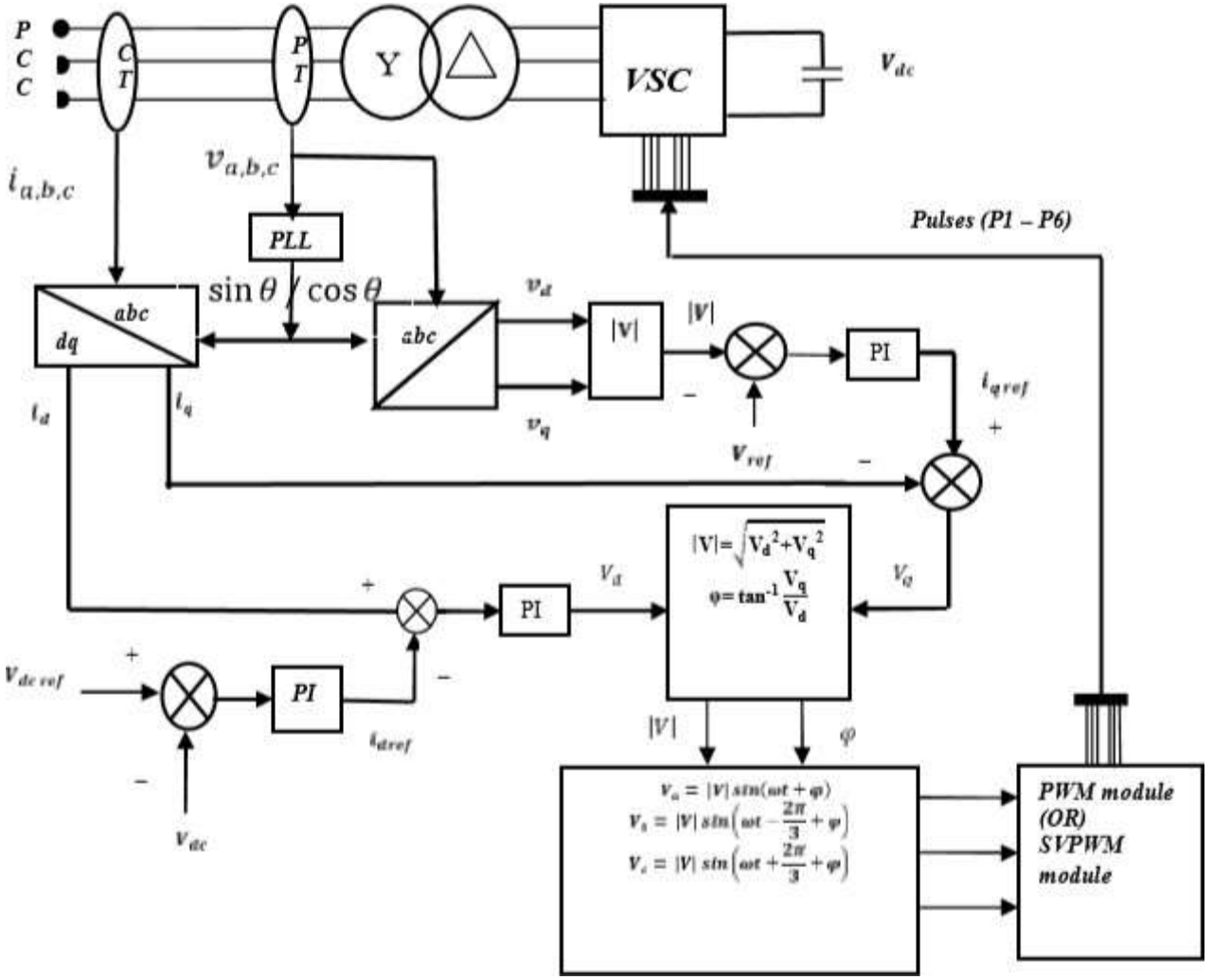
- The DSTATCOM has a voltage source converter (VSC) at its core that can be used for different application by appropriate control algorithms.
- In the control, a two-level VSC is used to realize the DSTATCOM. The bus voltage is regulated either by absorbing or by supplying reactive power to the bus.



Schematic of a DSTATCOM

DSTATCOM controller principle..

- The cascade controller for the voltage regulation application is shown in Figure.
- For voltage regulation, two voltages are controlled in the DSTATCOM.
- One is the AC voltage of the power system at the bus, where the DSTATCOM is connected, and the other is the DC link voltage across the capacitor.
- Both the regulators are of the proportional integral (PI) type.



DSTATCOM controller principle..

- The output current from the VSC is converted into the d-axis and the q-axis components using the Park's transformation technique.
- The error is regulated through a PI controller to get ref I_d. The ref I_q is obtained by regulating the
- ref V_{rms} and V_{rms} signals by another PI controller.
- These reference currents are then regulated by comparing the d and q components of currents with their respective components of reference current in another set of PI regulators, whose outputs

DSTATCOM controller principle..

- The voltage magnitude and phase angle are computed from and the computed voltage magnitude and phase angle are used to generate the three phase sinusoidal reference signals, without the use of inverse Park's transformation, to reduce the computation time, as given in Equations..

$$|V| = \sqrt{V_d^2 + V_q^2}$$

$$\varphi = \tan^{-1}\left(\frac{V_q}{V_d}\right)$$

$$V_a = |V| \sin(\omega t + \varphi)$$

$$V_b = |V| \sin\left(\omega t - \frac{2\pi}{3} + \varphi\right)$$

$$V_c = |V| \sin\left(\omega t + \frac{2\pi}{3} + \varphi\right)$$

- These reference signals are compared with a sawtooth wave to generate the SPWM signals in the SPWM module.
- With the same reference signal, the switching pulses are generated by the SVPWM algorithm in the PWM module.

Application of DSTATCOM

Potential applications at the distribution level include

- voltage regulation,
- power factor correction,
- load balancing,
- harmonic filtering.

Advantages

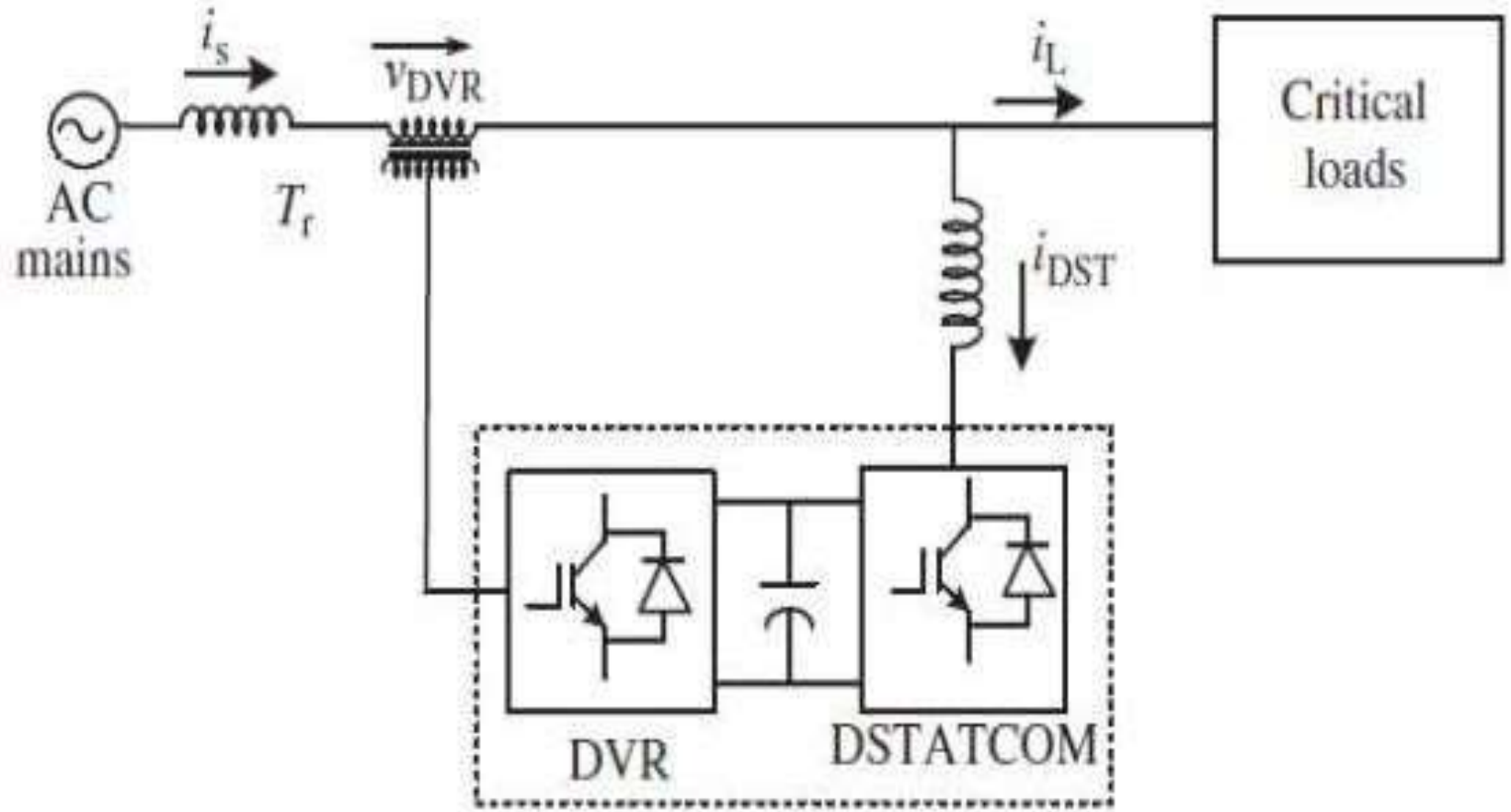
- Power factor to unity
- Harmonic current compensation
- Load balancing
- Distribution line voltage regulation
- Compensation of neutral current

UNIT - 3

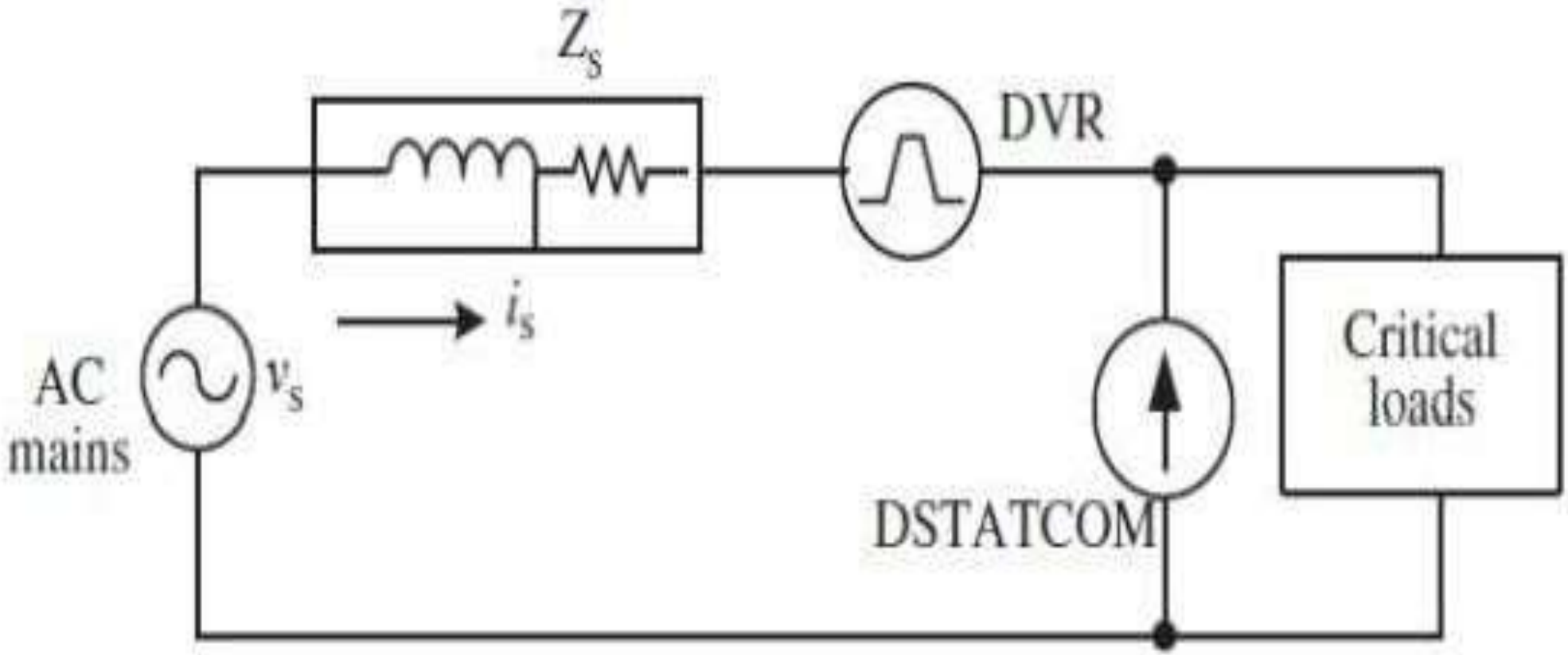
Unified Power Quality Conditioner (UPQC)

- The most complete configuration of hybrid filters is the unified power quality conditioner (UPQC), which is also known as the universal active filter. 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. It is a custom power device designed to mitigate the disturbances that affect the performance of sensitive and/or critical loads. UPQC has shunt and series compensation capabilities for harmonics, reactive power, voltage disturbances, and power-flow control..

A UPQC consists of two voltage-source converters with a common DC link designed in single-phase, three-phase three-wire, or three-phase four-wire configurations. One converter is connected in series through a transformer between the source and the critical load at the PCC and operates as a voltage-source inverter. The other converter is connected in shunt at the PCC through a transformer and operates as a current-source inverter. The active series converter compensates for voltage supply disturbances, performs harmonic isolation, and damps harmonic oscillations. The active shunt converter compensates for load current waveform distortions and reactive power, and performs the DC link voltage regulation


i_s
v_{DVR}
i_L
Critical loads
AC mains
T_r
i_{DST}
DVR
DSTATCOM

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


Z_S
DVR
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AC
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DSTATCOM

UNIT-4

EE465
POWER QUALITY

MODULE – 5

Harmonic elimination - Design and analysis of filters to reduce harmonic distortion – Power conditioners ,passive filter, active filter - shunt , series, hybrid filters,

HARMONIC ELIMINATION

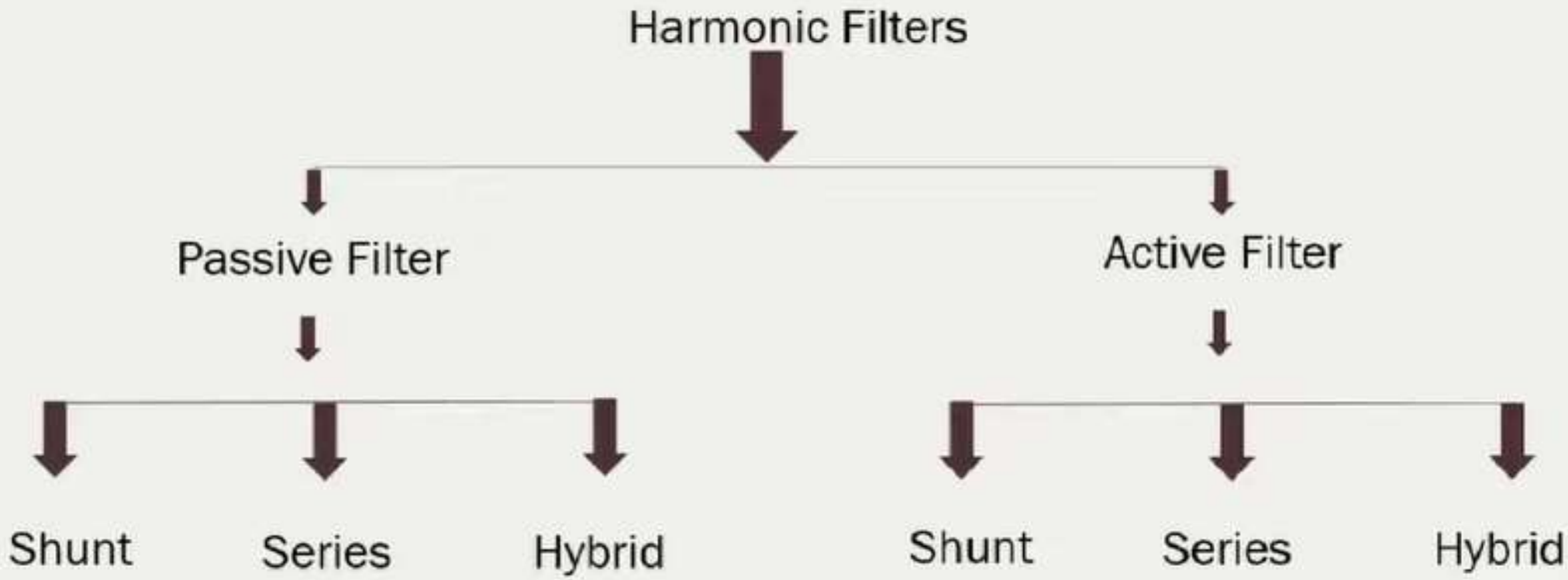
- Harmonic Elimination techniques are used to improve the power system performance with some objectives:

(1) To improve the system power factor and to compensate the reactive power

(2) To maintain a particular THD limit in current harmonic distribution

- Various devices and equipment serves the purpose of harmonic elimination from power system.
- Mostly current harmonic filters are used to reduce current harmonics in power system

HARMONIC FILTERS



PASSIVE POWER FILTER (PPF)

- It is the combination of series / parallel connection of passive elements such as capacitors, inductors and / or resistor.
- They provide a low resistance path for the harmonic current to flow owing to the formation of resonance at that particular harmonic frequency
- Thus, harmonic current is diverted through passive filter network and system current becomes distortion free
- PPF's reduce harmonics and capacitors are generally employed to improve the power factor of the AC loads
- The passive filters are classified into categories such as shunt, series and hybrid

1. Shunt Passive filter

- Passive shunt filters are connected in parallel to harmonic producing loads to provide low-impedance paths for harmonic currents so that these harmonic currents do not enter supply systems
- They are confined to flow in the local passive circuits consisting of lossless passive elements such as inductors (L) and capacitors (C) to reduce losses in the filter system
- Capacitors may have very low internal power losses
- Inductors have reasonable resistances and other losses
- Losses in the inductors cannot be neglected and an equivalent resistance connected in series with the inductors

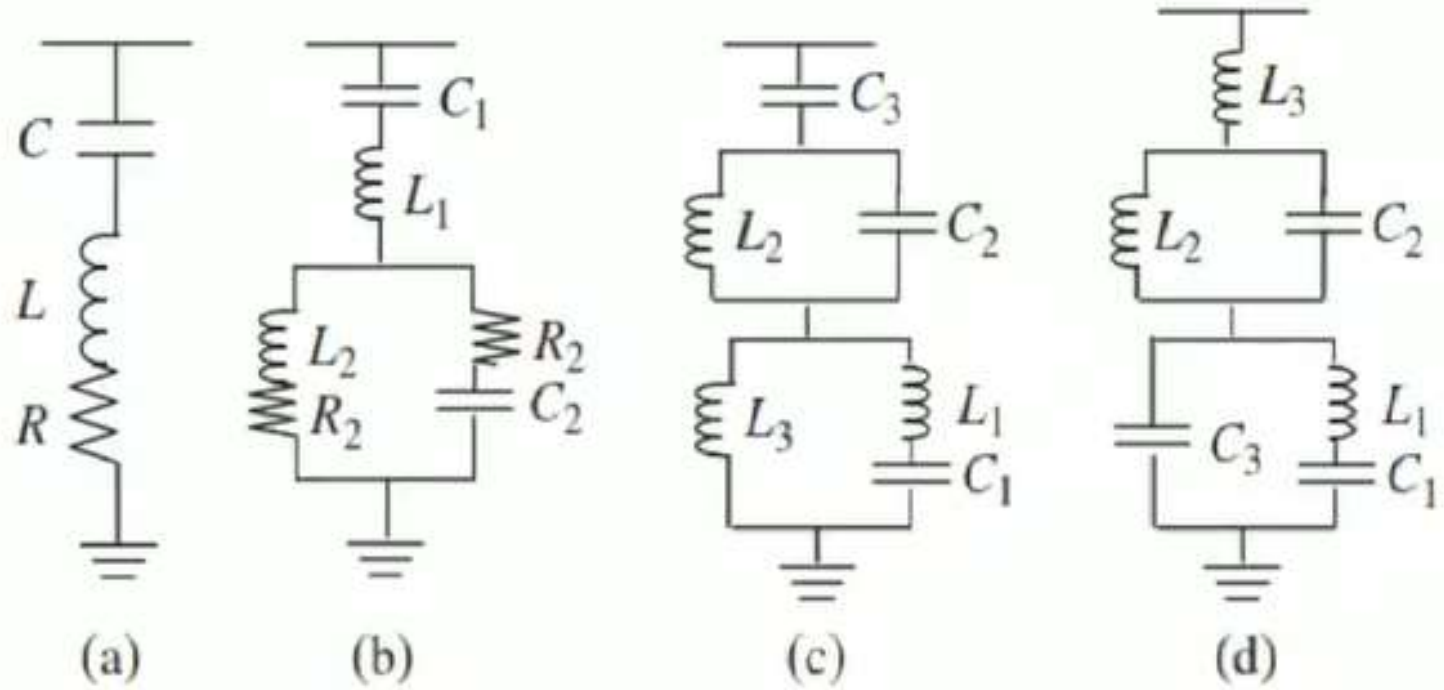


Figure 8.3 Shunt passive tuned or band-pass filters: (a) single tuned; (b) double tuned; (c) triple tuned with a series capacitor; (d) triple tuned with a series inductor

➢ Various types of passive shunt filters are shown below:

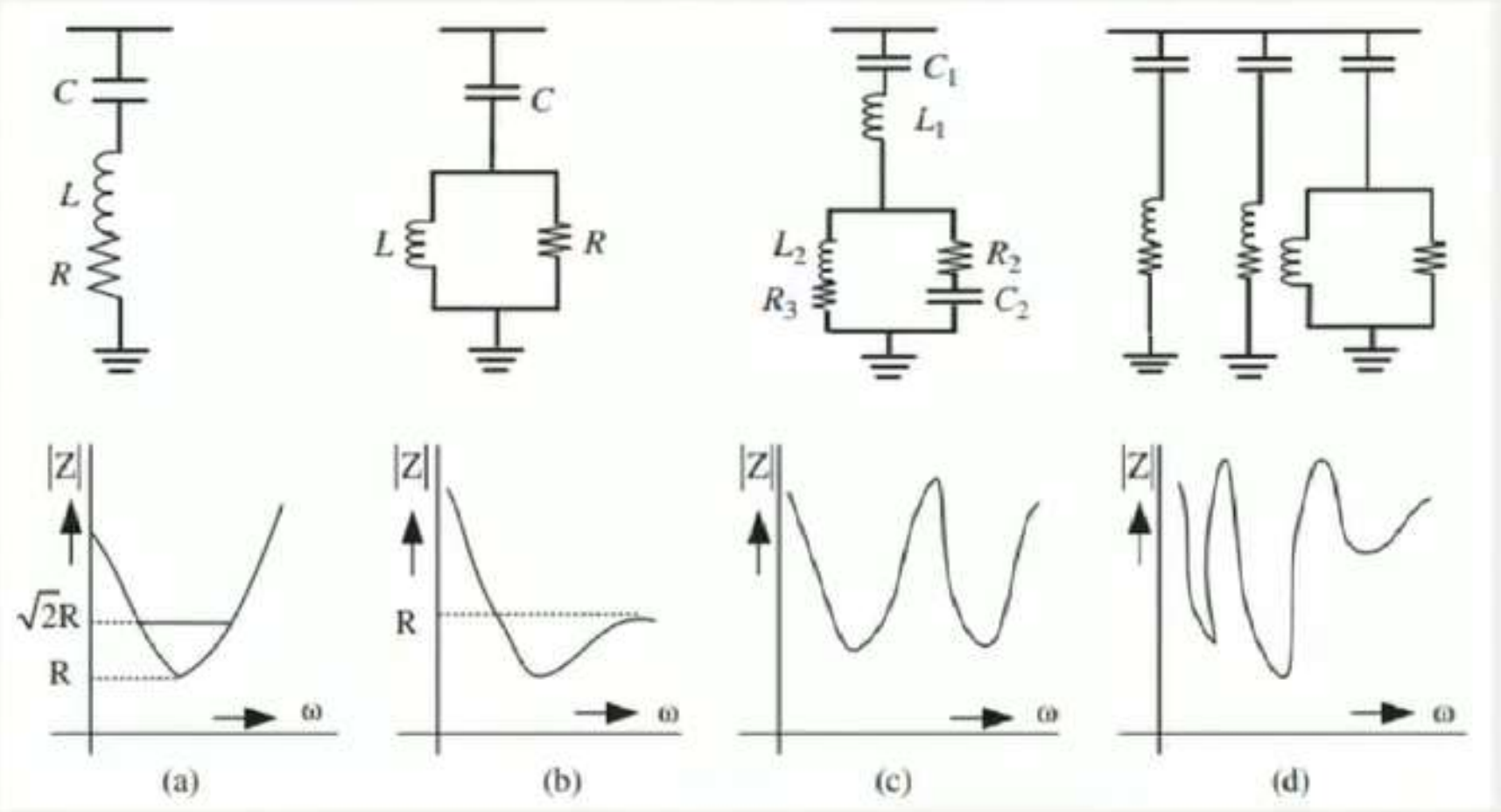


Fig. 1 (a) Band-pass (b) High-pass (c) Double band-pass (d) composite

- Fig. 1(a) Simple series RLC circuit, in which R – the resistance of the inductor
- The value of the capacitor (size of the filter) is decided by the reactive power requirements of the loads and its inductor value is decided by the tuned frequency.
- These type of filters provide harmonic current and voltage reduction and power factor correction because of capacitive reactive power at fundamental frequency behaves as capacitive impedance
- Fig. 1(c) Double tuned or double band-pass filter having minimum impedance at both the tuned frequencies.

- Main use is in high-voltage applications because of reduction in the number of inductors to be subjected to full line impulse voltages
- Fig.1 (b) and (d) are the high-pass filters that absorb all higher order harmonics
- They are also called as damped filters as they provide damping due to the presence of a resistor in the circuit
- These filters have higher losses, but at high frequencies not much higher currents and power losses are present in the loads
- For reducing the losses and for better filtering characteristics, third-order high pass-filters are used sometimes as in Fig.1 (d)

Disadvantages:

- They have problems of resonance with the source impedance and fixed compensation
- Poor power factor at light loads due to excessive leading reactive power injection

2. Series Passive filters

- Passive series filters are connected in series with harmonic-producing loads to provide high impedance for blocking harmonic currents so that these harmonic currents do not enter supply systems
- They are confined to flow in the local passive circuits consisting of parallel connected lossless passive elements – Inductors (L) and capacitors (C) to reduce losses in the filter system

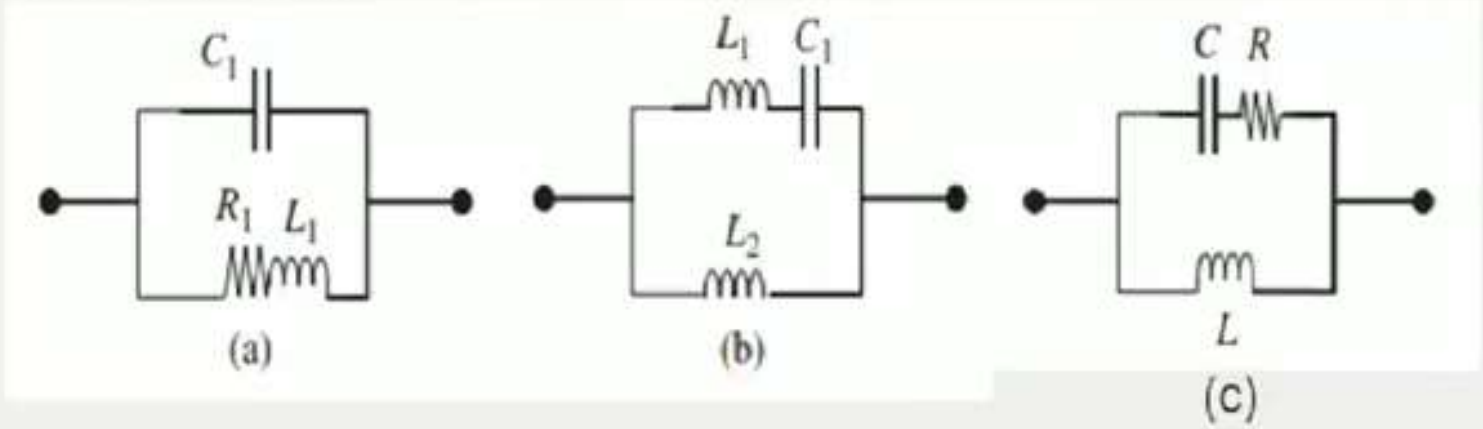


Fig. 2 (a) Series Passive tuned or band-block filters (a) single tuned (b) doubled tuned (c) series passive damped or high-block filter

- The passive series filter is a simple parallel LC circuit as in Fig. 2
- At fundamental frequency, the filter is designed to offer very low impedance, thereby allowing the fundamental current with negligible voltage drop and losses
- Series filters are used to block single harmonic current such as third harmonic current
- These are used in small power ratings in single-phase systems to block dominant third harmonic current
- For blocking multiple harmonic currents, multiple harmonic filters need to be connected in series
- These filters must be designed to carry full rated load current with overcurrent protection

3. Hybrid Filters

- Hybrid filters, consisting of series and shunt passive filters as shown in Fig. 3, can be used in many industrial applications
- Passive hybrid filter consisting of a single tuned passive series filter with a single tuned passive shunt filter and a high-pass passive shunt filter offers very good filtering characteristics
- Other types of passive hybrid filters such as low-pass broadband filters are considered a good option, which consist of leakage reactance of a series transformer for stepping down the voltage for the load
- A capacitor at the load offering good filtering characteristics with a low cutoff frequency and preventing harmonics from penetrating into the high-voltage side above this cutoff frequency.

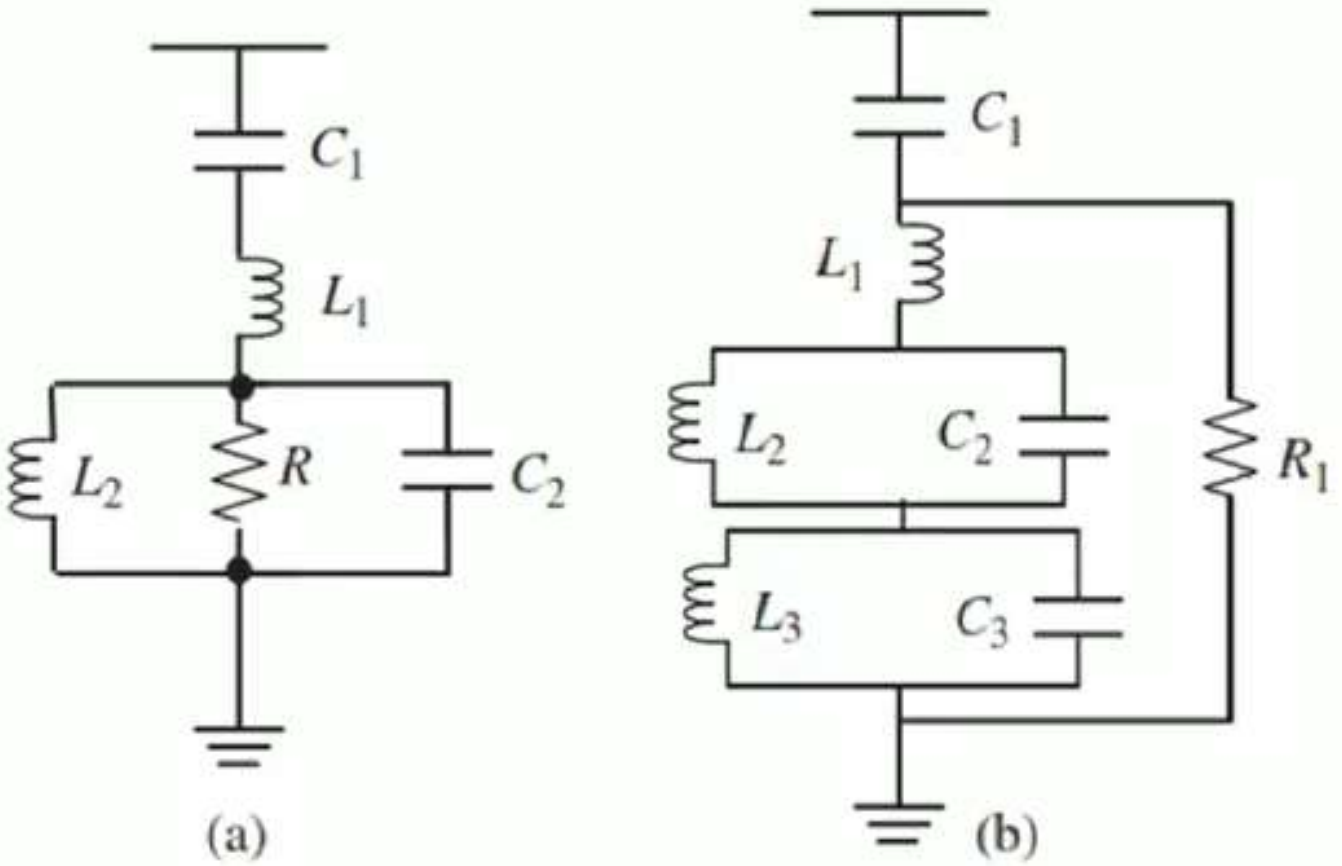


Figure 8.7 Hybrid passive filters: (a) damped double tuned; (b) damped triple tuned

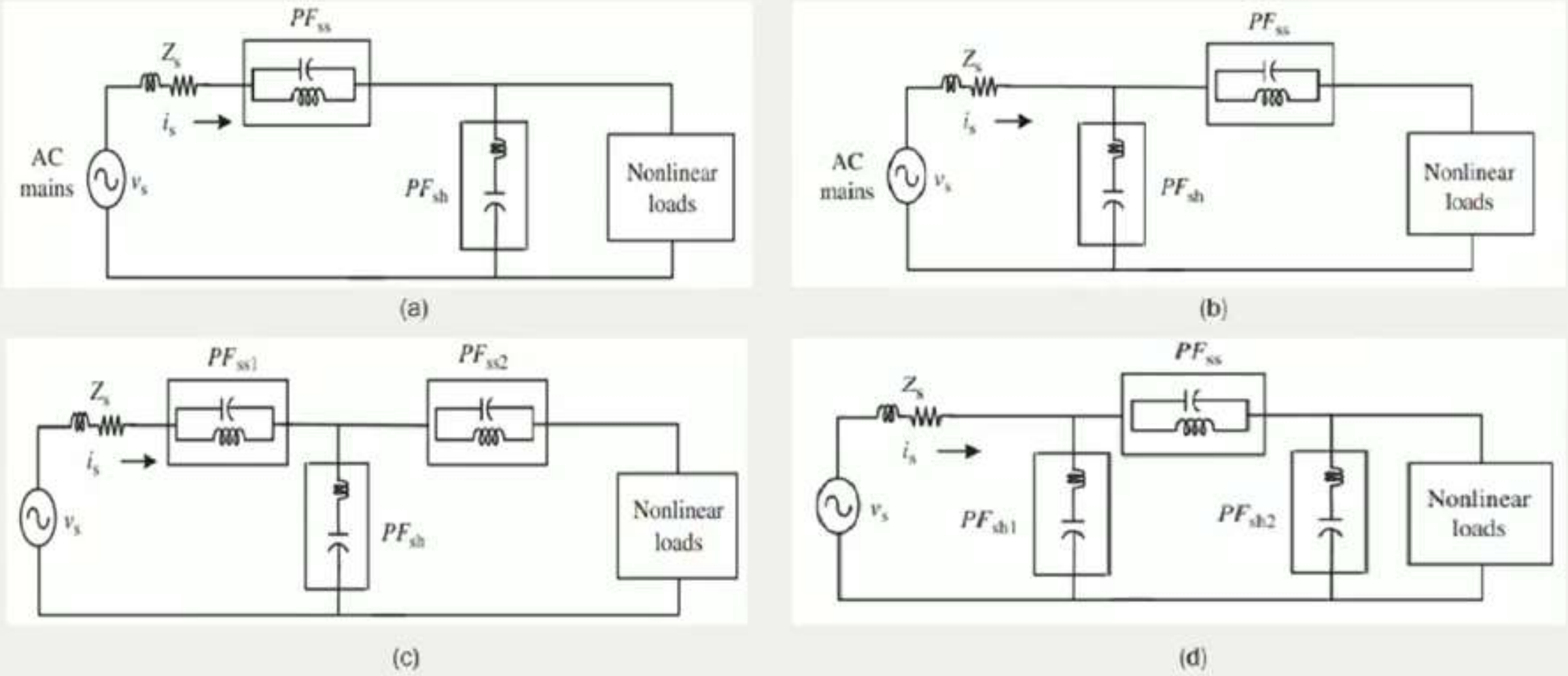


Fig. 3 Hybrid filter (a) combination of passive series (PF_{ss}) and passive shunt filters (PF_{sh}) (b) combination of passive shunt (PF_{ss}) and passive series filter (PF_{sh}) (c) passive series (PF_{ss1}) . passive shunt (PF_{sh}) and passive series (PF_{ss2}) (d) combination of passive shunt (PF_{sh1}) . passive series (PF_{ss}) and passive shunt (PF_{sh2})

Principle of operation of PPF's

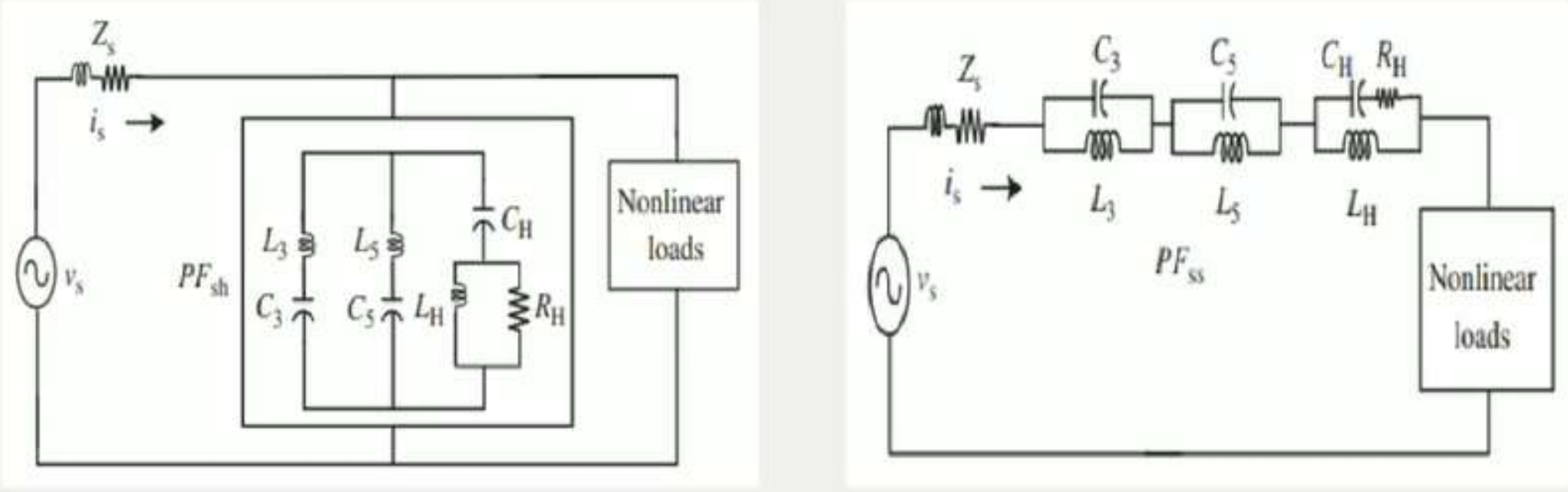
- The basic principle of operation of passive power filters may be explained through the following :

1. Objectives
2. Locations
3. Connections
4. Quality
5. Sharpness
6. Rating, size, cost

1. Objectives

- Main objective : to reduce harmonic voltages and currents in an AC power system to an acceptable level
- The AC passive shunt filter – provide the leading reactive power required in most of the non-linear loads
- The DC harmonic filters – used to reduce only harmonics on the DC bus of the load in the system
- Basic Operating Principle of passive shunt harmonic filter – to absorb harmonic currents in a low-impedance path realized using a tuned series LC circuit shown in Fig. 4 (b)

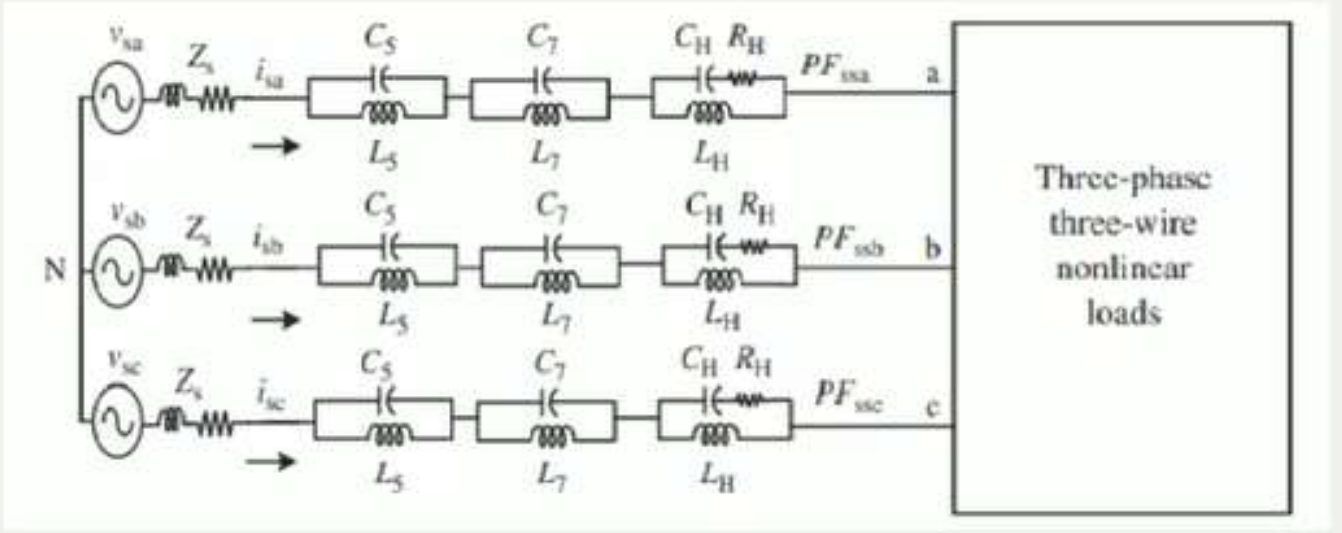
- Basic operating principle of a passive series filter - to block harmonic currents entering the AC network by a passive tuned parallel LC circuit offering high impedance for harmonic currents as shown in Fig. 4 (a)



(a) (b)

Fig. 4 (a) single- phase passive series filter (b)single-phase passive shunt filter

(a)



(b)

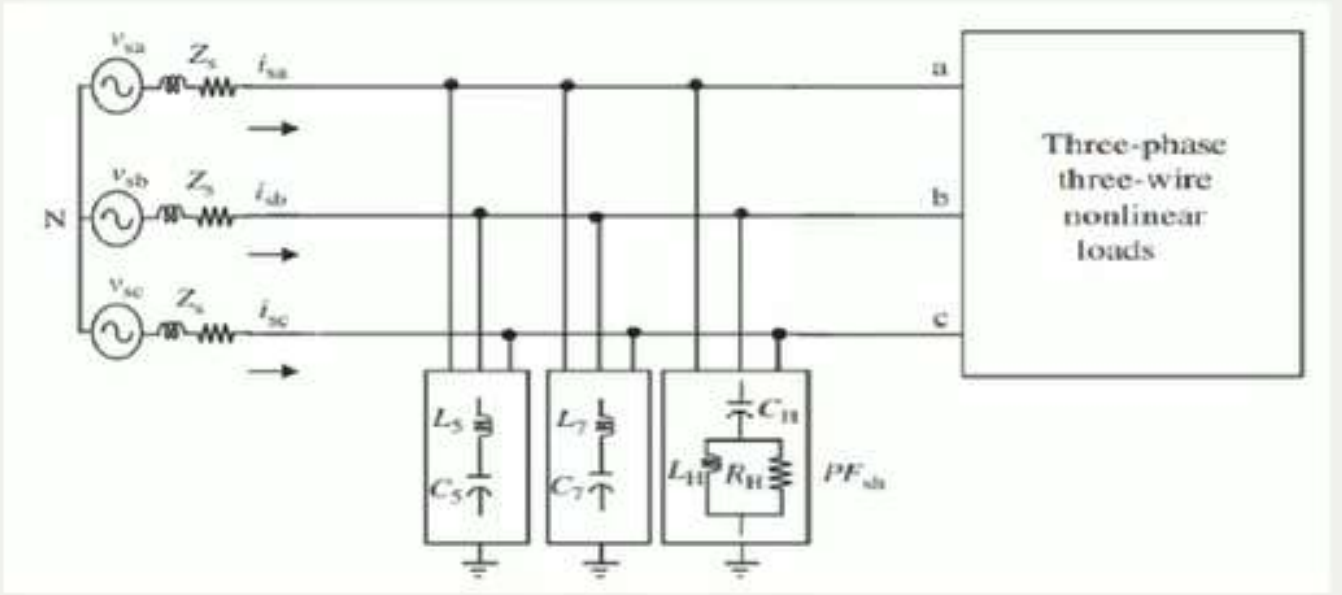


Fig. 5 (a) Three-phase three-wire passive series filter (b) Three-phase three-wire passive shunt filter

2. Location

- The passive filters are located very close to the loads either on AC or DC lines.
- Normally, the passive filters are connected at PCC where loads are connected
- Passive filters may be used for high-voltage harmonic-producing loads that require transformers and tertiary winding of the same transformer is designed to use the passive filters
- Sometimes they are connected to the tertiary winding of the transformer designed for this purpose at optimum voltage to reduce the cost and to increase effectiveness because of the properly designed leakage reactance of this tertiary winding

3. Connection and configuration

- The passive filters are used in shunt, series, and hybrid configurations
- The passive shunt filters, which are connected in shunt or parallel to the harmonic-producing loads or network, consist of series RLC circuits tuned at slightly low frequency at which they absorb harmonic currents
- For multiple harmonics, multiple tuned series RLC circuits are used to absorb the harmonic currents
- The passive series filters, which are connected in series with the AC mains and the harmonic-producing loads or network, consist of parallel LC circuits tuned at slightly low frequency at which they have to block harmonic current
- A hybrid passive filter - avoids the drawbacks of the series filter by using shunt filters and demerits of shunt filters are overcome by a series filter

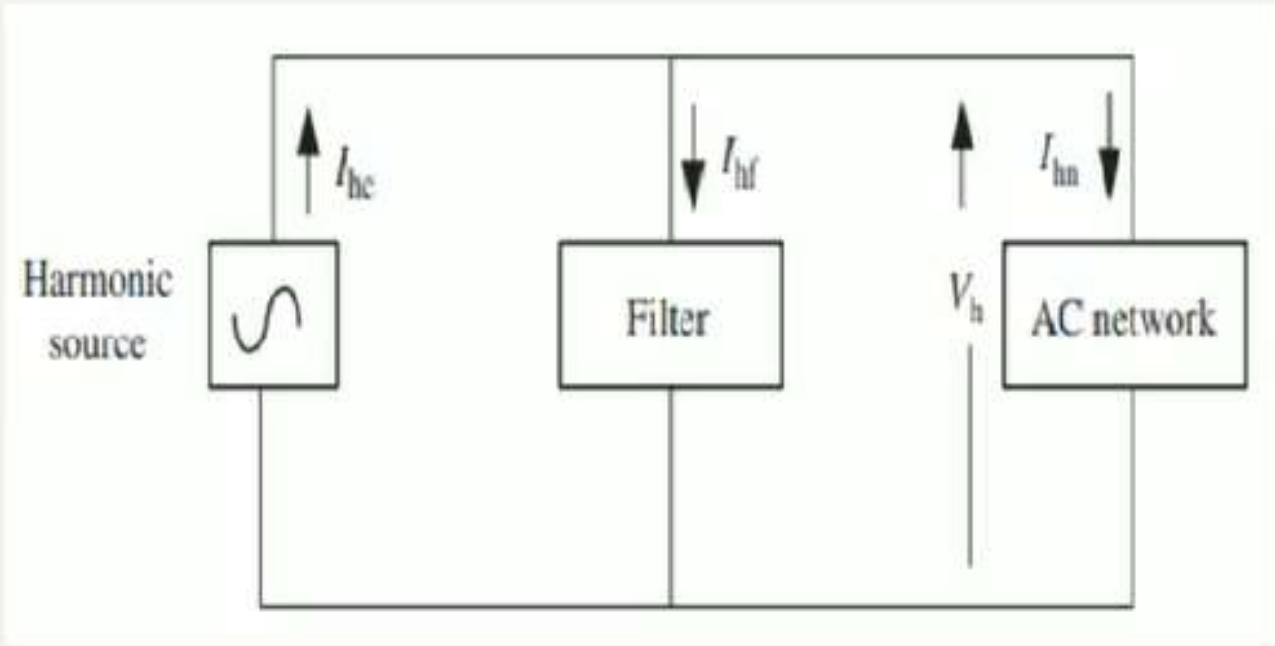


Fig. 6 Circuit for computation of harmonic currents and voltages on the AC side

4. Sharpness of Tuning of Passive filters

- It is one of the important properties of the passive filters
- It is quantified in terms of a quality factor of the inductor (Q) and is known as sharpness of tuning of the passive filter
- Passive shunt filters tuned at lower frequencies are sharply tuned and have a high value of quality factor, typically 10–100 and between 30 and 60
- High-pass filters, are tuned for high frequencies and have a low value of quality factor, typically 0.5–5 and preferably between 1 and 2
- The high-pass passive filters offer low impedance over a broad band of frequency bandwidth

5. Cost of Passive filters

- The cost of the passive filter is reasonable and sometimes it reaches 15–20% of the equipment
- The cost factor should be taken into account while designing the passive filters
- The cost of the passive filter may also be partially supplemented to the reactive power supplied by it

Design of Passive Power Filters

The design procedure of a passive filter generally involves the following steps:

- Estimate or record the input current frequency spectrum of the nonlinear load and its displacement power factor
- Obtain the frequency response of the power distribution equivalent impedance at the PCC where a passive filter is to be connected in the system
- Select the numbers, types, and tuned frequencies of passive filters (out of the tuned – single, double, triple, etc.; damped – first order, second order, and C-type filters; normally a C-type filter is recommended for low frequency and a high-pass filter for high frequency)
- Appropriately assign the reactive power to be generated by each unit of the passive filter
- Estimate the parameters of each unit of the passive filte

- Evaluate the attenuation factor of each unit of the passive filter as a function of the frequency
- Check the existence of resonance frequencies of each unit of the passive filter
- If these resonance frequencies of passive filter units are close to current harmonics generated by the nonlinear load, then change the tuned frequency of the filter and accordingly calculate new parameters of the passive filter to avoid the parallel resonance with the supply system
- Validate the performance of the distribution system with filter scheme connected through simulation, and estimate the harmonic distortion of voltage and current and displacement power factor
- Iterate this design procedure of the passive filter till satisfactory performance is achieved for the distribution system in terms of total harmonic distortion (THD) of the current and voltage and power factor.

(1) Design of Passive Shunt Filters

- It consists of a series combination of an inductor and a capacitor tuned to a particular frequency
- In a single-phase system, the third and fifth harmonic filters are designed using a series tuned filter and a high-pass filter is designed using a second-order damped filter
- In a three-phase system, the fifth and seventh harmonic filters are designed using a series tuned filter and a high-pass filter is designed using a second-order damped filter
- Initially, the size of the capacitors is calculated from the reactive power requirement (Q_C) of the load

- The absolute value of capacitance (C_n) is calculated by

$$C_n = \frac{Q_C}{m\omega V_s^2}$$

Where, m – number of branches in the passive filter for all the phases, V_s - per phase fundamental voltage across it, ω – fundamental frequency of the supply

- To trap the nth harmonic current, the inductance for the nth-order filter is calculated as

$$L_n = \frac{1}{n^2\omega^2 C_n}$$

- The series resistance for the inductor of the nth-order filter is calculated as

$$R_n = \frac{n\omega L_n}{Q_n}$$

Where, Q_n - the quality factor of the inductor of the nth-order filter $10 < Q < 100$

Limitations of Passive Filters

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

- The passive filters are designed with a large number of elements and loss/damage of some of the elements may change its resonance frequencies. This may result in increased distortion in the distribution above the permissible limits
- In case of large filters, the power losses may be substantial because of resistive elements.
- The parallel resonance due to interaction between the source and the filter can cause amplification of some characteristic and non-characteristic harmonics. Such problems enforce constraints on the designer in selecting tuned frequency for avoiding such resonances
- The size of the damped filter becomes large in handling the fundamental and harmonic frequencies

- The environmental effects such as aging, deterioration, and temperature change and detune the filters in a random manner
- The presence of a small DC component and harmonic current may cause saturation of the reactors of the filter
- A special switching is required for switching in and switching out passive filters to avoid the switching transients
- The grounded neutral of star connected capacitor banks may cause amplification of third harmonic currents in some cases
- Special protective and monitoring devices are required in passive filters.

Active Power Filters(APFs)

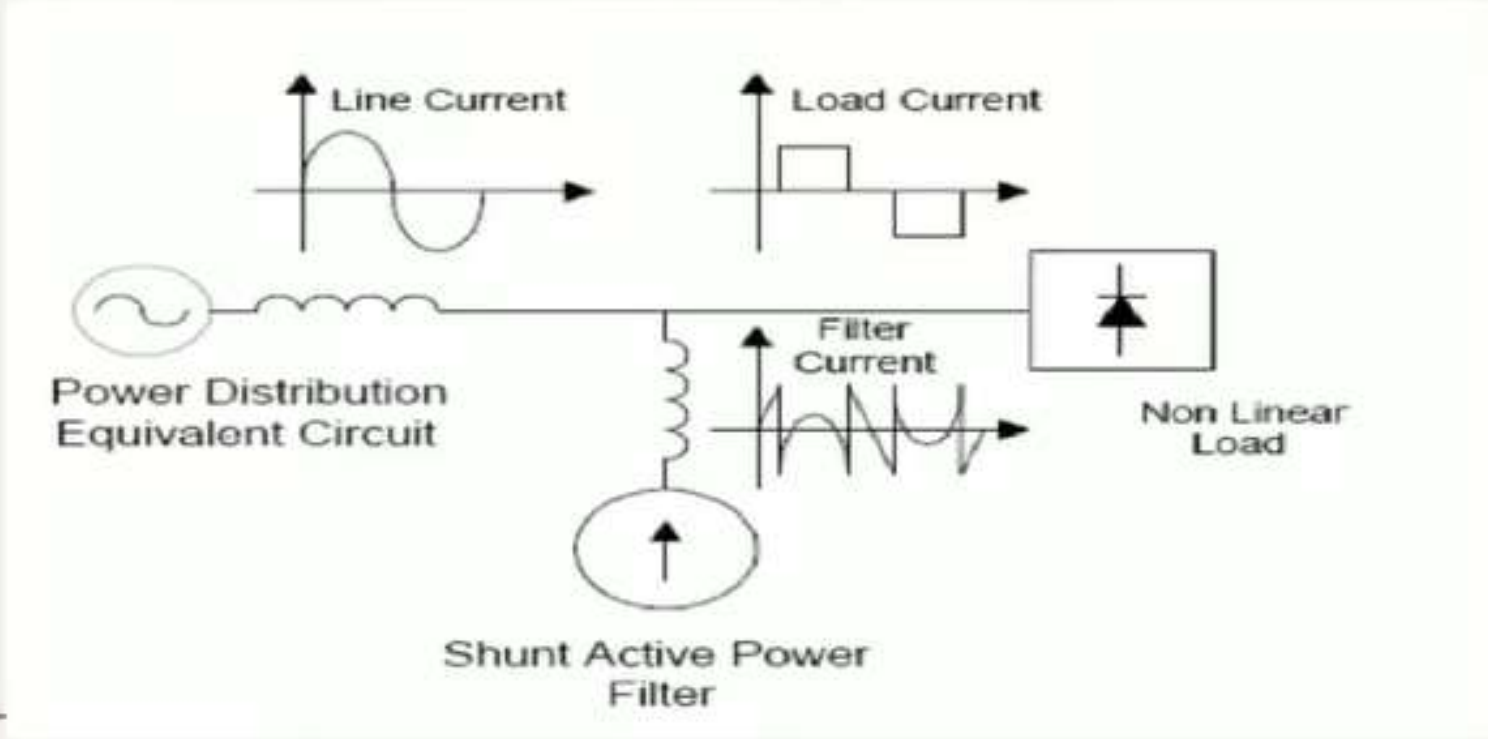
- Active power filter has been proposed since 1970s.
- It provides functions such as

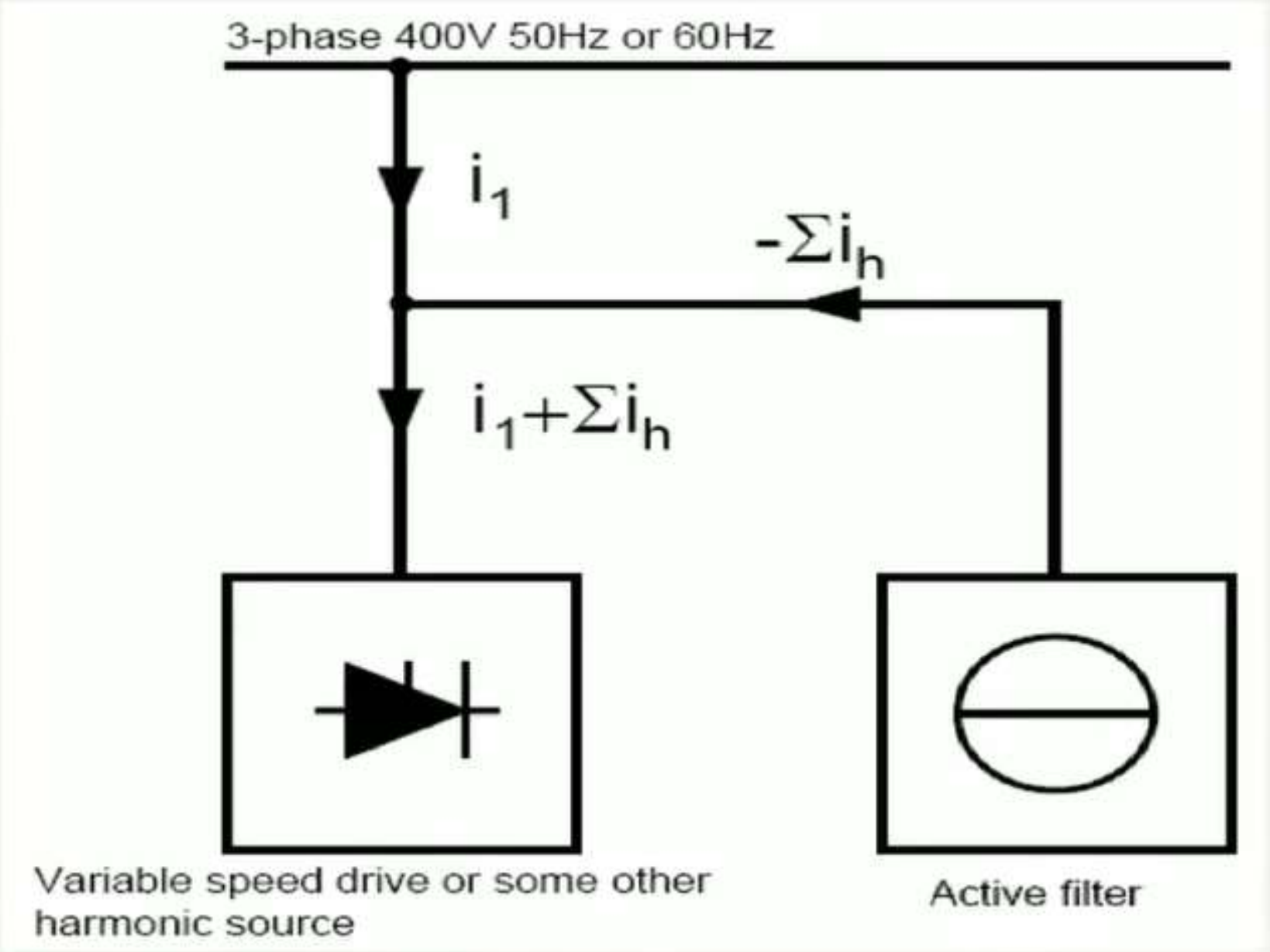
reactive power compensations
harmonic compensations
harmonic isolation
harmonic damping
harmonic termination
negative-sequence current or voltage compensation
and voltage regulation etc.

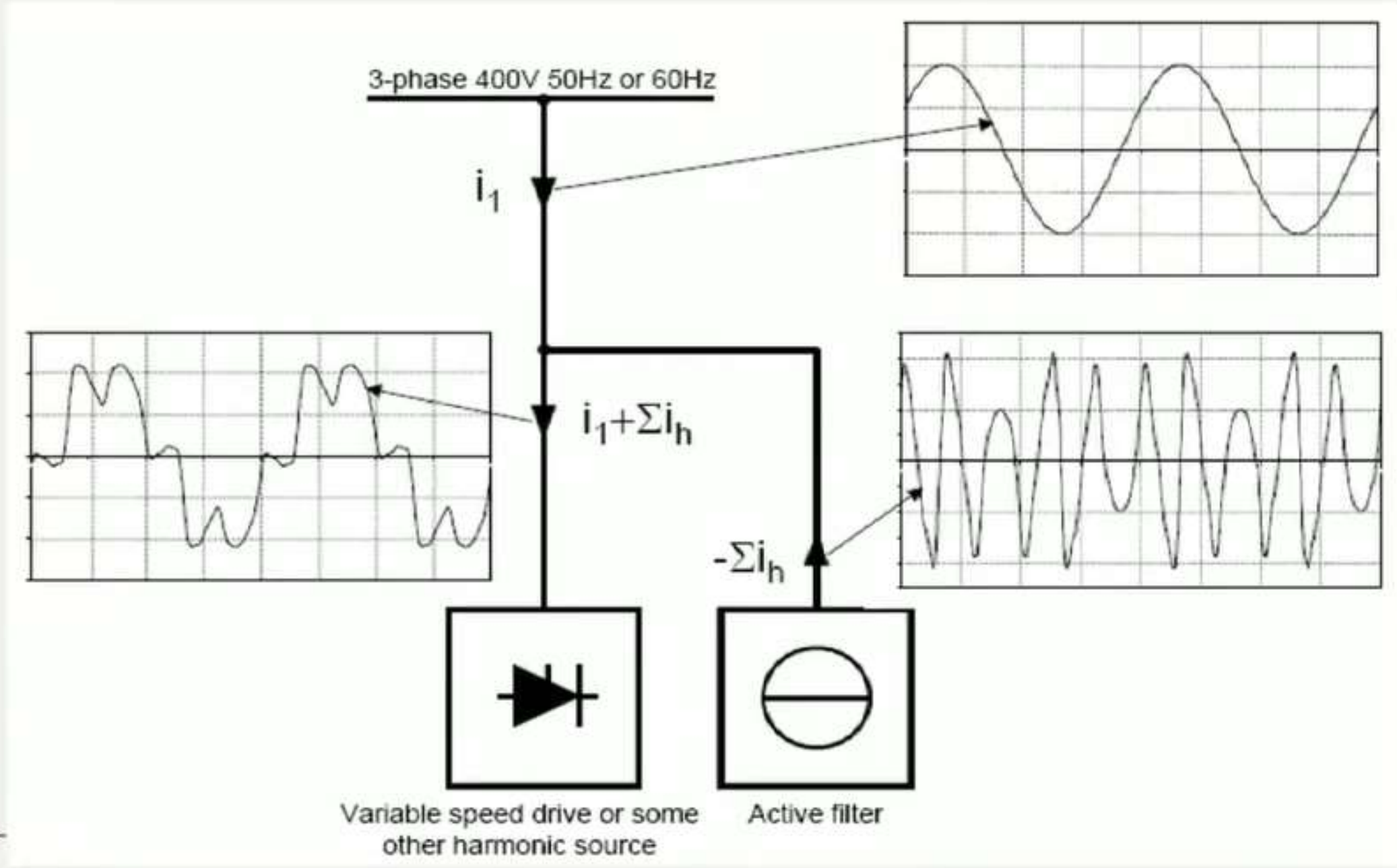
- APF consists of an inverter with switching control circuit.

- The inverter ⟶ generate the desired compensating harmonics based on the switching gates provided by the controller.

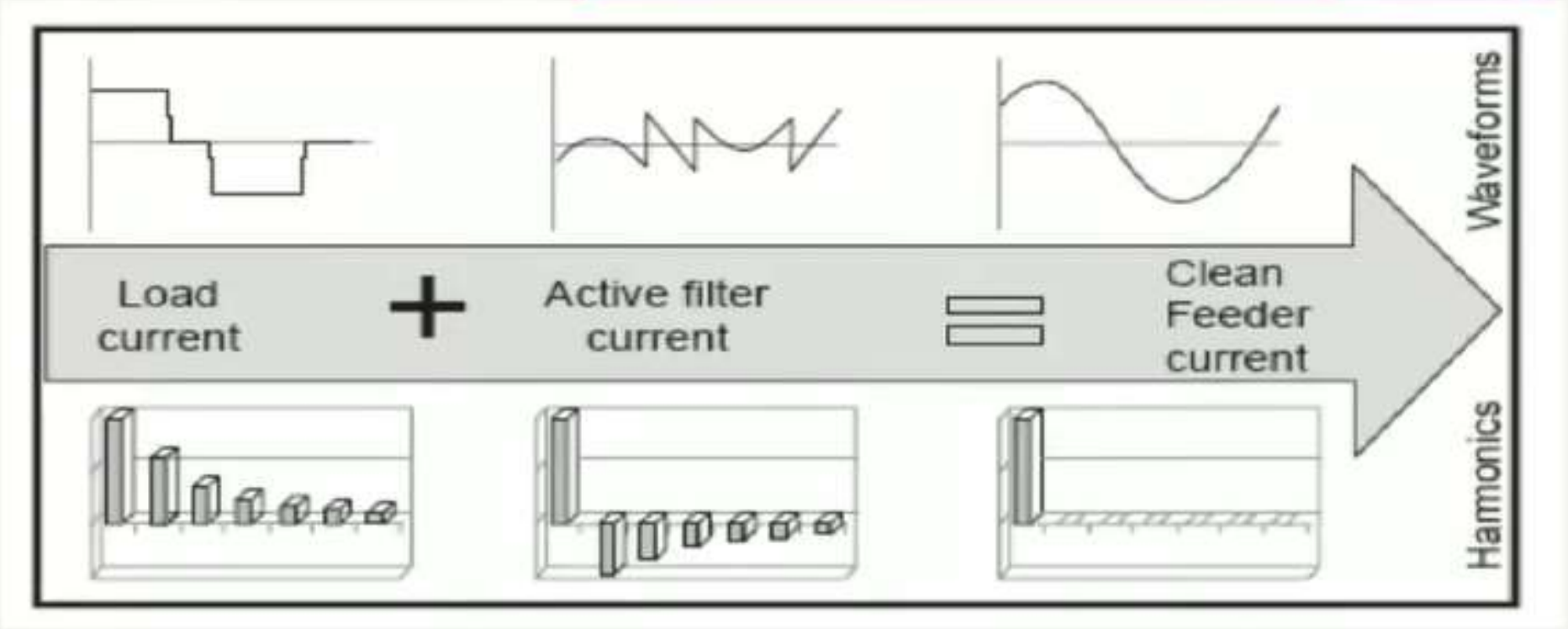
- The APF injects an equal-but-opposite distortion harmonics back into the power line and cancel with the original distorted harmonics on the line.




3-phase 400V 50Hz or 60Hz
i_1
$-\Sigma i_h$
$i_1+\Sigma i_h$
Variable speed drive or some other harmonic source
Active filter


3-phase 400V 50Hz or 60Hz
i_1
$i_1+\Sigma i_h$
$-\Sigma i_h$
Variable speed drive or some other harmonic source
Active filter

Active Power Filters(cont.)

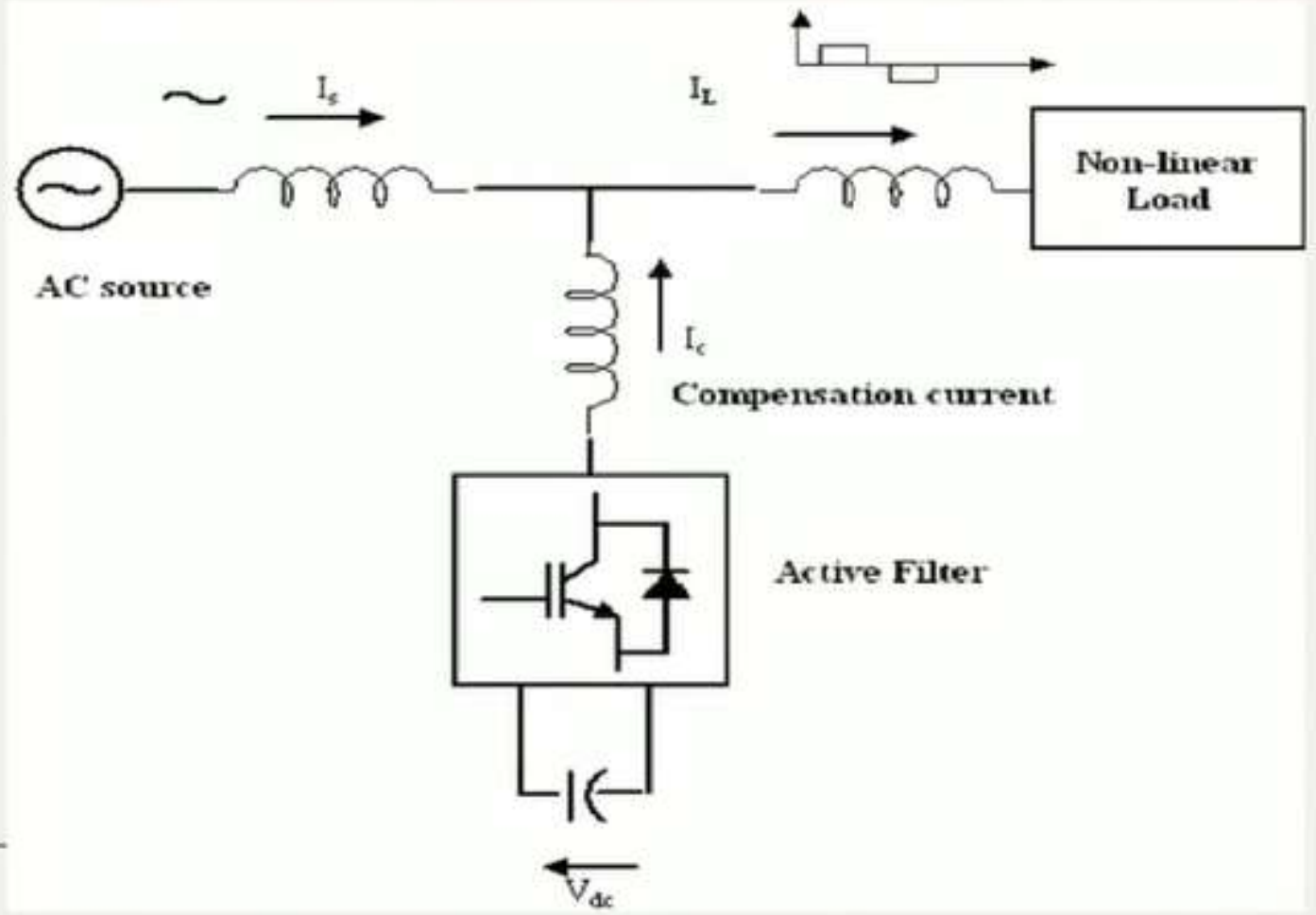


- Based on topology APF can be classified as

(i) Shunt active power filter
(ii) Series active power filter
(iii) Hybrid active power filter

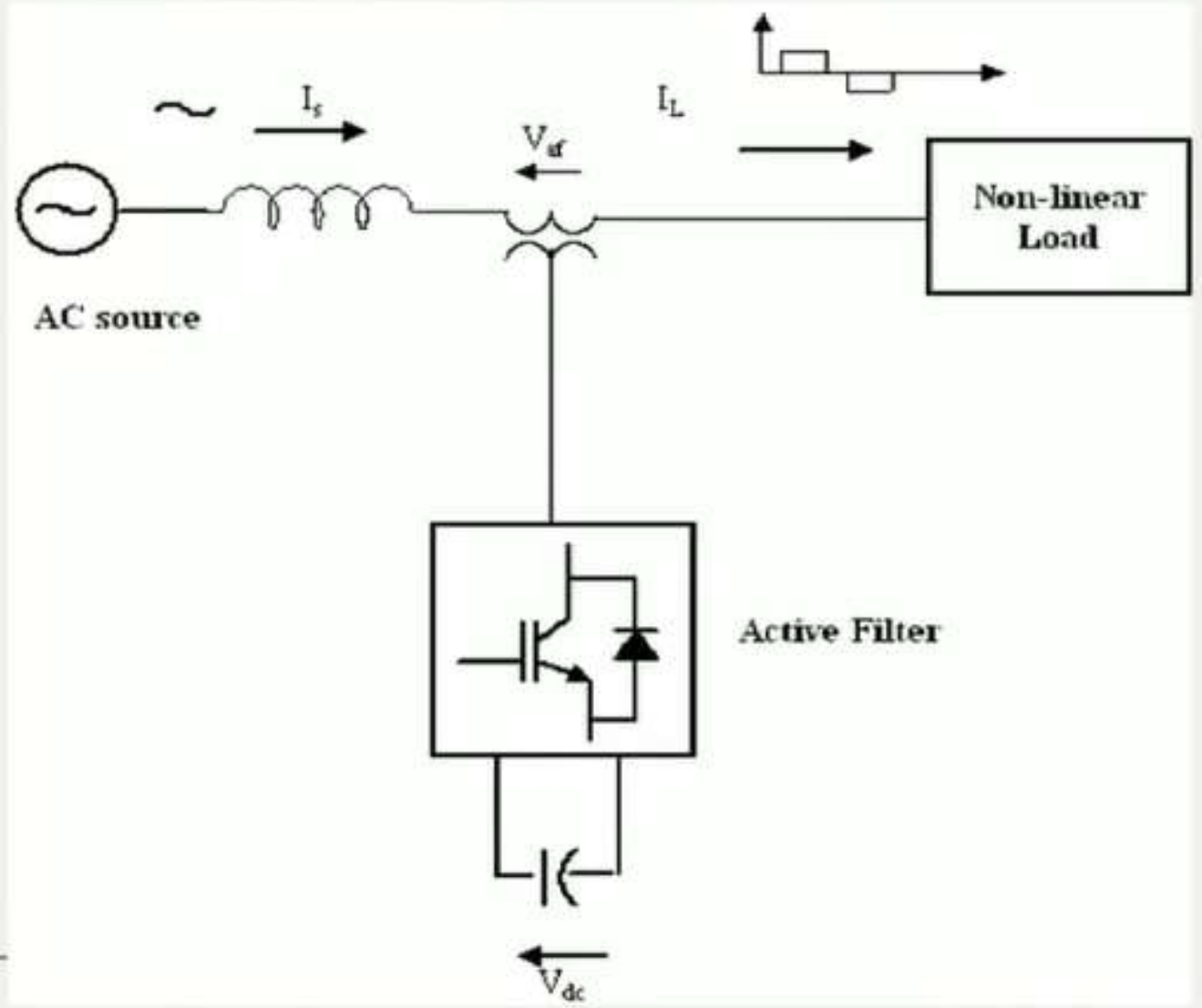
Shunt active power filter

- Used to compensate, current harmonics, reactive power and load current unbalance
- Static VAR generator in power system networks for stabilizing and improving voltage profile



Series active power filter

- Eliminates voltage unbalance, sag, swell etc



- Series active filter is expected to filter voltage harmonics appearing in the supply systems so that the loads are supplied with clean sinusoidal supply voltage
- Series active power filters are having substantial applications for eliminating voltage harmonics present in the supply system or created by the nonlinear loads at the point of common coupling (PCC) and current harmonics in both voltage-fed and current-fed loads depending upon the applications
- The series APFs are classified into three major categories: single-phase two-wire, three-phase three-wire, and three-phase four-wire series APFs
- The series active power filters are mainly used to eliminate voltage harmonics

- They can be used to regulate the terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems, with additional cost and rating
- The series active power filters are also used to eliminate harmonic currents in voltage-fed nonlinear loads
- They are also used in current-fed nonlinear loads along with passive filters
- **Objective:** series active power filters are achieved either individually or in combination depending upon the requirements and control strategy and configuration that need to be selected appropriately

- It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and/or passive shunt compensators

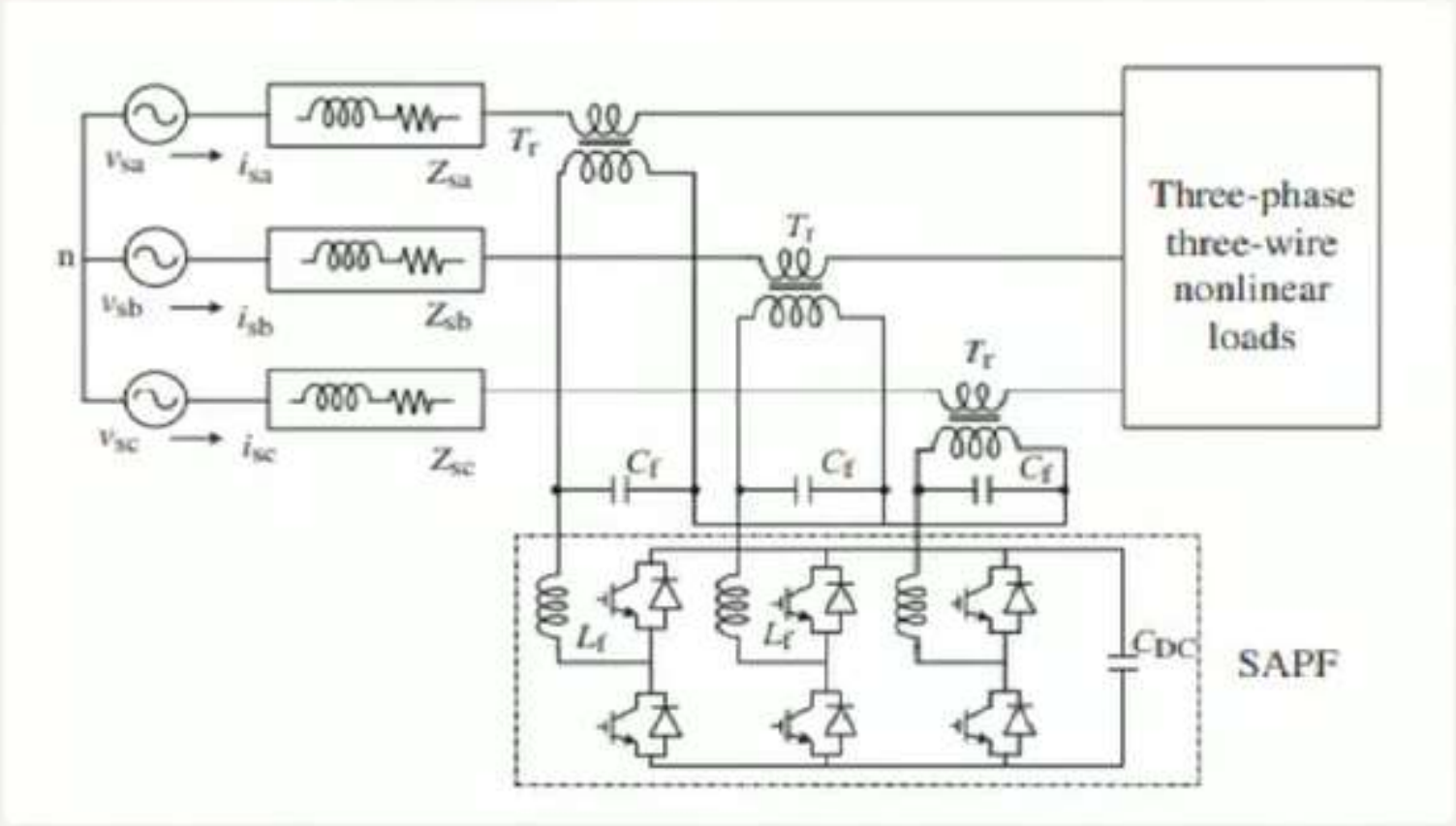


Fig. 5 Three-phase three-wire active series filter

Principle of Operation

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

Active power filter control techniques(cont.)

load current detection, supply current detection and voltage detection.

(i) Instantaneous-reactive-power algorithm
(ii) Synchronous-detection algorithm
(iii) constant-active power algorithm
(iv) unity power factor algorithm
(v) Fictitious-power-compensation algorithm
(vi) Synchronous-frame-based algorithm
(vii) Synchronous-flux-detection algorithm

Reference current generation using Instantaneous Active and Reactive Power method(p-q method)

- The three phase supply voltages and load currents could be transformed into the (α-β). orthogonal coordinates as follows:

$$\begin{bmatrix} Vs\ \alpha \\ Vs\ \beta \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}.$$

$$\begin{bmatrix} iL\ \alpha \\ iL\ \beta \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix}.$$

- Instantaneous real power p(t) and imaginary power q(t) is given by the expression

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} Vs\,\alpha & Vs\,\beta \\ -Vs\,\beta & Vs\,\alpha \end{bmatrix} \begin{bmatrix} iL\,\alpha \\ iL\,\beta \end{bmatrix}$$

where, p(t) and q(t) contain dc and ac terms and can be written as:

$$p(t) = \overline{p} + \tilde{p}$$
$$q(t) = \overline{q} + \tilde{q}$$

The compensation power could be obtained by filtering out the ac components

$$p^*(t) = \tilde{p}$$
$$q^*(t) = \overline{q} + \tilde{q} = q$$

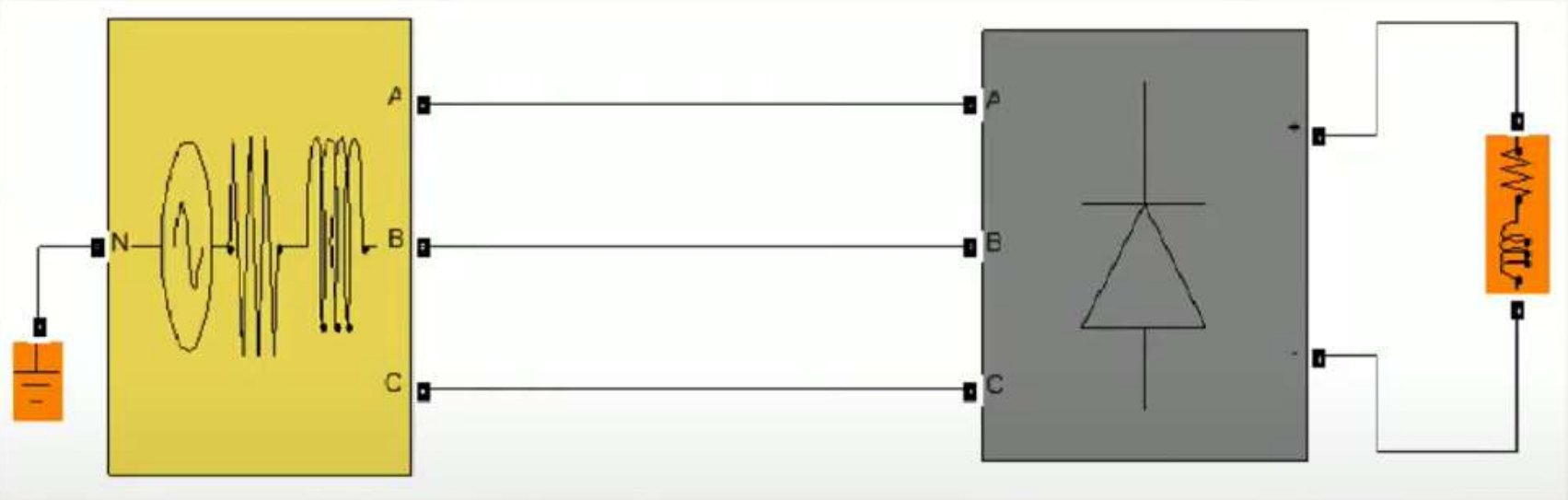
- The reference compensation current in the a-b plane is given by the expression:

$$\begin{bmatrix} ic\alpha^*(t) \\ ic\beta^*(t) \end{bmatrix} = \begin{bmatrix} Vs\alpha & Vs\beta \\ -Vs\beta & Vs\alpha \end{bmatrix}' \begin{bmatrix} p^*(t) \\ q^*(t) \end{bmatrix}$$

The reference compensation currents for phase a,phase b and phase c given as

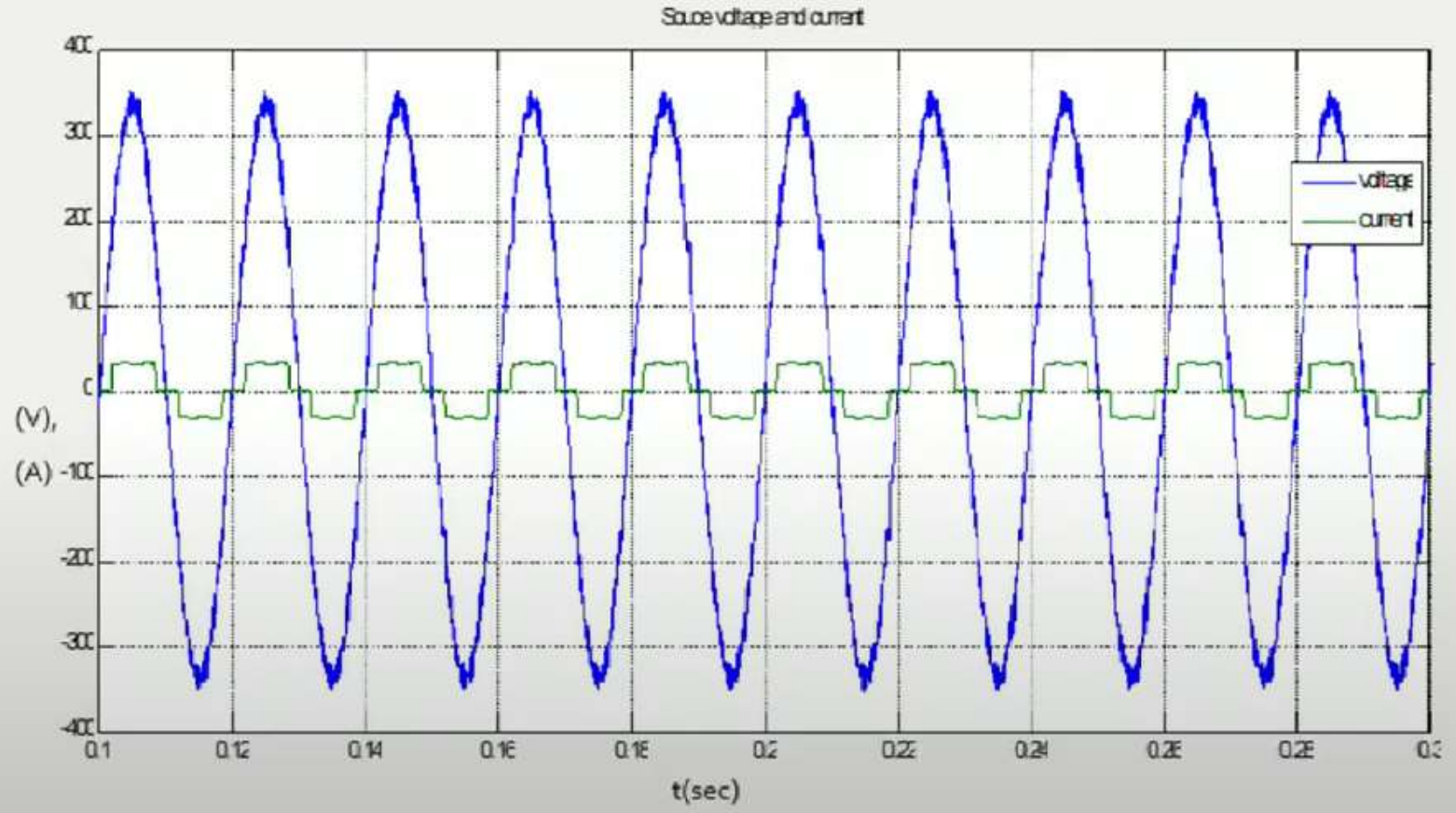
$$\begin{bmatrix} ica^*(t) \\ icb^*(t) \\ icc^*(t) \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} ic\alpha^*(t) \\ ic\beta^*(t) \end{bmatrix}$$

System without APF



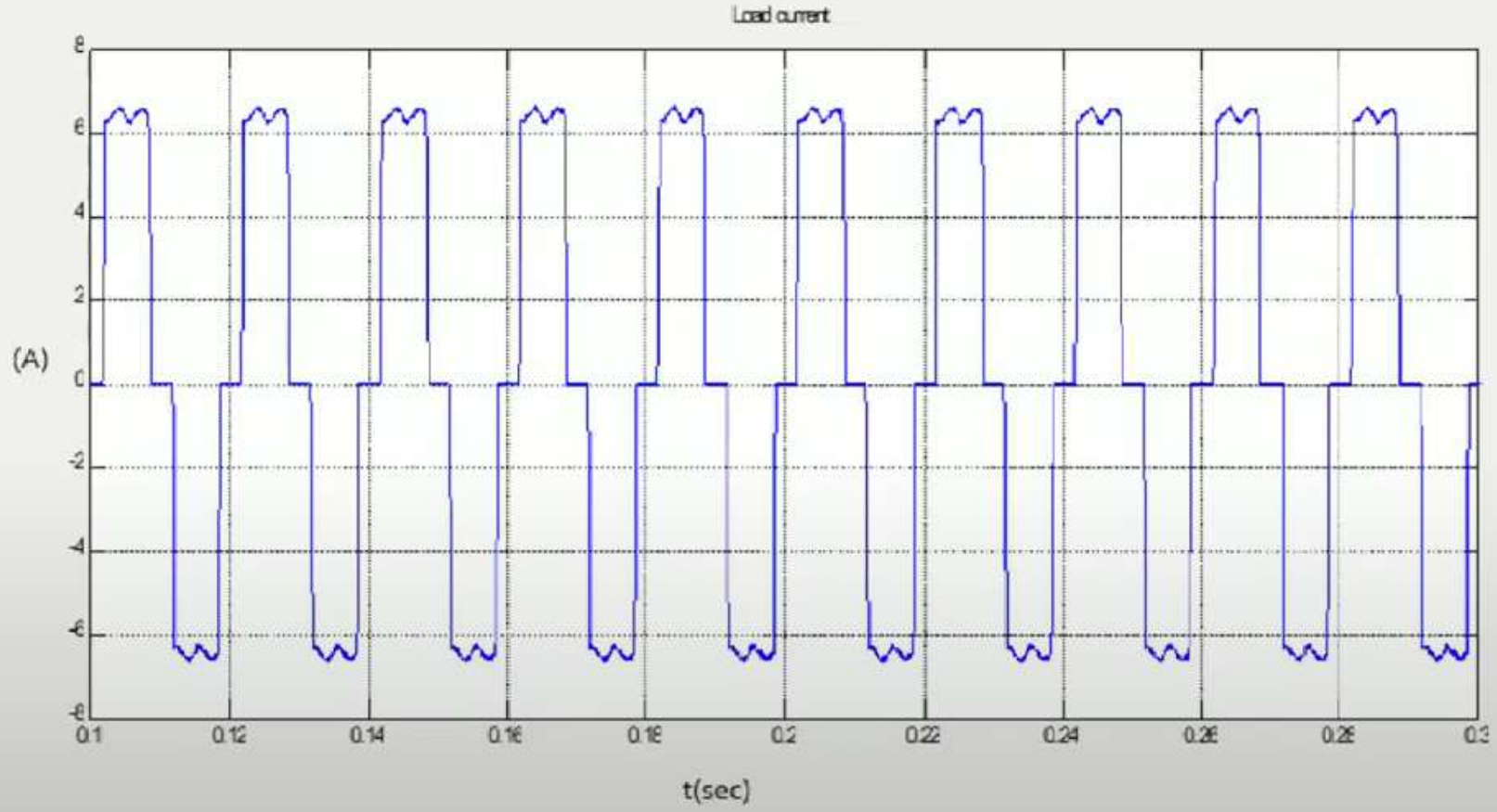
System without APF(cont.)

Source voltage and current



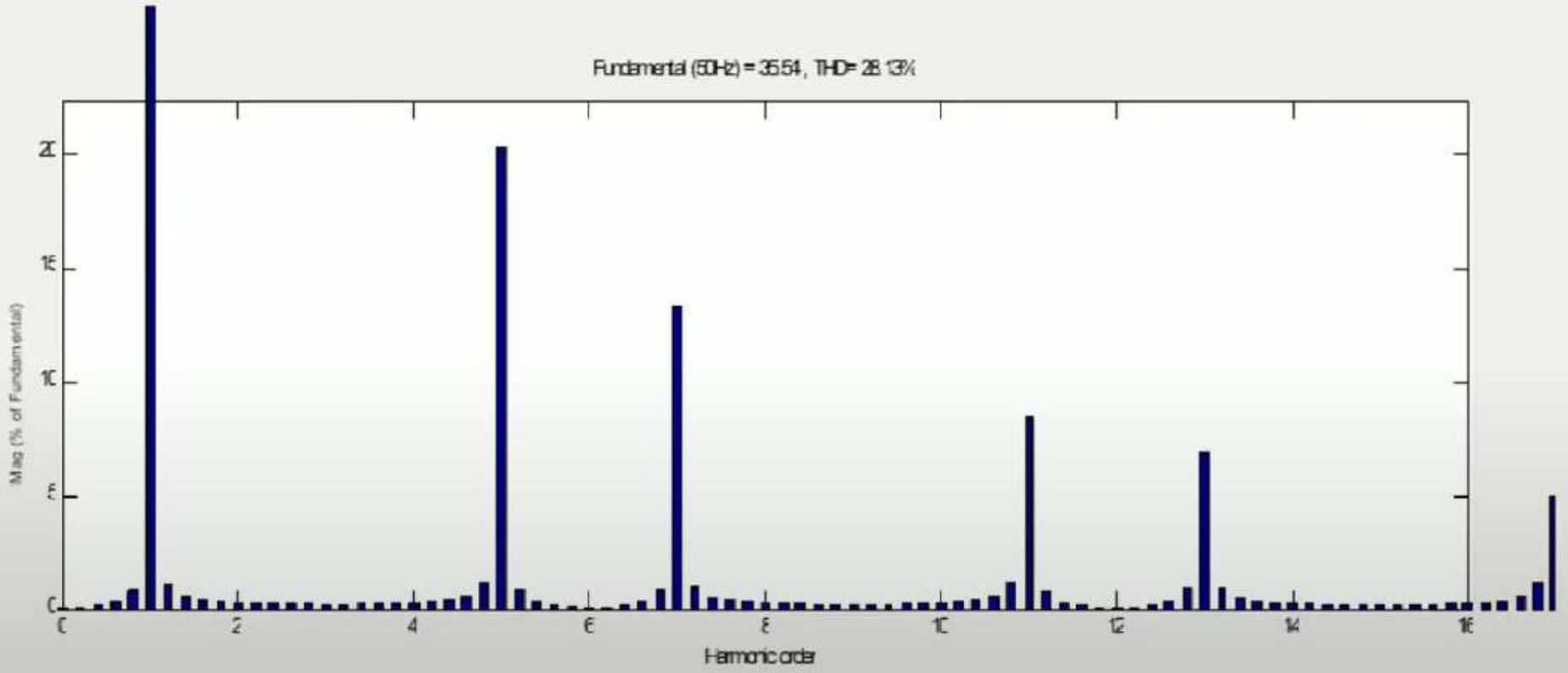
System without APF(cont.)

Load current



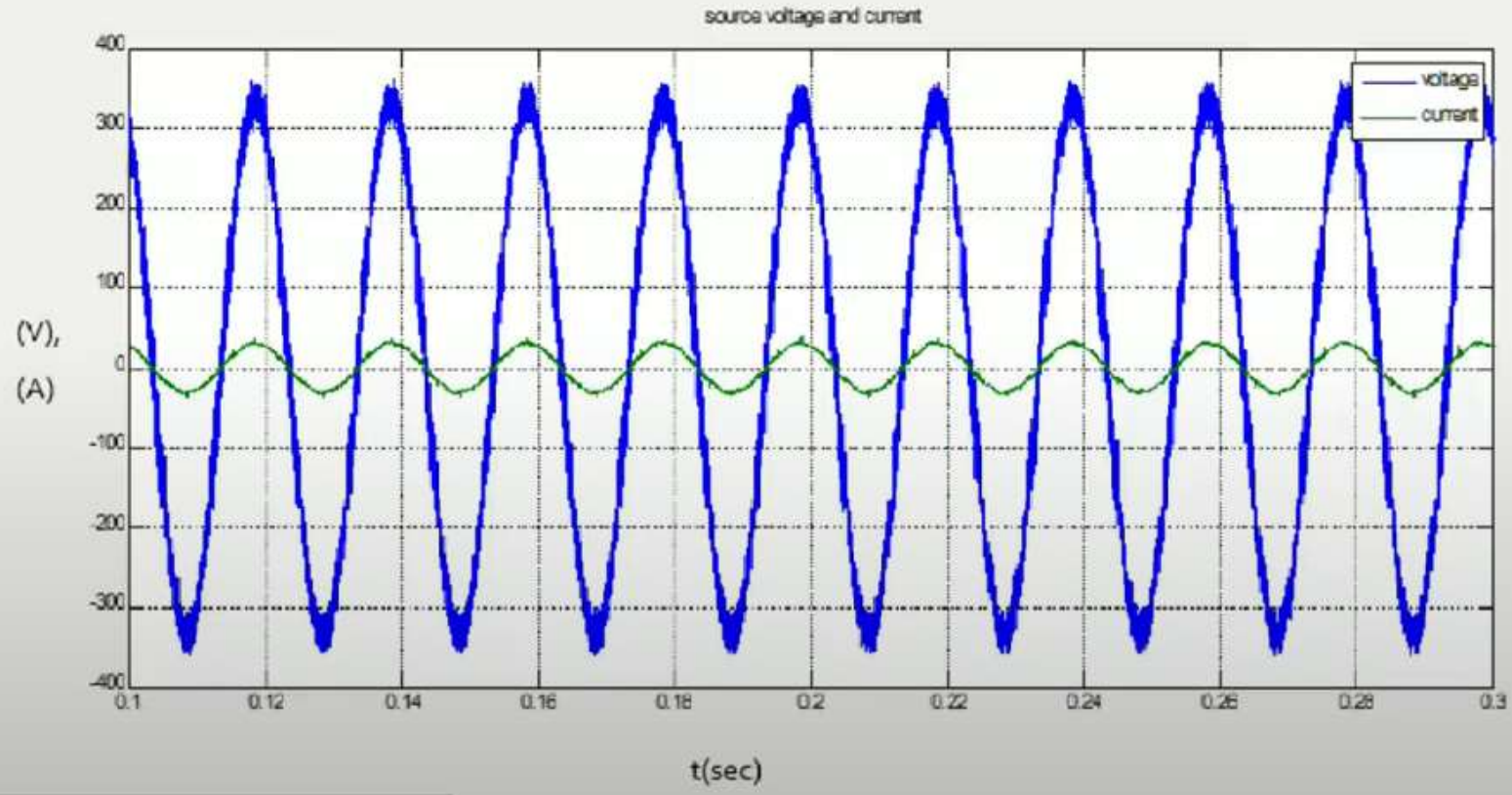
System without APF(cont.)

THD of Source current – 28.13%

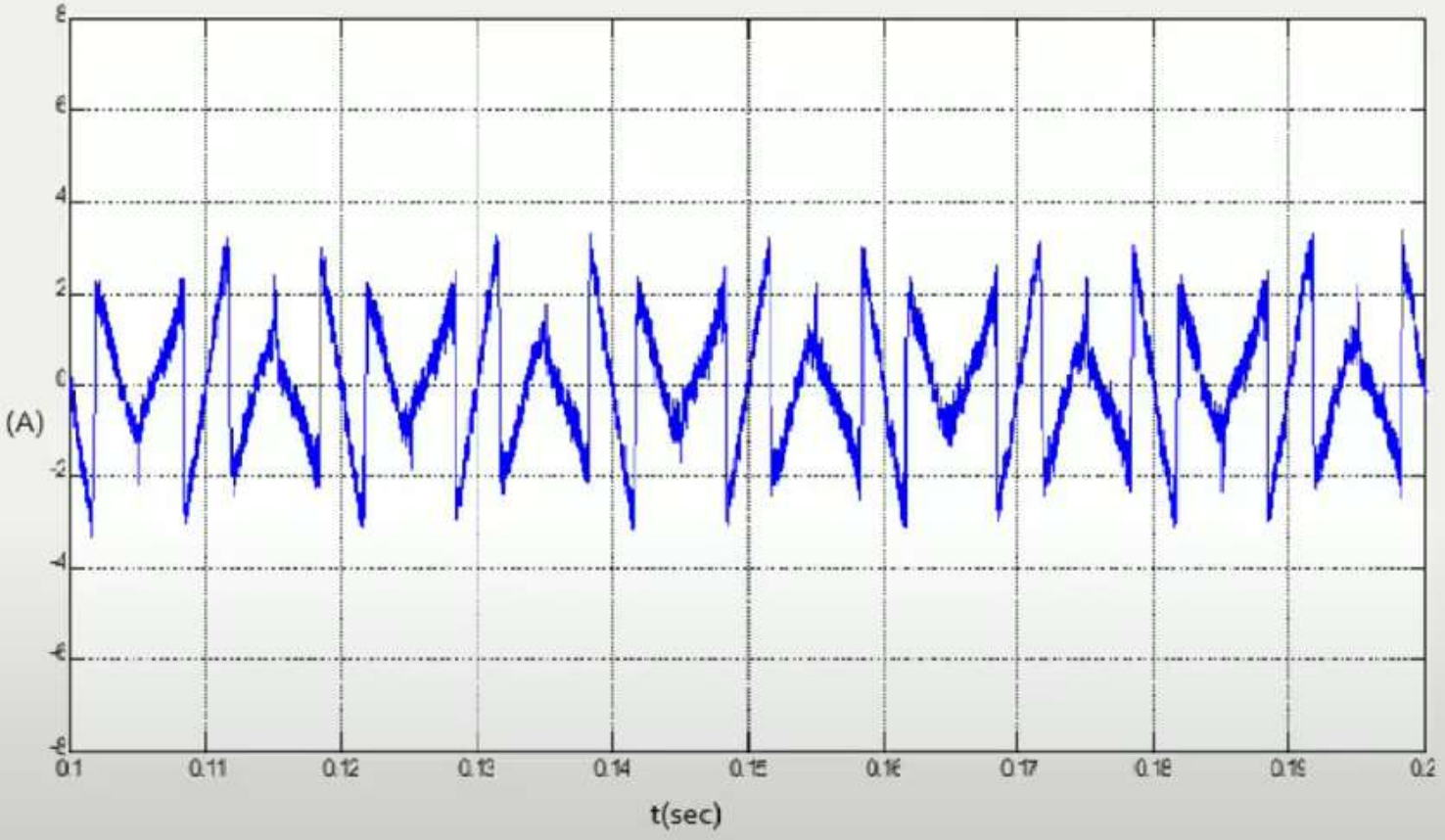


Harmonic compensation considering a non-linear load of 3-phase diode bridge with resistive load

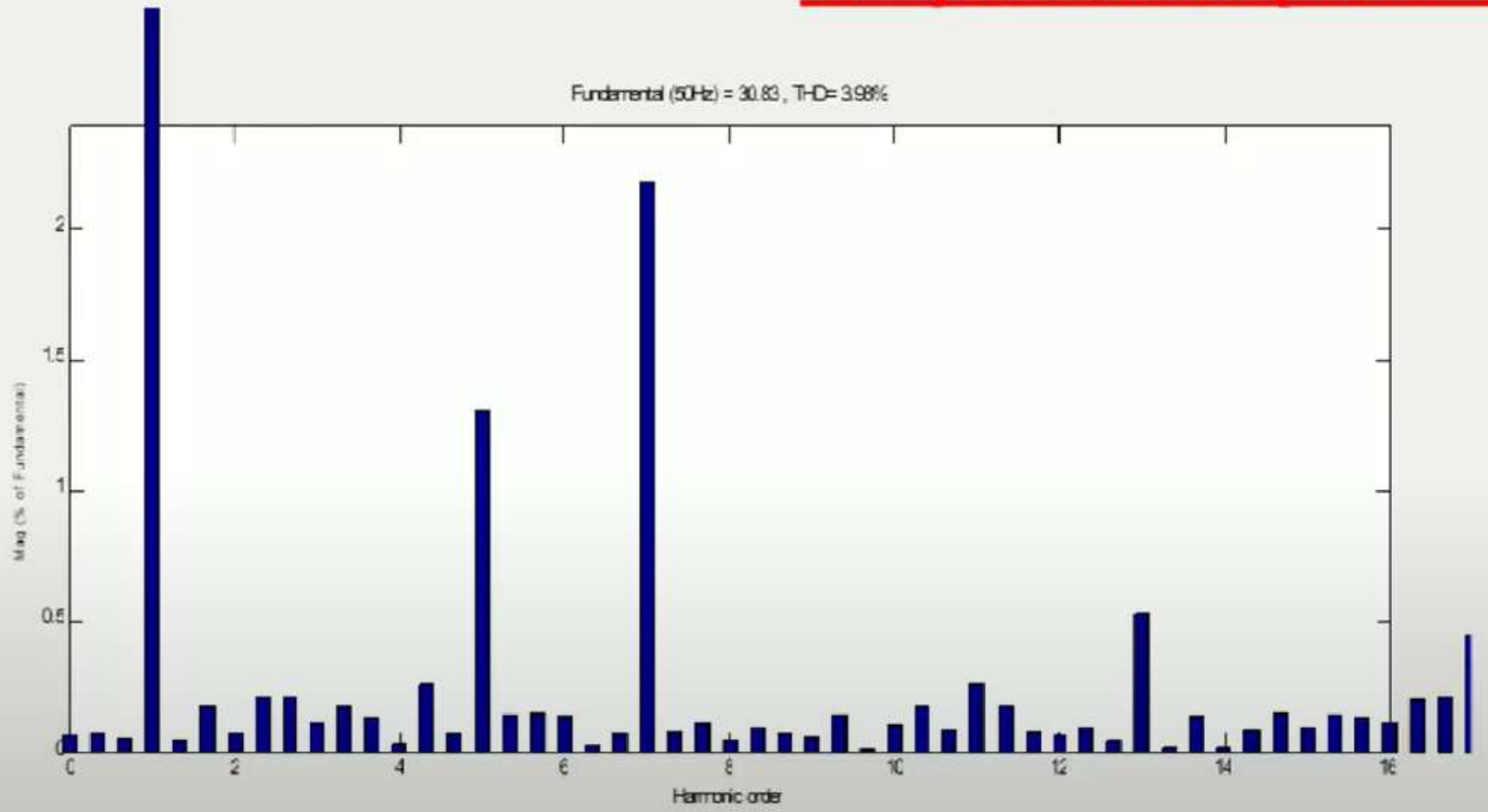
- **Source voltage and current**



- **Injected harmonic current**



Total harmonic distortion of the source current after compensation (THD=3.98%)



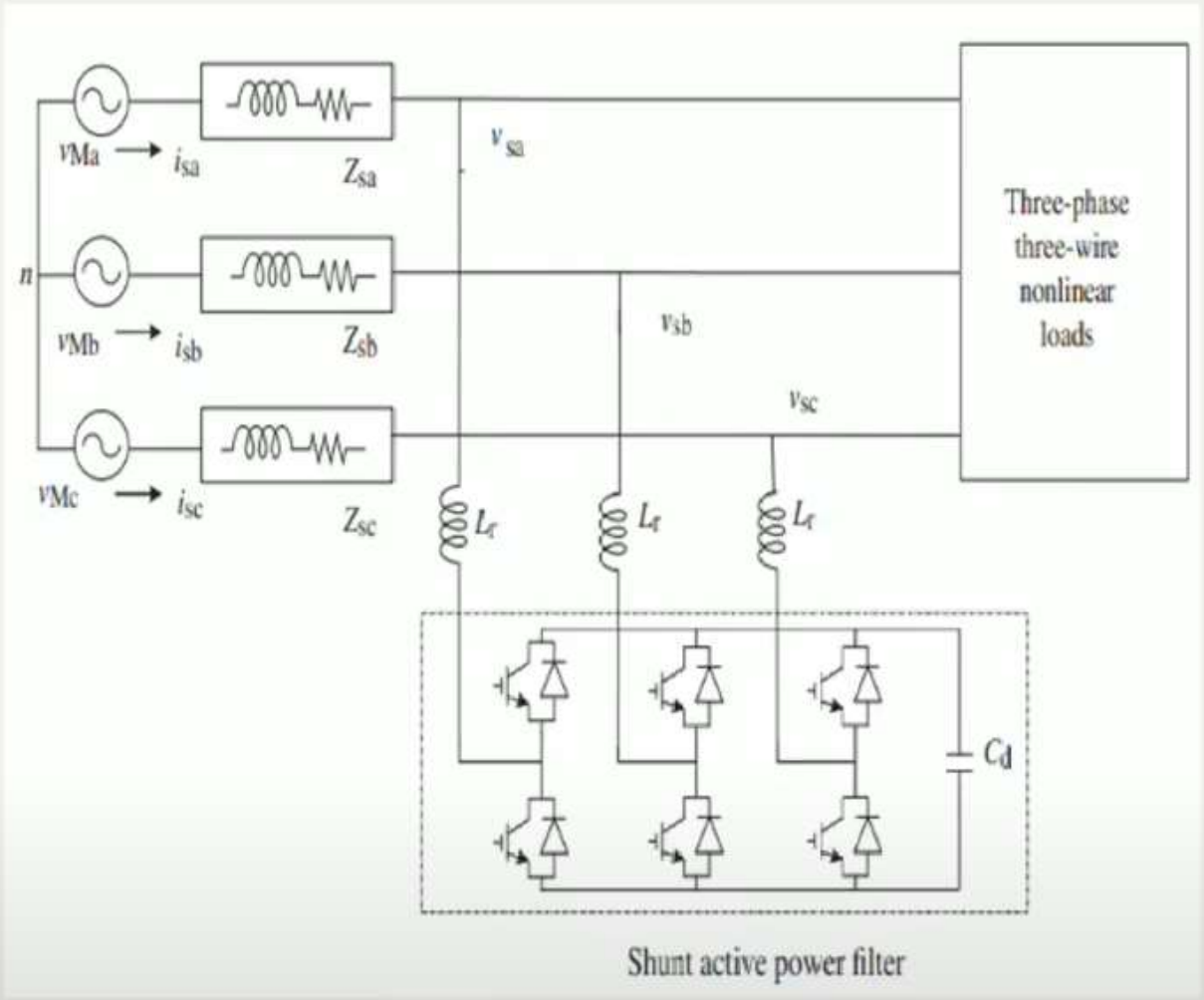


Fig.3 Three-phase three-wire shunt Active power filter

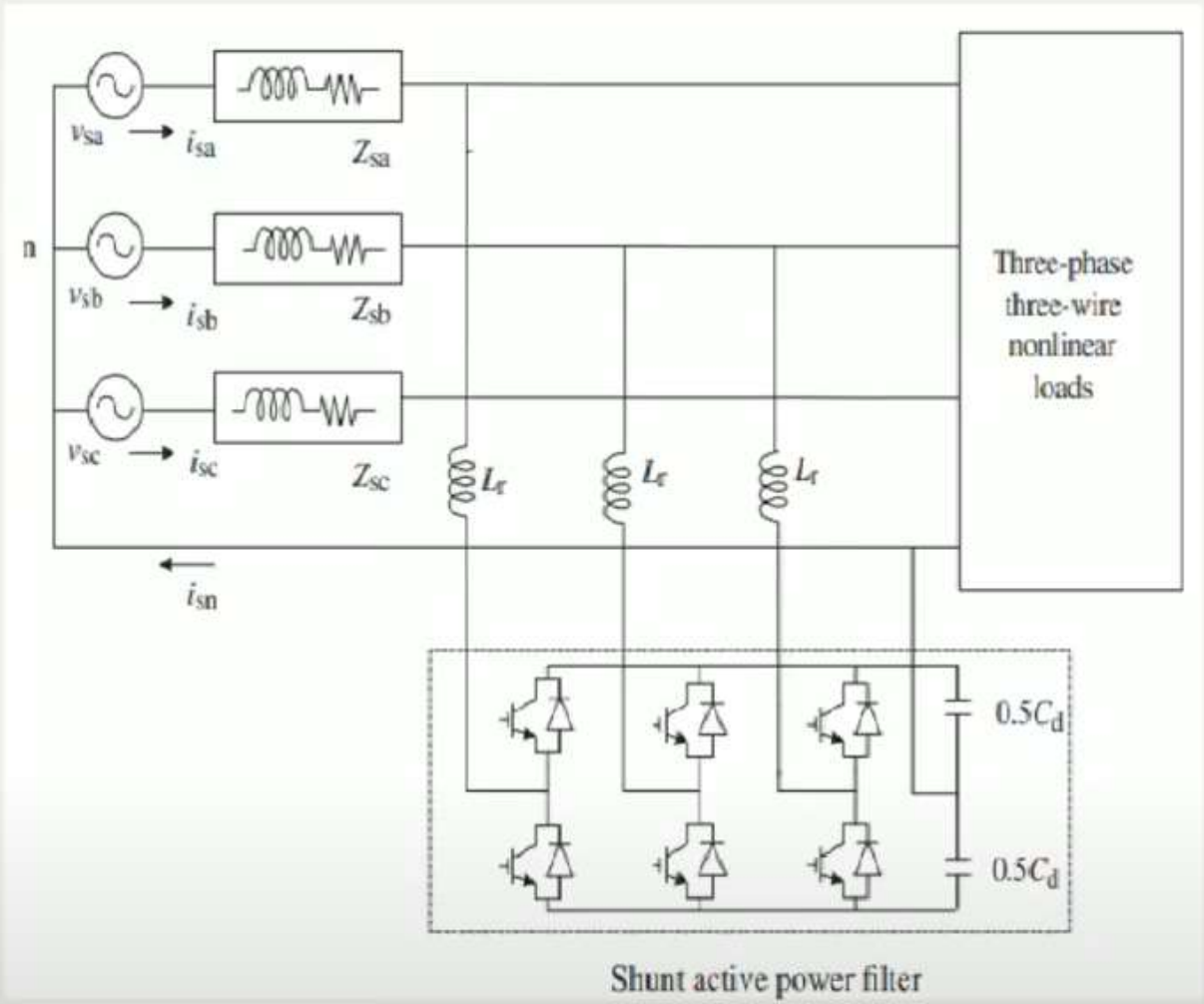
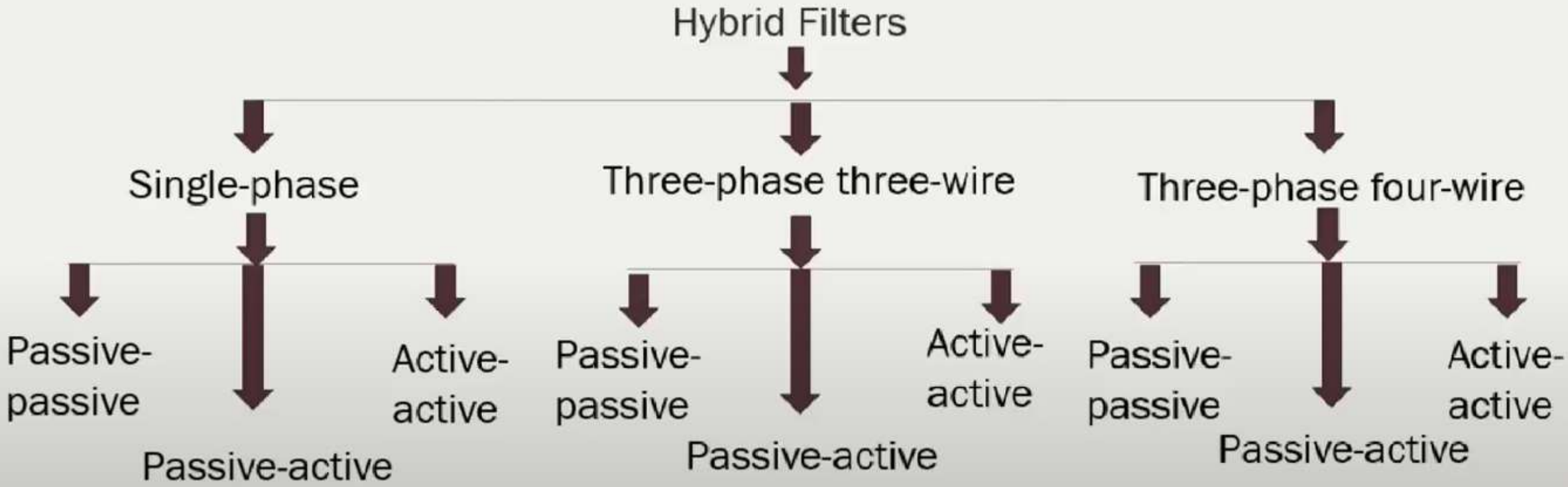


Fig. 4 Three-phase four-wire shunt active power filter with capacitor midpoint technology

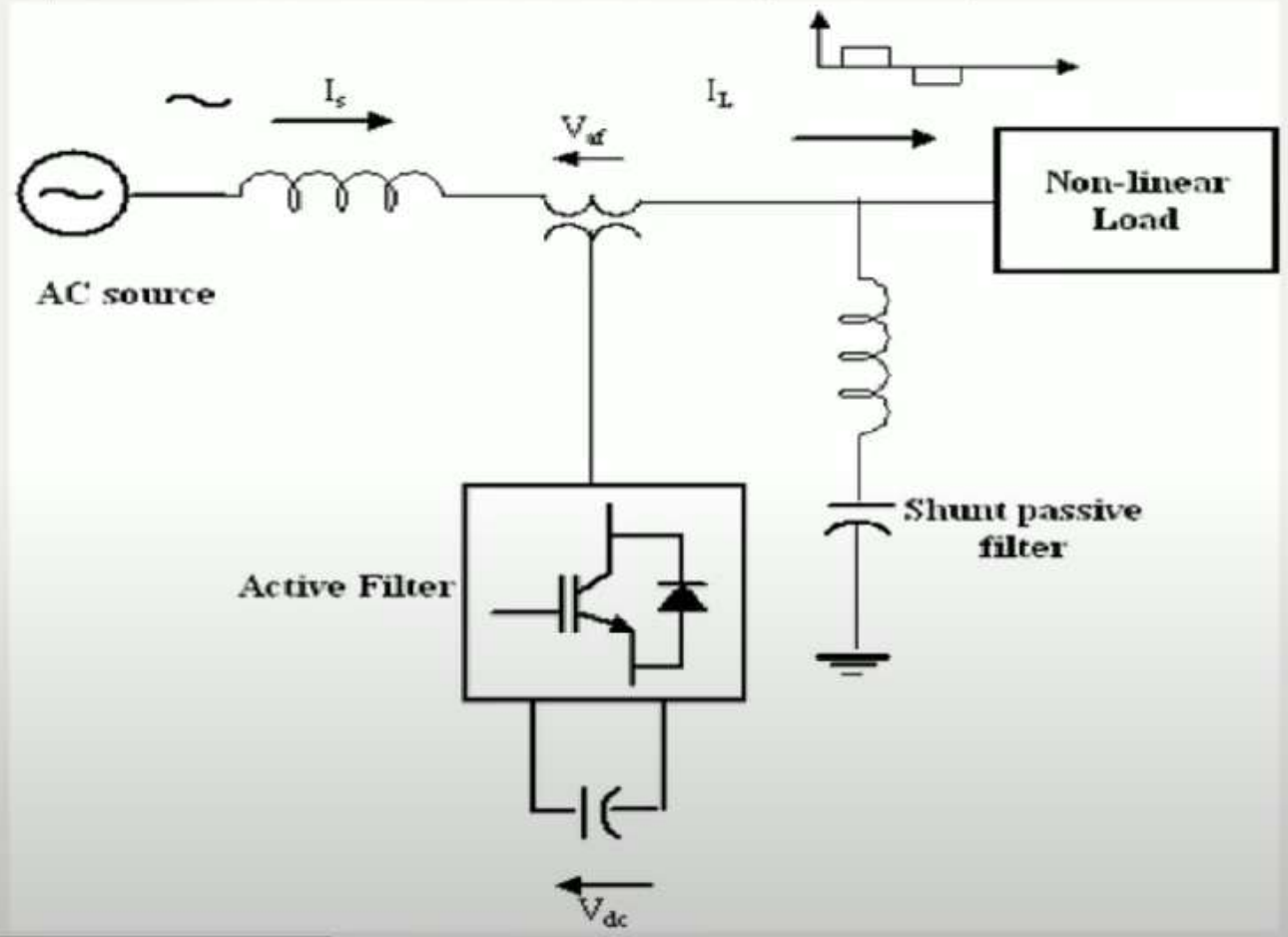
(3) HYBRID POWER FILTERS

- A series of hybrid power filters (HPFs) is evolved and extensively used in practice as a cost-effective solution for the compensation of nonlinear loads



Hybrid active power filter

- Used for compensation of high power systems
- Power rating of active power filter can be reduced significantly

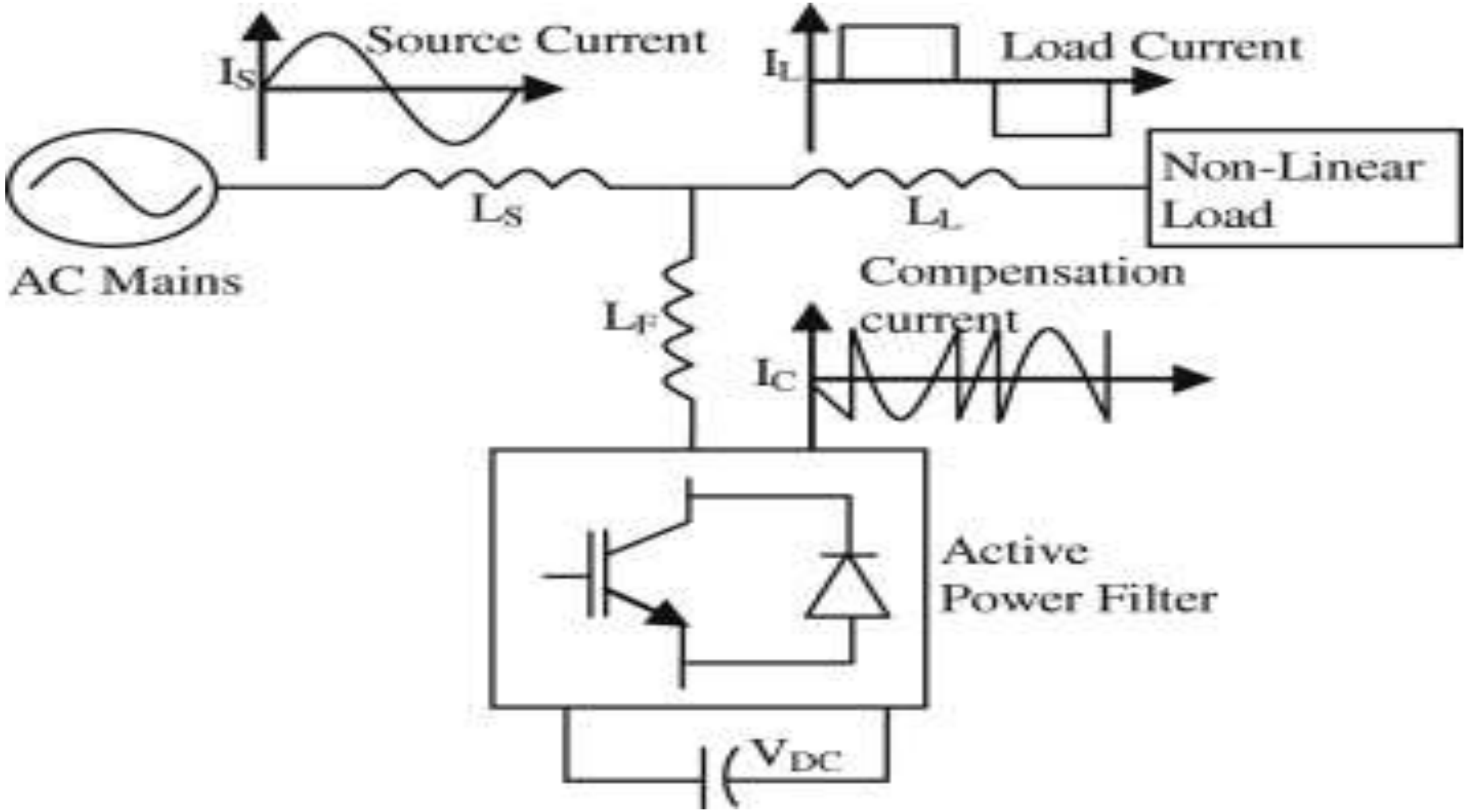


Passive filters

- A passive filter component is a combination of capacitors and inductors that are tuned to resonate at a single frequency, or through a band of frequencies. In power systems, passive filters are used to suppress harmonic currents and decrease voltage distortion appearing in sensitive parts of the system.
- Passive filters work by exhibiting different impedance values at the resonant frequency. A filter connected in series should present high impedance to the harmonic frequency that needs to be blocked. Although a series configuration is possible, it is more common to connect filters in parallel. Such a shunt configuration diverts harmonic currents to ground, and simultaneously provide reactive power, which may be used to correct the power factor. As such, passive shunt filters are designed to be capacitive at the fundamental frequency.

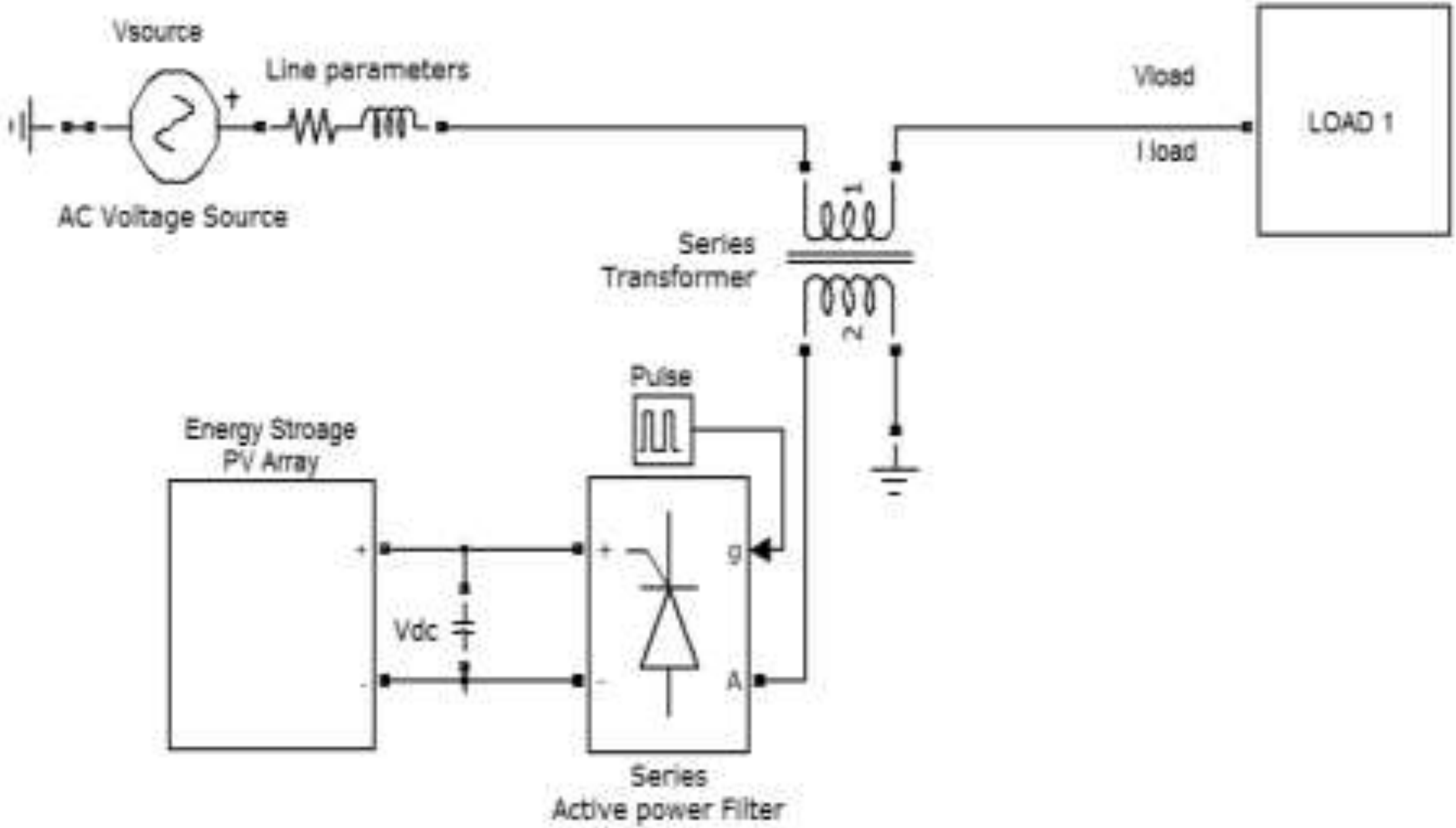
SHUNT ACTIVE POWER FILTERS:

- Shunt active power filters (APFs) are used to compensate the power quality problems of harmonic currents of various harmonics, such as characteristic harmonics, noncharacteristic harmonics, interharmonics, and subharmonics, reactive current, fluctuating current, unbalanced currents, and excessive neutral current produced by nonlinear loads. These shunt APFs offer the best solution for current-fed type and mix of current-fed and voltage-fed types of nonlinear loads with moderate rating. PWM-based voltage source inverters (VSIs) are preferred to realize shunt APFs because of low cost, reduced size, light weight, and reduced losses. The shunt APFs are classified on the basis of the supply system into three major categories, which include single-phase two-wire, three-phase three-wire, and three-phase four-wire APFs. An analytical study of various performance indices of shunt APFs for the compensation of nonlinear loads is made in detail with several numerical examples to study the rating of power filters and how it is affected with the nature of various kinds of nonlinear loads. Shunt APFs are observed as one of the best retrofit solutions for mitigating the power quality problems due to nonlinear loads for reducing the pollution of AC mains.


Source Current
I_S
I_L
Load Current
Non-Linear
Load
L_S
L_L
AC Mains
L_F
Compensation
current
I_C
Active
Power Filter
V_{DC}

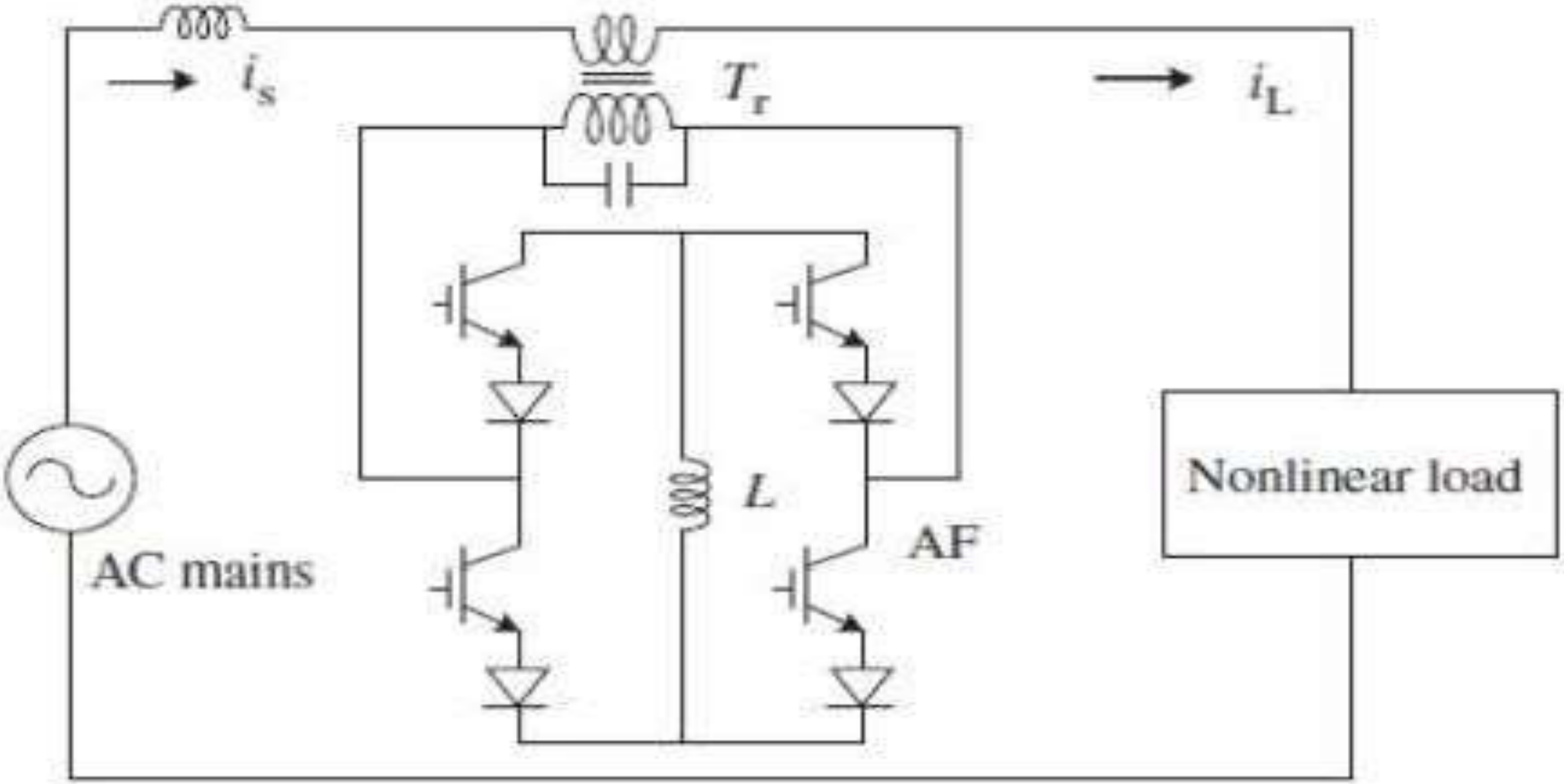
SERIES ACTIVE POWER FILTER:

- SERIES ACTIVE POWER FILTER SAPF injects a voltage component which is connected in series with the supply voltage, thus compensating the voltage sags and swells on the load side. Control response is of the order of 3msec, ensuring a secure voltage supply under transient conditions. The main function of a SAPF is the protection of sensitive loads from voltage sags/swells coming from the network. The SAPF is located on the basis of sensitive loads. If a fault occurs on other lines, DVR inserts series voltage and compensates load voltage to pre fault value. The momentary amplitudes of the three injected phase voltages are controlled in such a way to eliminate any detrimental effects of a bus fault to the load voltage.

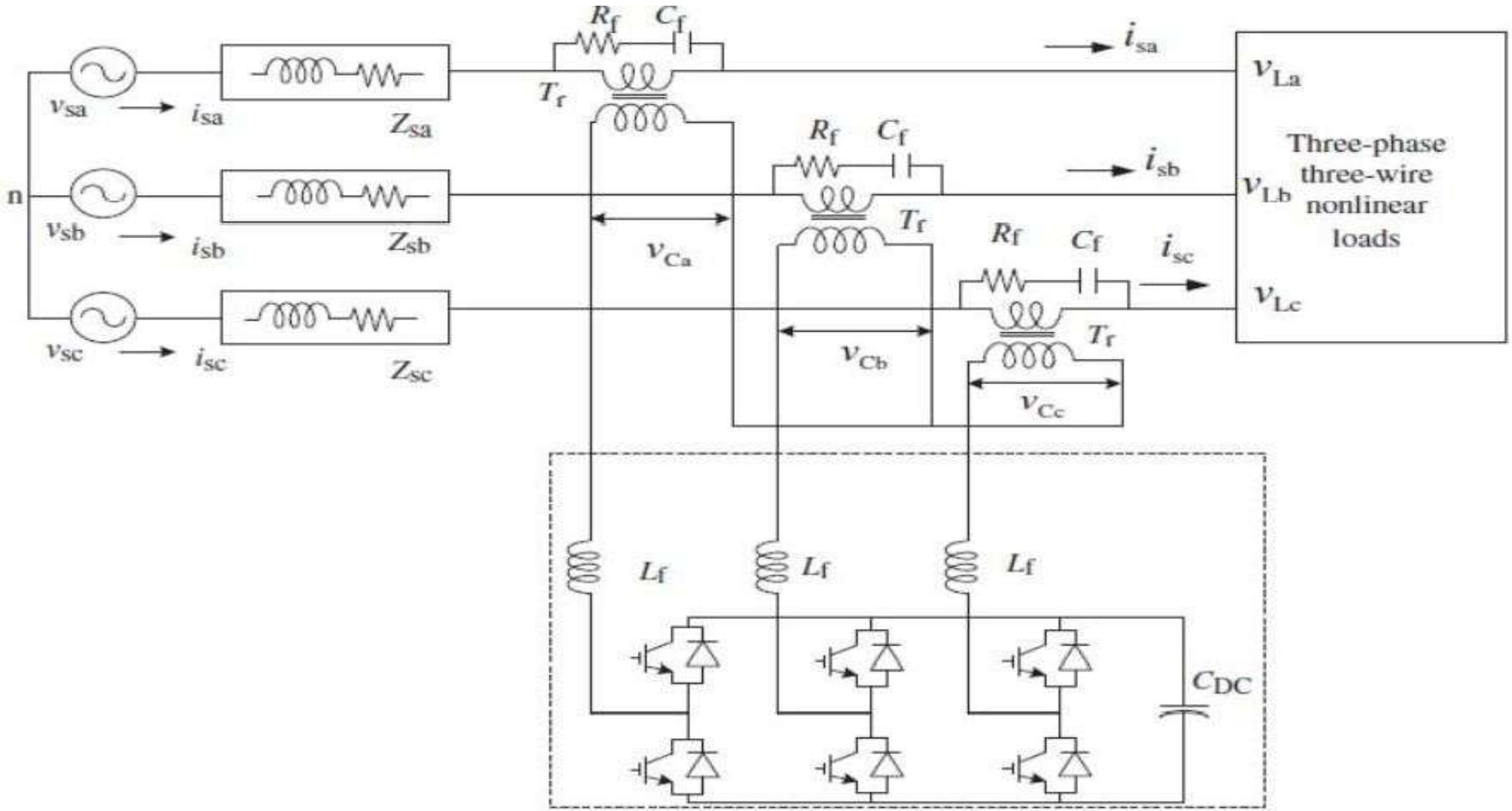

Vsource
Line parameters
AC Voltage Source
Vload
I load
LOAD 1
Series
Transformer
Pulse
Energy Stroage
PV Array
Vdc
g
A
Series
Active power Filter

Series Active Power Filters

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

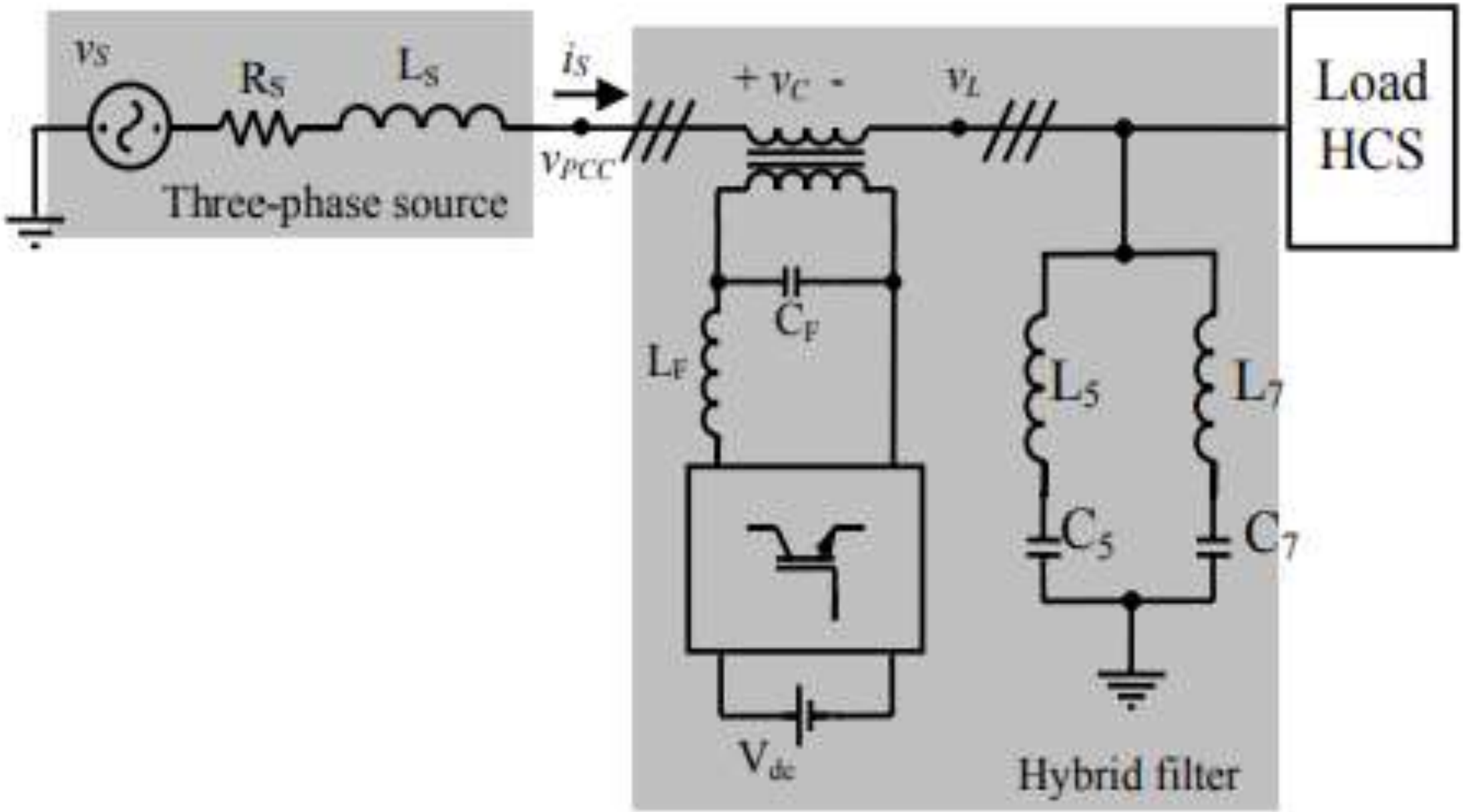

i_s
T_r
i_L
L
AF
AC mains
Nonlinear load

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

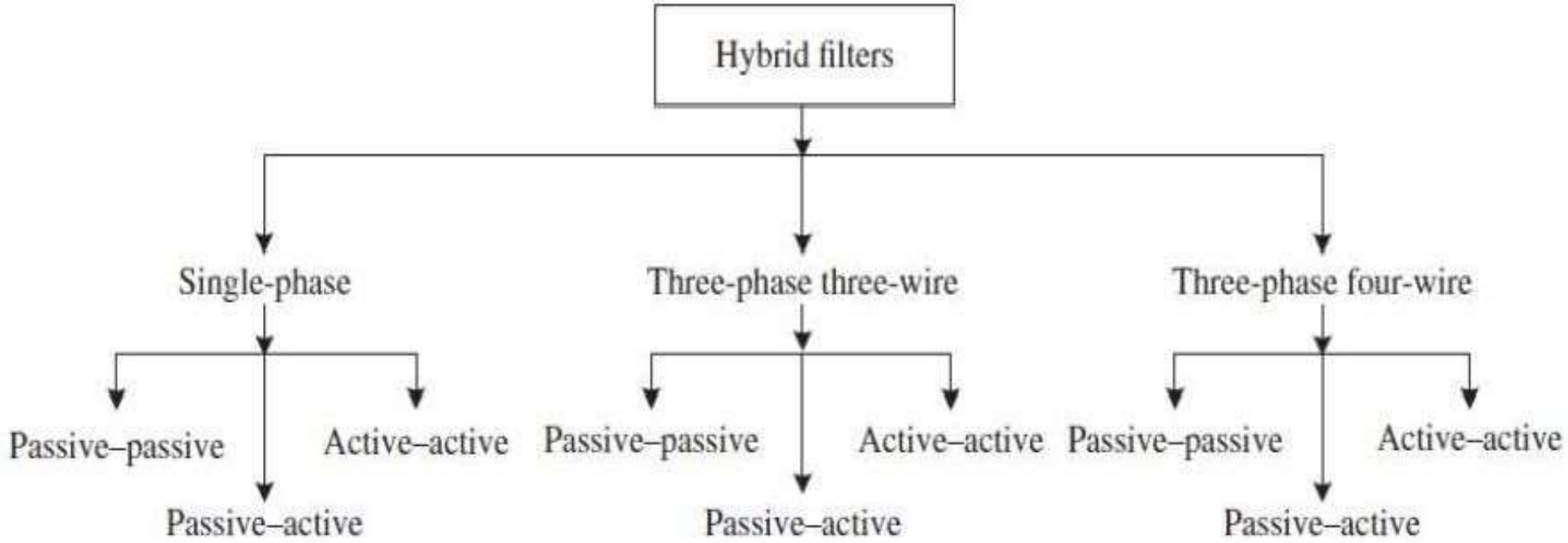

n
v_{sa}
i_{sa}
Z_{sa}
v_{sb}
i_{sb}
Z_{sb}
v_{sc}
i_{sc}
Z_{sc}
R_f
C_f
T_f
v_{Ca}
v_{Cb}
v_{Cc}
L_f
C_{DC}
v_{La}
v_{Lb}
v_{Lc}
Three-phase three-wire nonlinear loads

Hybrid Active Power Filter:

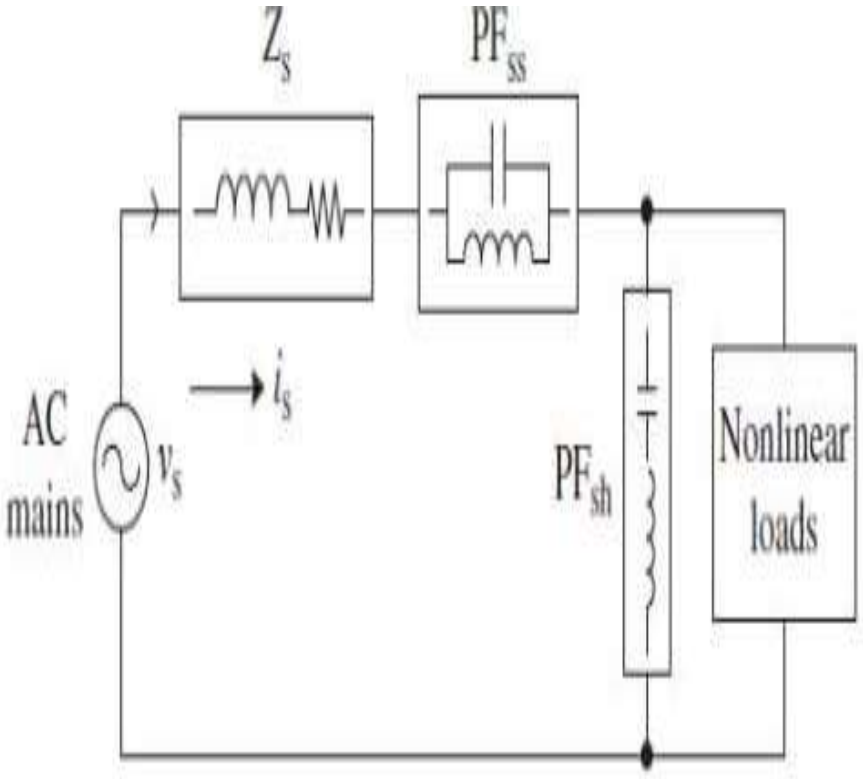
- HCS type nonlinear load and a SAPPF hybrid filter. The source impedance is constituted by a resistance RS and an inductance LS. The active power filter is connected in series with the source through a coupling transformer. The passive filter is connected in parallel with the load. It consists of two LC branches tuned to 5th and 7th current harmonics.


v_S
R_S
L_S
i_S
v_{PCC}
Three-phase source
+ v_C -
v_L
Load
HCS
C_F
L_F
L_5
L_7
C_5
C_7
V_{dc}
Hybrid filter

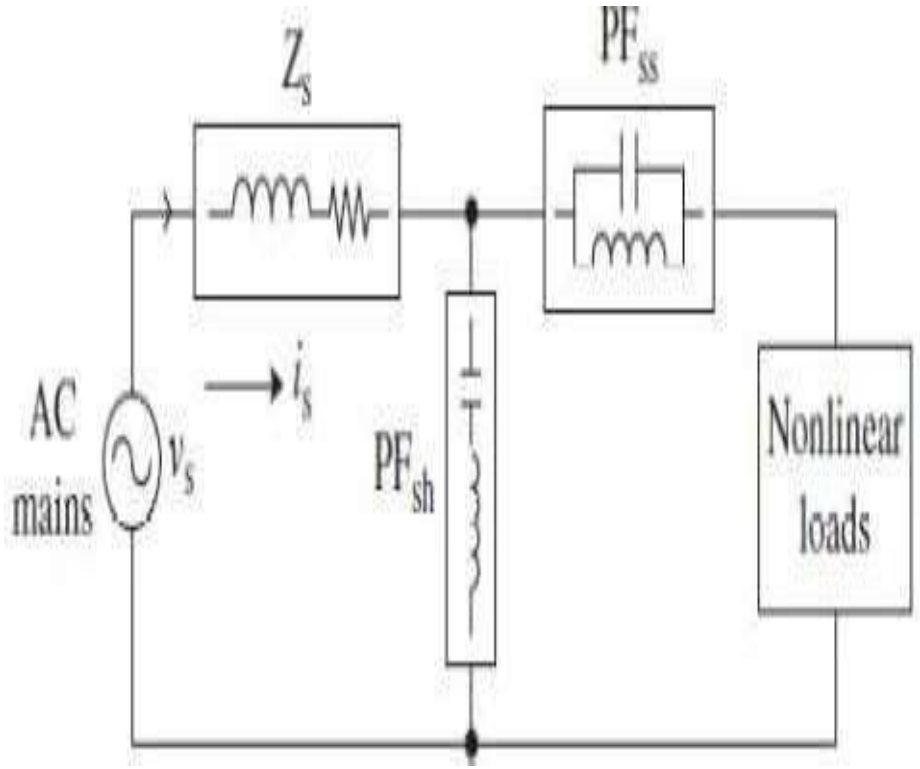
Hybrid Active Power Filter



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



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



UNIT - 5

AC–DC Converter-Based AC–DC Converter-Based

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

Power Quality problems improvement

- Power quality management is major issue today. Power conversion ac-dc and power quality suffers from operating problems of poor power factor, injection of harmonics into the ac mains, variations in dc link voltage of input ac supply, equipment overheating. In power system harmonic cause is normal problem that is increase losses and stability of electric system. Due to ac-dc conversion is harmonic current absorption, voltage distortion due to the voltage drop caused by harmonic currents flowing through system impedances. Here is proposed 3 Leg ac-dc converters, which are improved power quality ac- dc converters. Proposed system is control output dc voltage by varying the modulation index. Here used PID controller-based control system which control voltage and current variation through inject 3rd Harmonic Injection. The main emphasis of this investigation has been on a compactness of configurations, simplicity in control, reduction in rating of components, thus finally leading to saving in overall cost. In this is based on varying R load.

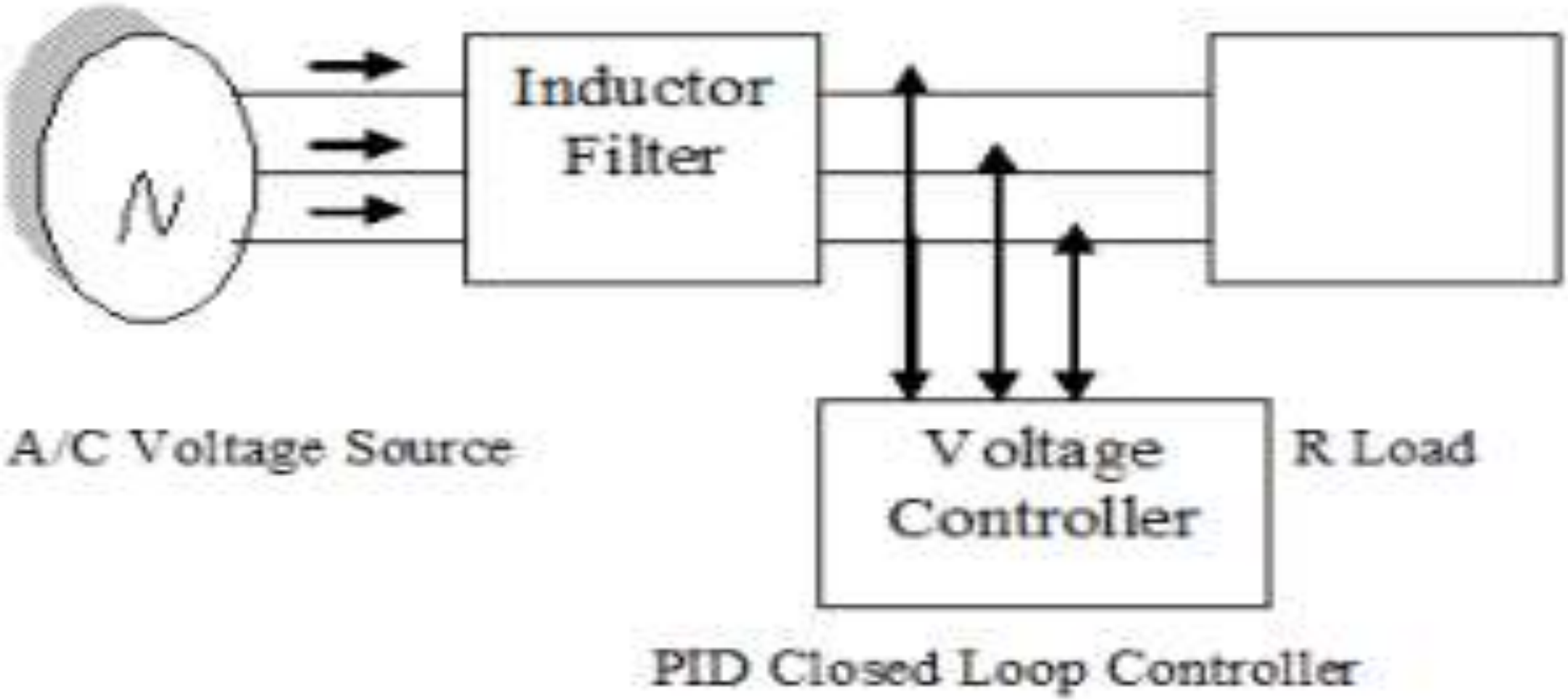


Fig. 1: Block diagram 3 phase AC-DC Converter

Power Quality converters

- The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the RMS value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows,

Power quality improvement in electrical applications:

- Majority of power quality problems are mainly caused by the use of nonlinear loads. The nonlinear loads draw non-sinusoidal current from AC mains, which consists of various harmonic currents such as characteristic harmonics, non characteristic harmonics, inter harmonics, sub harmonics, reactive power component of current, fluctuating current, unbalanced currents, and so on. These nonlinear loads are classified into different categories considering the severity of the created problems. A number of practical examples of these nonlinear loads are given to have a proper exposure of power quality problems. An analytical study of various performance indices of these nonlinear loads is made in detail with several numerical examples to study the level of power quality they may cause in the system. Since these nonlinear loads cannot be dispensed due to many economic advantages, energy conservation, and increase in production; therefore, it is quite important to study the behavior of these nonlinear loads to find out proper mitigation techniques for power quality improvements to reduce the pollution of the supply system.