INDEX

NAME: G. VIJAYA AP/EEE ROLL NO:

SUBJECT: EE3006 & Power Quality STD: III Y DIV: V Sem

SCHOOL: DMI College of Engineering

SR.NO.	DATE	TITLE	PAGE NO.	SIGNATURE

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** **(7+2 Skill) 9**

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 (7+2 Skill) 9

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 (7+2 Skill) 9

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 Plots for a Three-Branch 33 kV Filter.

UNIT IV LOAD COMPENSATION USING DSTATCOM (7+2 Skill) 9

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 (7+2 Skill) 9

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

TOTAL : 45 PERIODS

SKILL DEVELOPMENT ACTIVITIES (Group Seminar/Mini Project/Assignment/Content Preparation / Quiz/ Surprise Test / Solving GATE questions/ etc) 10

1. Harmonic analysis of single phase power converters (Semi converters and Full Converters) with R and RL load via simulation
2. Harmonic analysis of three phase power converters (Semi converters and Full Converters) with R and RL load via simulation
3. Harmonic analysis of single phase inverters with R and RL load via simulation
4. Harmonic analysis of three phase inverters with R and RL load via simulation
5. Mitigation of Harmonics using Tuned Filter

List of Open Source Software/ Learning website:

1. http://nptel.iitm.ac.in/courses.php
2. https://old.amu.ac.in/emp/studym/2442.pdf
3. https://electricalacademia.com/electric-power
4. https://www.intechopen.com/books/6214
5. https://www.cde.com/resources/technical-papers/Mitigation-of-Harmonics.pdf
6. https://www.academia.edu/43237017/Use_Series_Compensation_in_Distribution_Networks_33_KV

EE3006 - Power Quality:

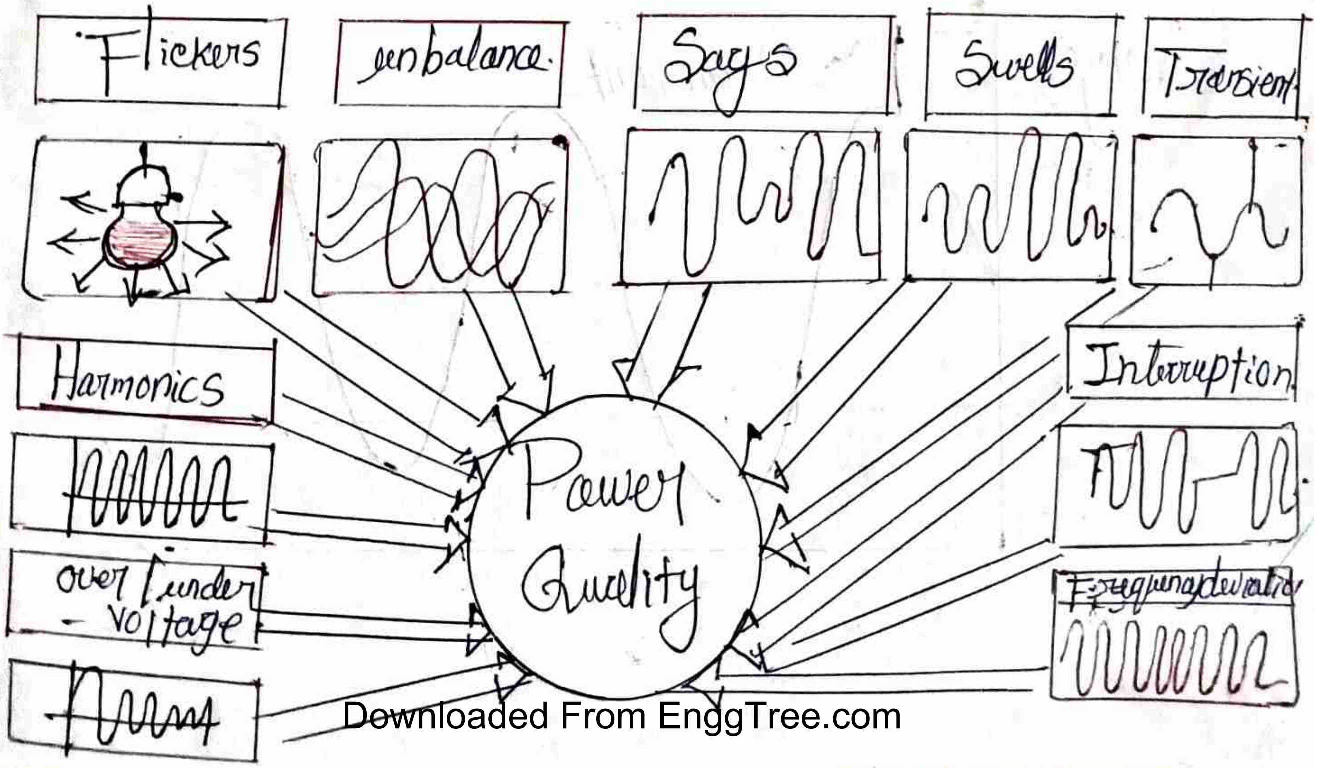
UNIT-1: Introduction:

Introduction - Characterisation of Electric power Quality: Transients, Short duration and long duration Voltage Variations. Voltage imbalance, waveform distortion, voltage fluctuation, power frequency Variation, power acceptability curves - Power quality Problem: Poor load power factor, Non linear and balanced loads, Dc offset in loads, Notching in load Voltage, Disturbance in Supply Voltage, Power Quality Standards.

Introduction: Power Quality:

Nowadays, the important of power Quality aspects has increased due to the booming development in power electronic devices and renewable energy resources under the umbrella Smart Grid Power Quality will play as essential role in Modern electrical Power System. Voltage Quality focus on Variations of Voltage from its ideal waveform (i.e characterized by sine wave of constant Magnitude and frequency), while current Quality is concerned with the deviation of the current from the ideal Sinusoidal waveform.

Component of Power Quality problem:



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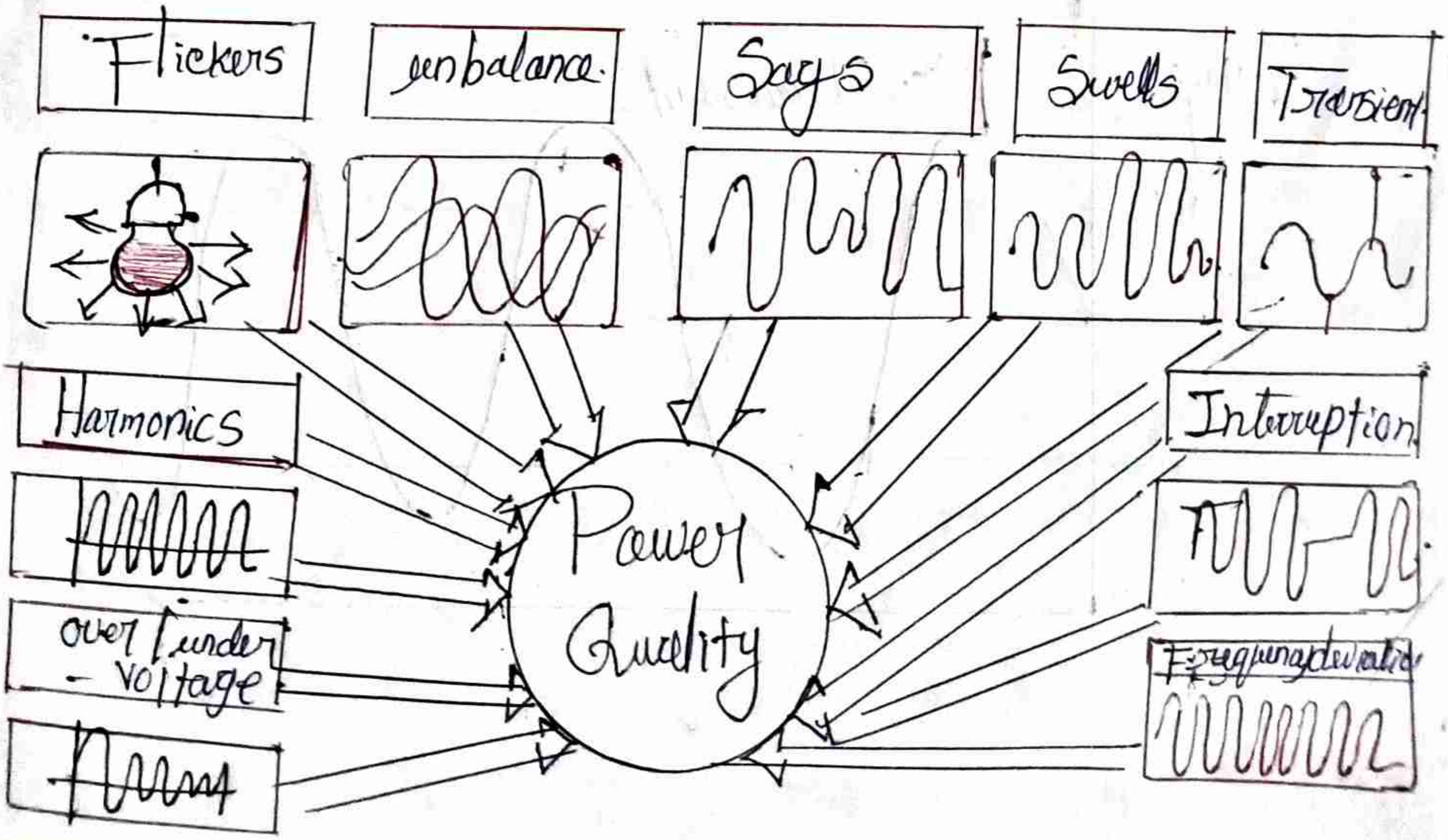


Characterization of Electric Power Quality:

Transient:

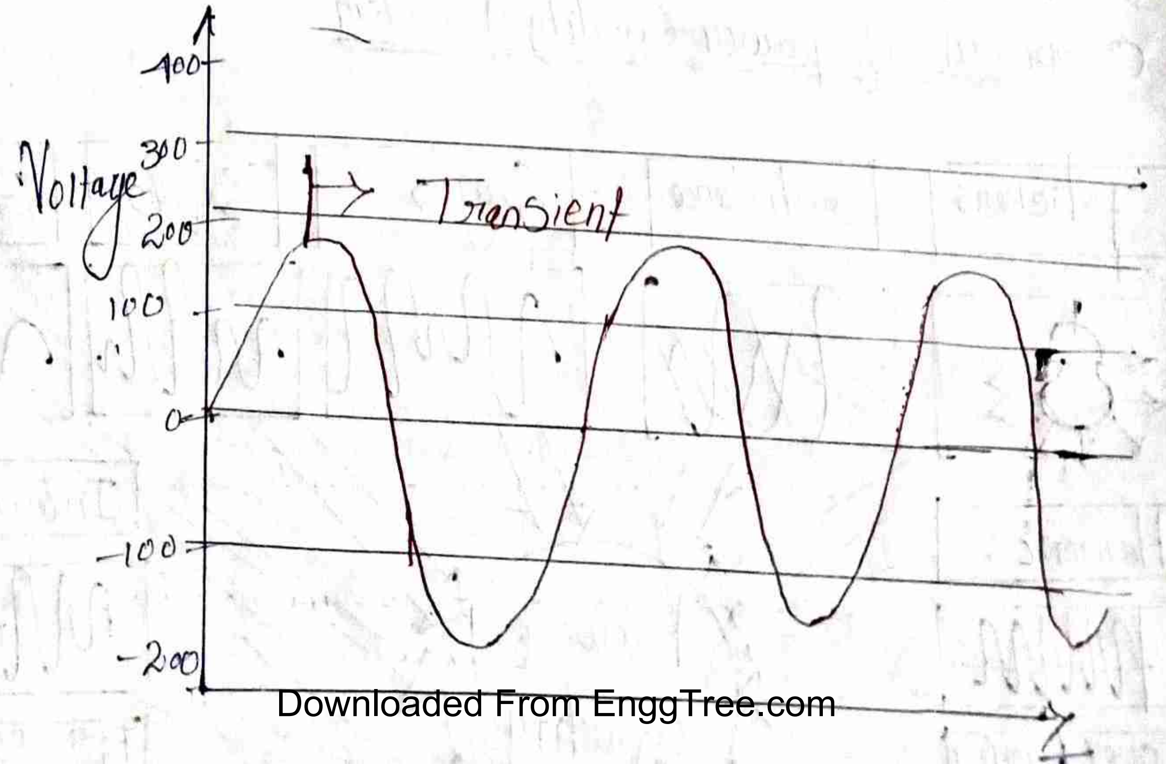
Transient over voltages in electrical transmission and Distribution Networks results from the unavoidable effect of lightning strike and network switching operations. Response of an electrical Network to a Sudden Change in network condition.

Types of Transient:

1. Impulse transient.
2. Oscillatory transient.

Impulse Transient:

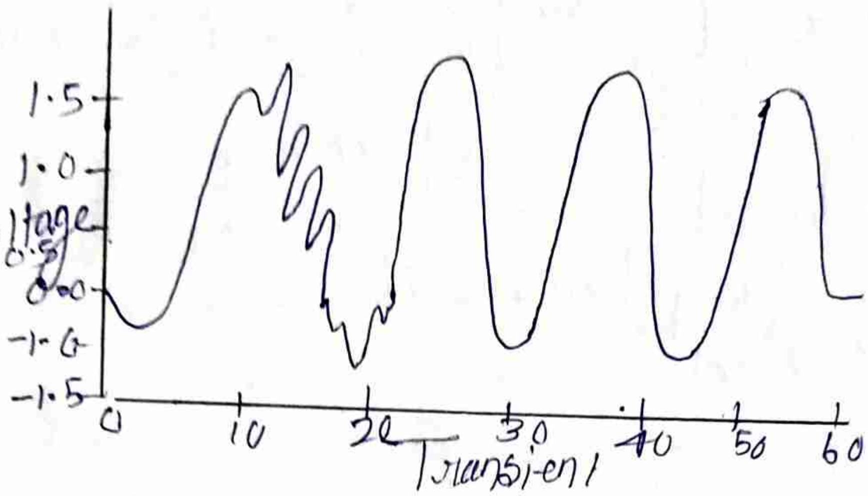
A Sudden, non power frequency change in the Steady State condition of voltage or current that is unidirectional in polarity as shown in figure.



2) Impulse Transient

1. Oscillatory Transient:

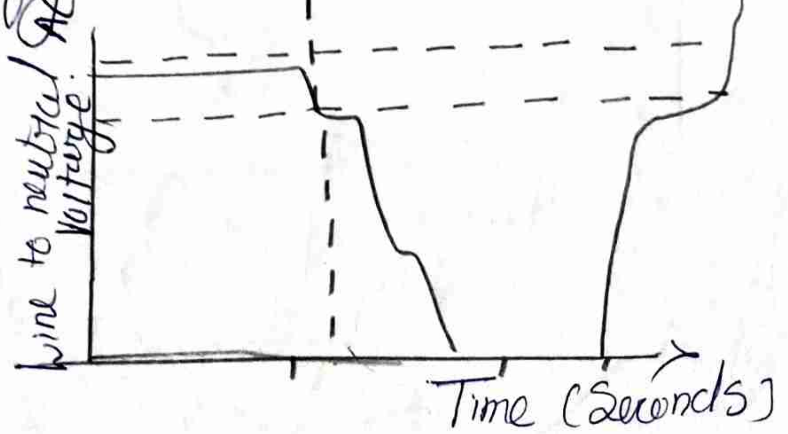
A Sudden, non power frequency change in the steady state condition of voltage or current that is bidirectional in polarity as shown in figure.

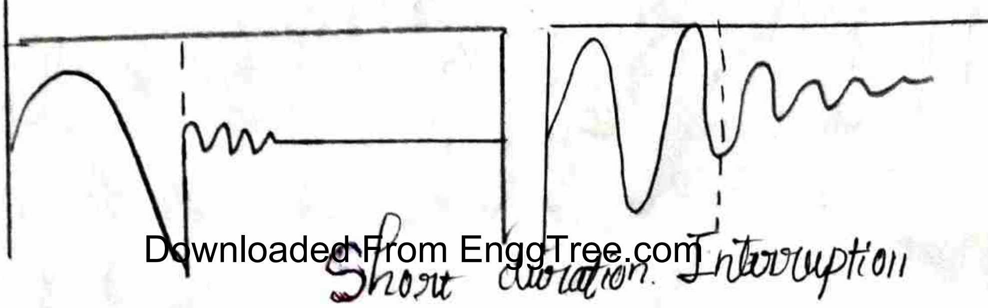


Oscillatory transient.

Short duration Voltage Variation:

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



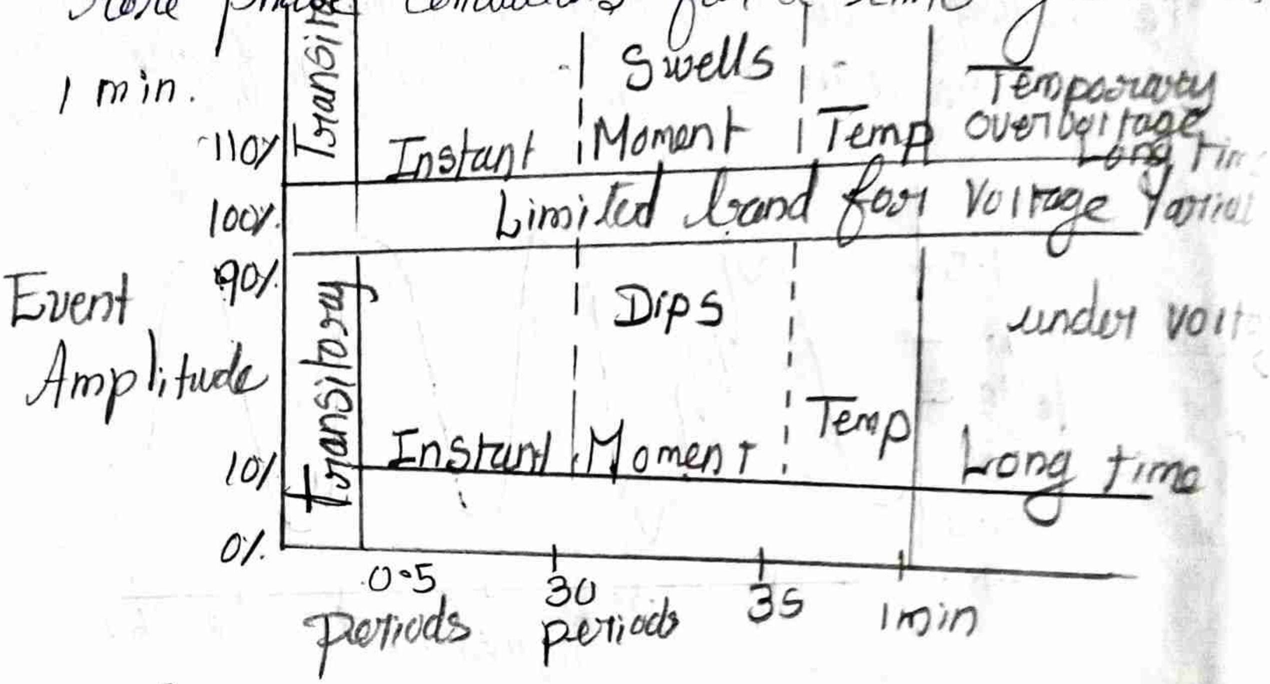


Short duration Interruption

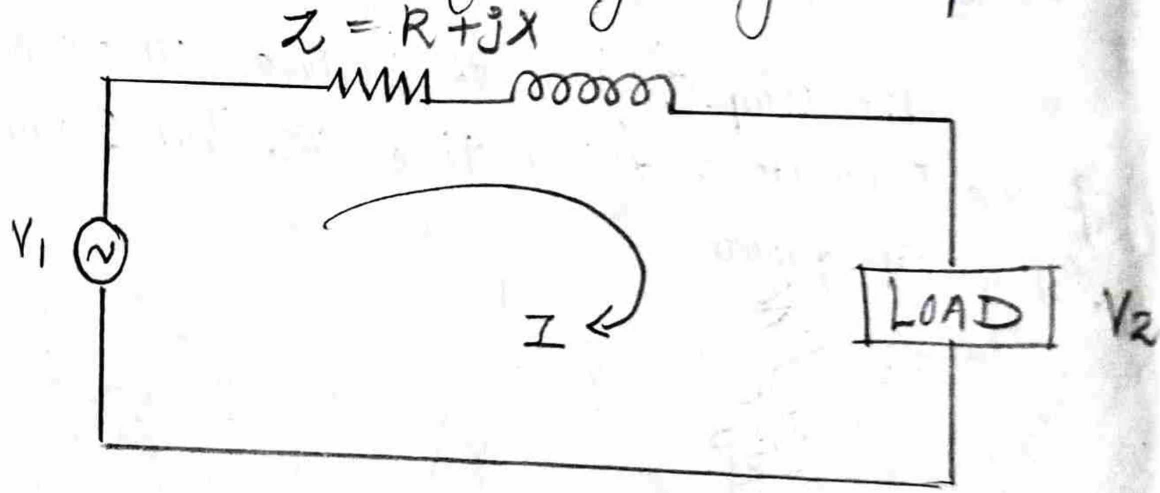
Characterization of Electric Power Quality:

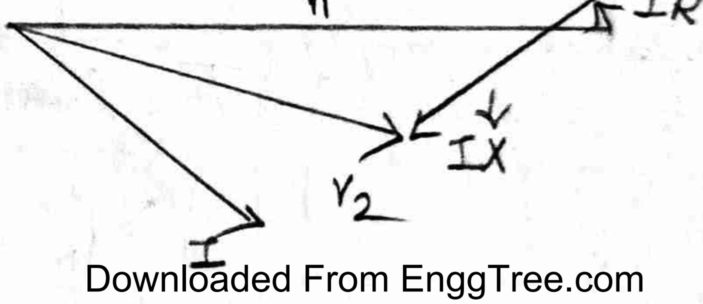
Long Duration Voltage Variation:

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



The Voltage drop across the System impedance is the root cause of Voltage regulation problem





The Variation of the RMS Value of Voltage from its normal nominal Values for a time greater than 60 Seconds is called Long duration Variation. These Variations are further described by using magnitude of Voltage Variation.

- under Voltage
- over Voltage
- Sustained Interruption.

under Voltage:

undervoltage decrease in RMS ac Voltage to less than 90% at the power frequency for duration longer Than 60 Seconds. These can be caused by Switching on a large load or Switching off a large capacitor bank undervoltage will lower the output from capacitor banks

An undervoltage will lower than the output from capacitor bank that utility or customer will often install to help maintain Voltage and reduce losses in the System by Compensating for the inductive nature of many conductors and loads.

overvoltage:

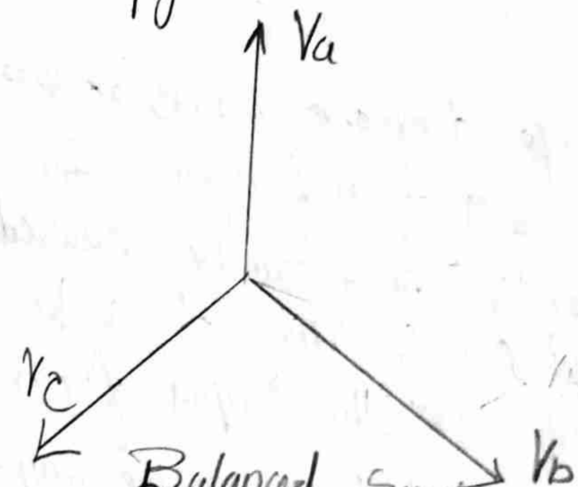
An overvoltage is an increase in the RMS ac Voltage to a level greater than 110% at the power frequency for duration longer than 60 Seconds. These are caused by Switching off a large load or energizing a Capacitor bank.

Sustained Interruption:

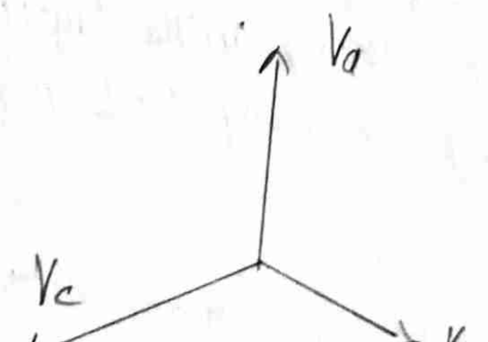
It is helpful to a distinguish the term outage used in reliability terminology from Sustained Interruption when the Supply Voltage is zero for longer than 1 min.

Voltage Imbalance:

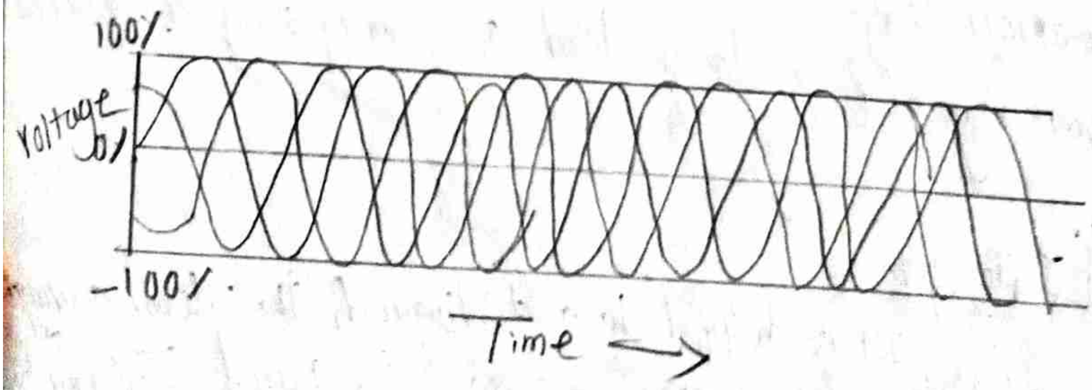
In a balanced Sinusoidal Supply System the three line – neutral Voltages are equal in Magnitude and are phase displaced from each other by 120 degree as shown in figure. Any differences that exist in the three Voltage Magnitude and/or a Shift in the phase Separation from 120° degree is said to give rise to an unbalanced Supply as illustrated in figure.



Balanced System



unbalanced System



The utility can be the source of unbalanced voltages due to malfunction 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 transformation. Also voltage unbalance can also be caused by uneven single-phase load distribution among the three phases - the likely culprit for a voltage unbalance of less than 2%. Furthermore severe case (greater than 5%) can be attributed to single-phasing in the utility distribution labor feeders because of a blown fuse due to fault or overloading on one phase.

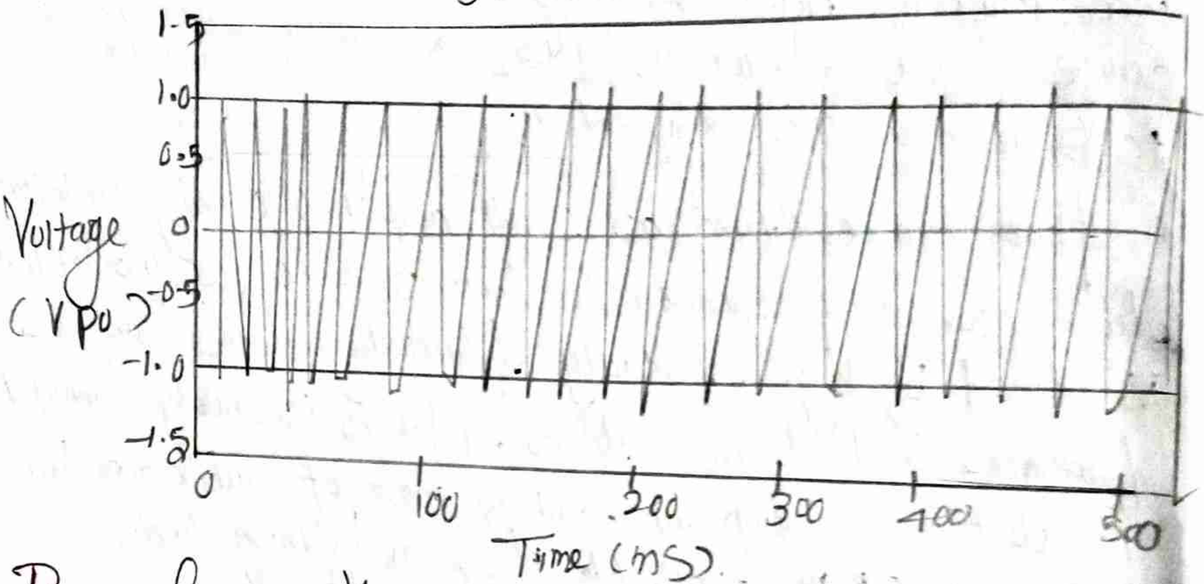
Waveform Distortion:

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

- Dc offset
- Harmonics
- Inter Harmonics.
- Notching.
- Noise.

a) Dc offset: The presence of a dc voltage or current in an ac power system is termed dc offset. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters. Incandescent light bulb life extenders, for example, may consist of diodes that result of reduce RMS voltage supplied to the light bulb by half wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer core so they saturate in normal operation.

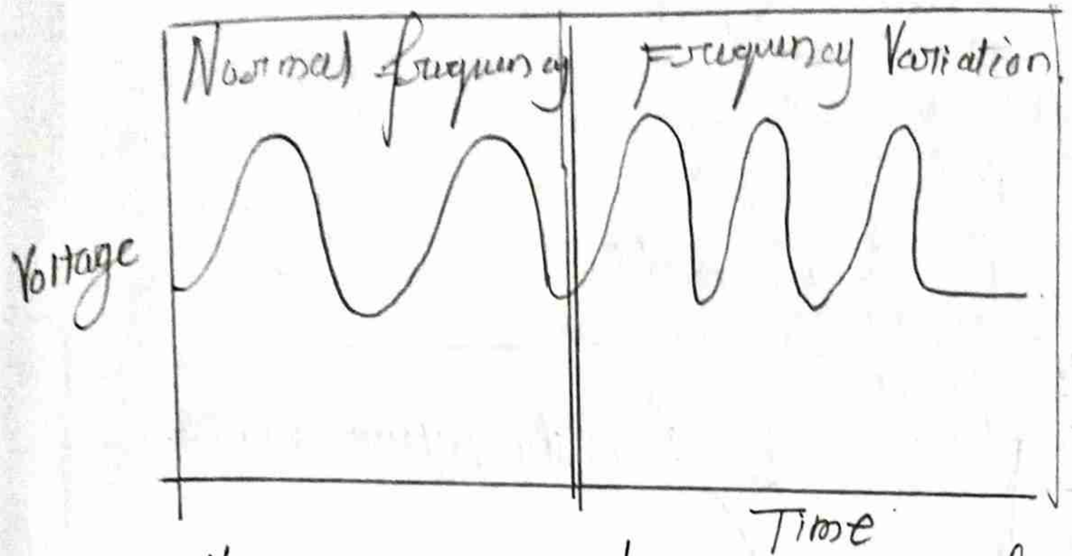
Any load that has significant current variations, especially in the reactive component, can cause voltage fluctuations. Loads that exhibit continuous, rapid variations in load current magnitude can cause voltage variations erroneously referred to as flicker. Arc furnace are the most common cause of voltage fluctuations on the transmission and distribution system which is shown in figure.



Power frequency Variation:

Power frequency variation are a deviation from the normal supply frequency (50 Hz to 60 Hz) The supply frequency is a function of the rotational speed of the generators used to produce the electrical energy.

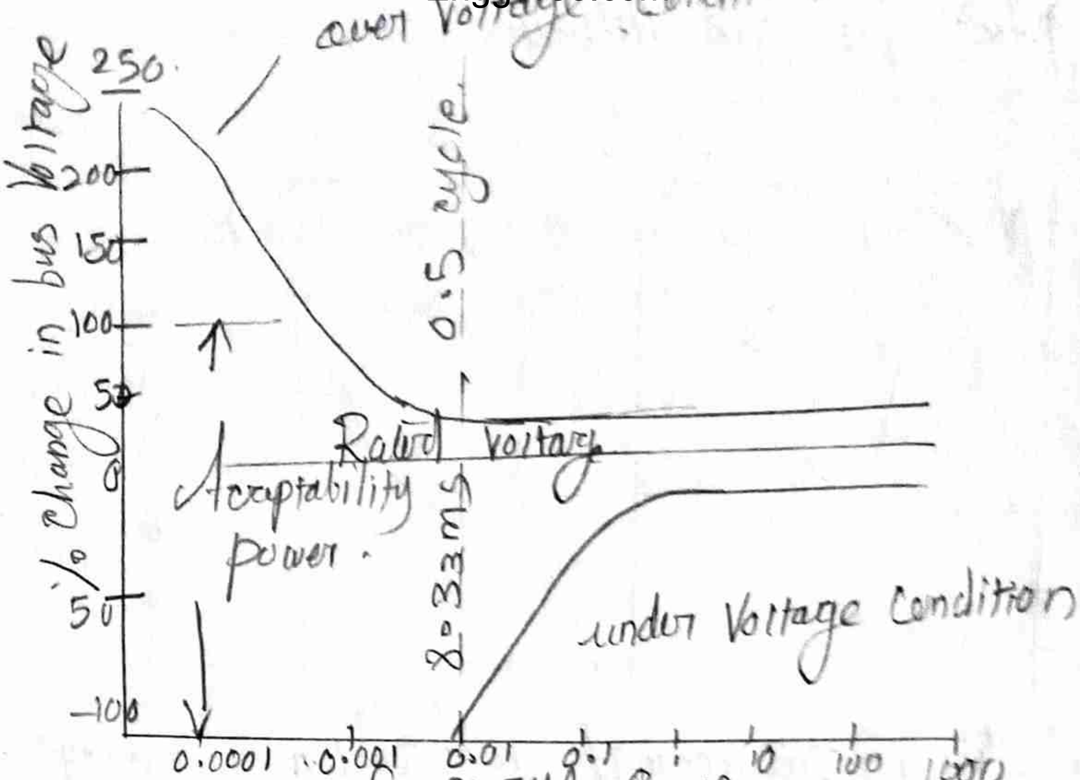
At any instant, the frequency depends on the balance the load and the capacity of the available generation. A frequency variation occurs if a generator becomes un-synchronous with the power system. Causing an inconsistency that is manifested in the form of a variation. The specified frequency variation should be with in the limits of ± 2.5%. Hz at all times for grid Network.



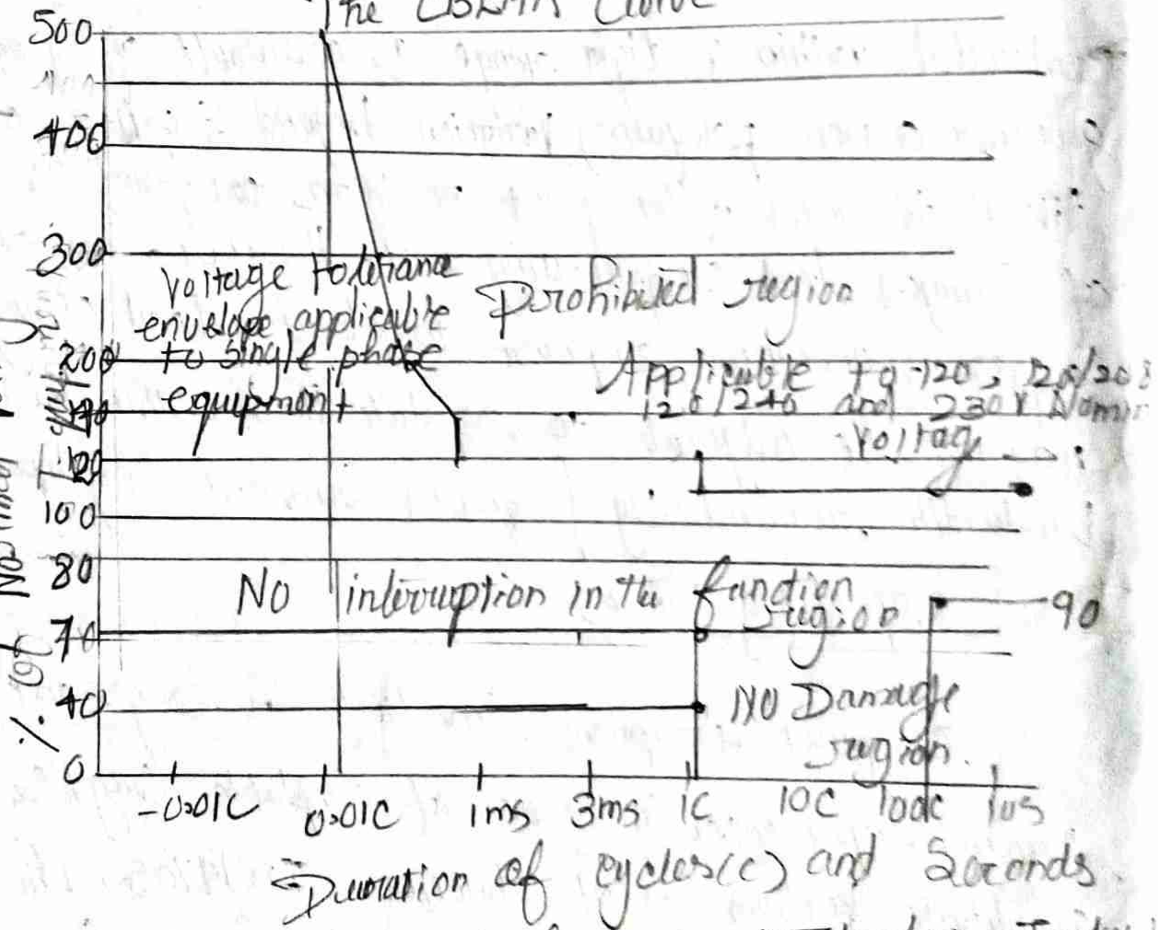
In Modern Interconnected power System. frequency is controlled within a tight range as a result of good governer action. frequency Variation beyond ±0.1Hz are likely to occur under fault conditions for form the loss of a major load or generating unit. However, an isolated system, governor response to abrupt load change may not be adequate to regulate them within the narrow bandwidth required by frequency Sensitive equipment.

Power acceptability curves:

Computer equipment Sensitivity to Sags and Swells can be represented in curves of acceptable Sag/Swells amplitude Versus event duration. In 1970s, The computer Business Equipment Manufactures Association (CBEMA) developed the curve of Figure employing historical data from mainframe Computer operations. Showing the range of acceptable power Supply Voltage for computer equipment The horizontal axis Shown the duration of the Sags or Swell and the Vertical axis Shown %line V



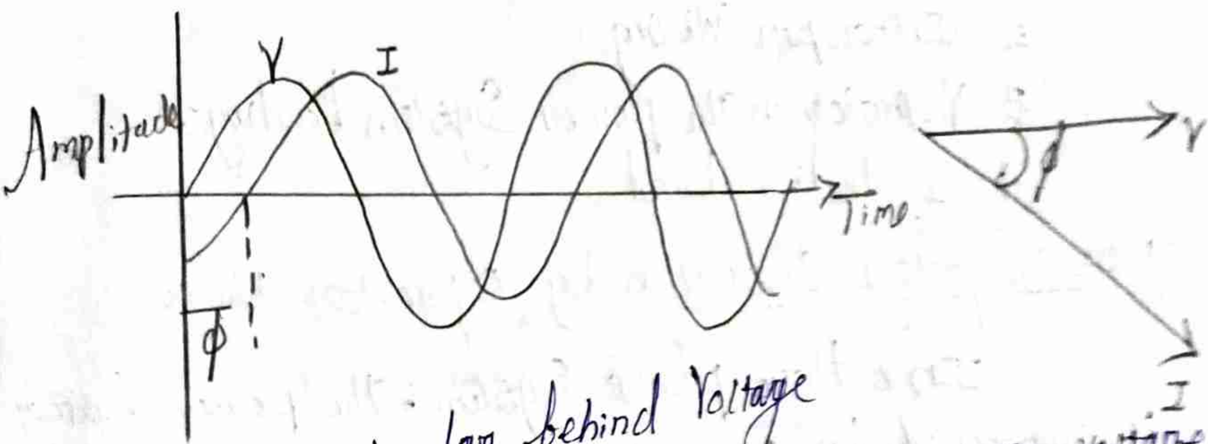
The CBEMA Curve



In the 1990s, the information Technology Industi. council (ITIC) curve was developed by a working group of CBEMA. In recent years, the ITIC cur. has replaced the CBEMA curve in general usage for single phase supply system.

Power Quality problem: Poor Load Power factor:

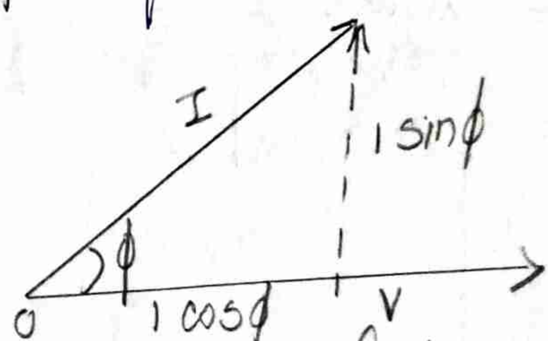
A low power factor means a higher load current than necessary and accompanying higher line losses. Inductive loads are the main cause of a low p.f with inductive Motors are the main major contributors. under operating conditions a Motor May often be operating underloaded due to one or More of the following reasons:



Current lag behind Voltage

In a circuit when the current lags behind the voltage then the power factor of the circuit is known as a lagging power factor. The power factor lags when the circuit is Inductive load. Load such as coils, motors and lamps are inductive and lagging power factor.

Power factor Triangle:



Power factor = cosϕ

VI sinϕ = Reactive power in VAR

VI cosϕ = Active power (in watts)

VI = Apparent power (VA)

Power factor

Power factor = cos φ = Active power (W) / Apparent power (VA)

Effects of Low power factor

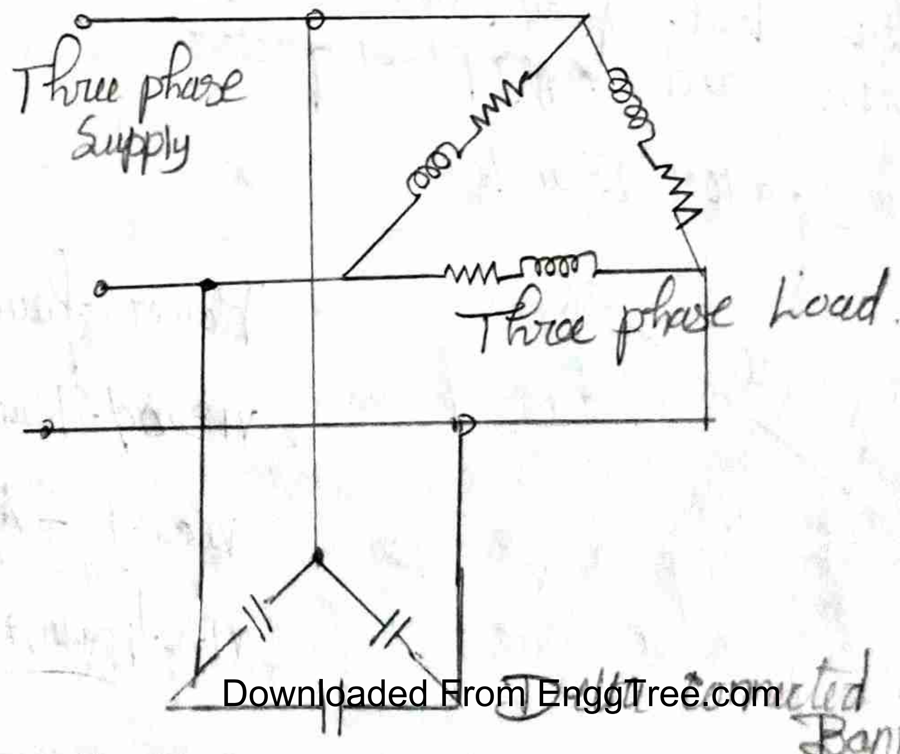
1. Large Copper Losses
2. Large KVA rating [KVA = KW / cos φ]
3. poor Voltage regulation.

Causes of Low power Factor:

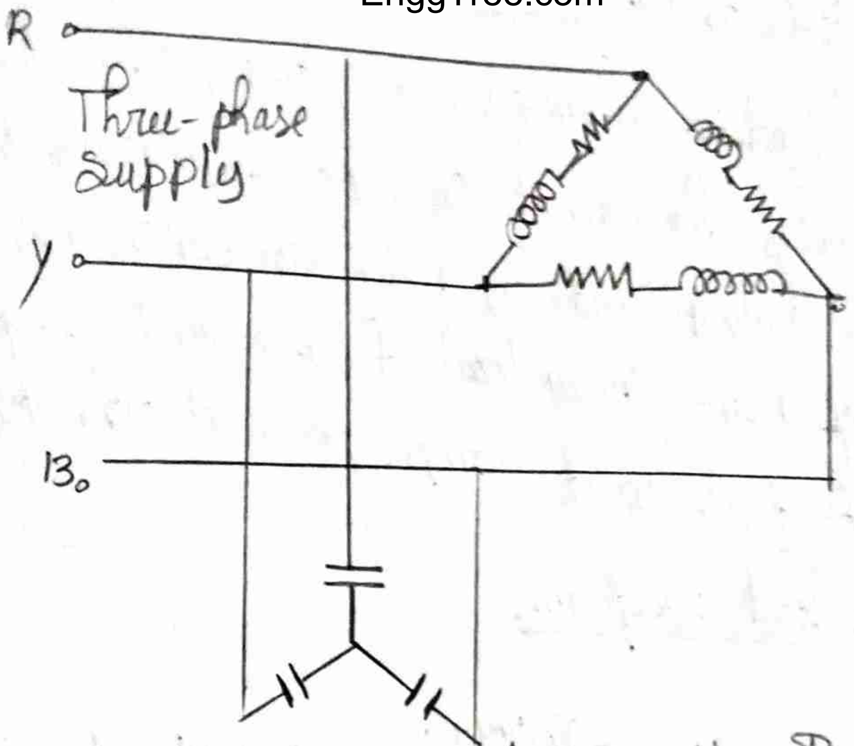
1. Harmonic Current
2. Improper Wiring
3. Variation in the power System Loading.
4. Inductive Load

Power factor Correction by capacitor Bank:

In a three phase System, the power factor is improved by connecting capacitors in Star or delta. The Star and delta connections of the Capacitor banks are shown in diagram below.



Delta Connected Capacitor Bank



Star connected Capacitor Bank

V_L - Line Voltage

C_Y — Capacitance per phase connected in stars

C_Δ - Capacitance per phase Connected in Delta.

Q_C = Var rating of each phase.

V_P = phase Voltage.

Delta Connection:

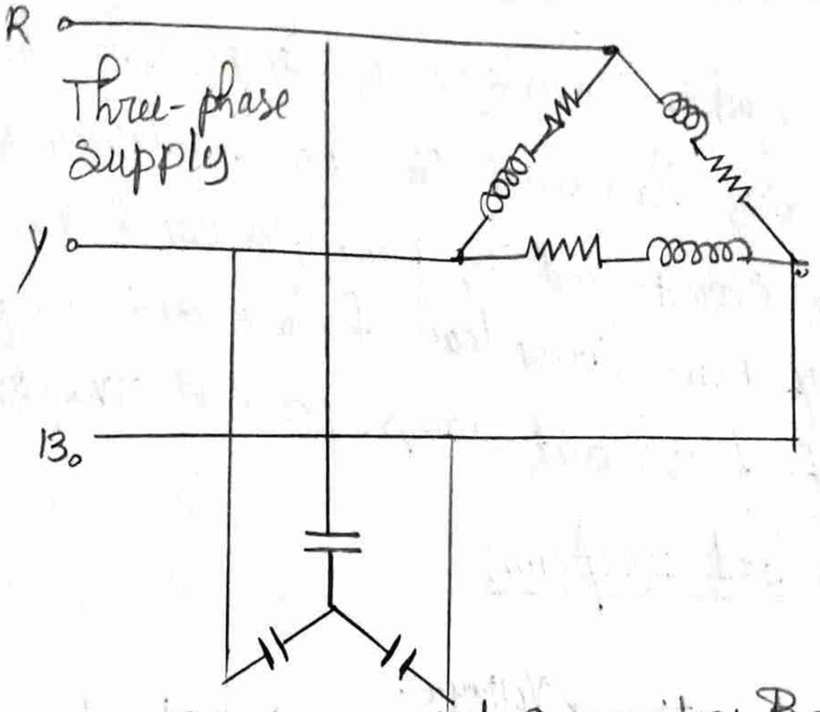
$$V_P = V_L$$

$$C = \frac{Q_C}{\omega V_P^2} = \frac{Q_C}{\omega V_L^2}$$

Star Connection:

$$V_P = \frac{1}{3} V_L$$

$$C_Y = \frac{Q_C}{\omega V_P^2} = \frac{Q_C}{\omega \left(\frac{V_L}{\sqrt{3}}\right)^2} = \frac{3 Q_C}{\omega (V_L)^2}$$



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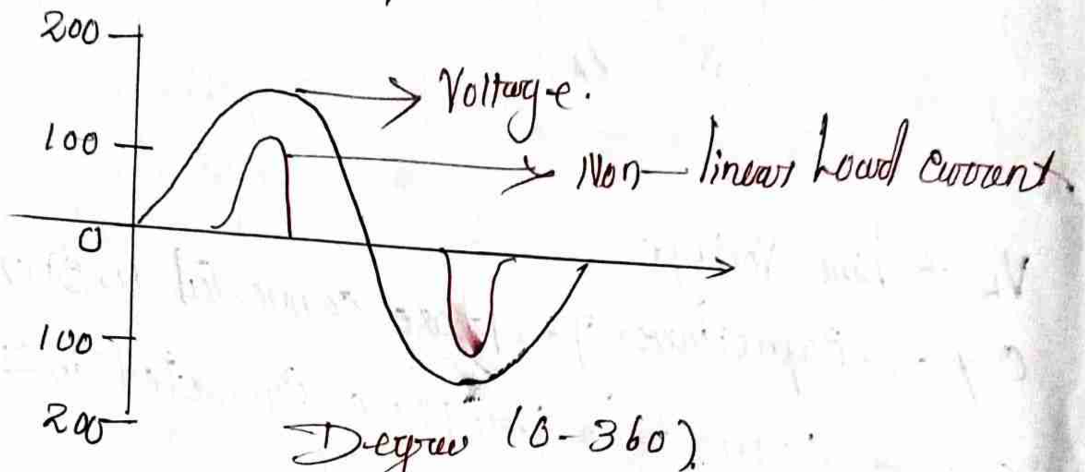
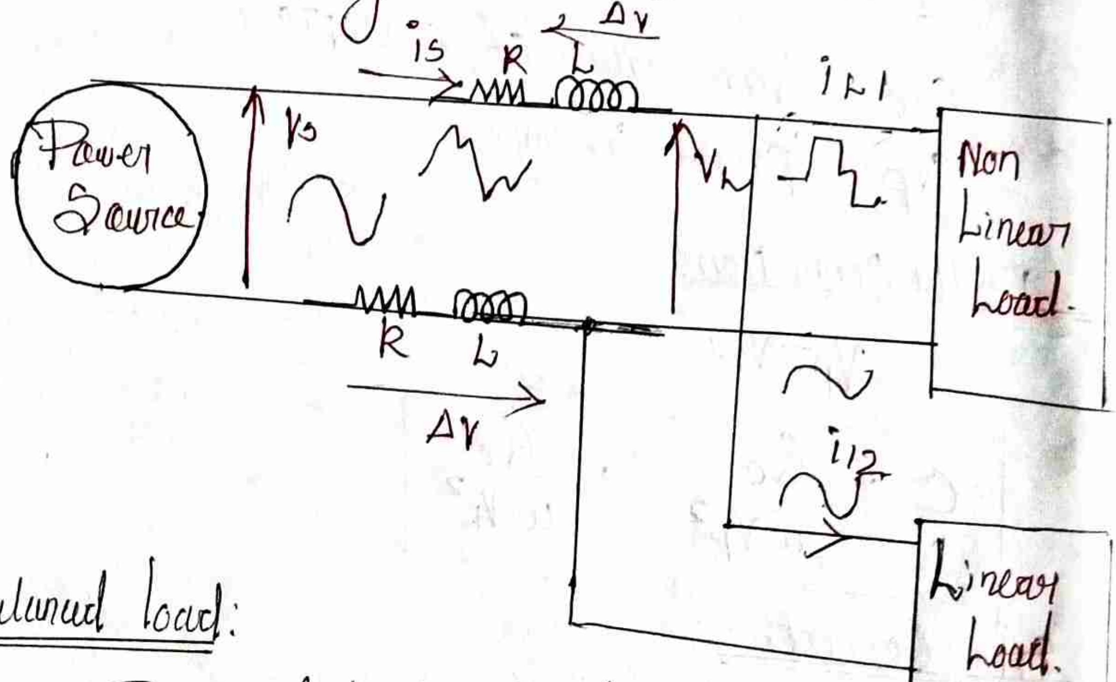
Non linear and Balanced loads:

Linear load is incandescent lamp, Non-linear load generates harmonic currents in addition to the original AC current and its powerfactor is less than 1. Example of non-linear load fluorescent lamp, electronic ballast of fluorescent lamp, pc and TV, etc.

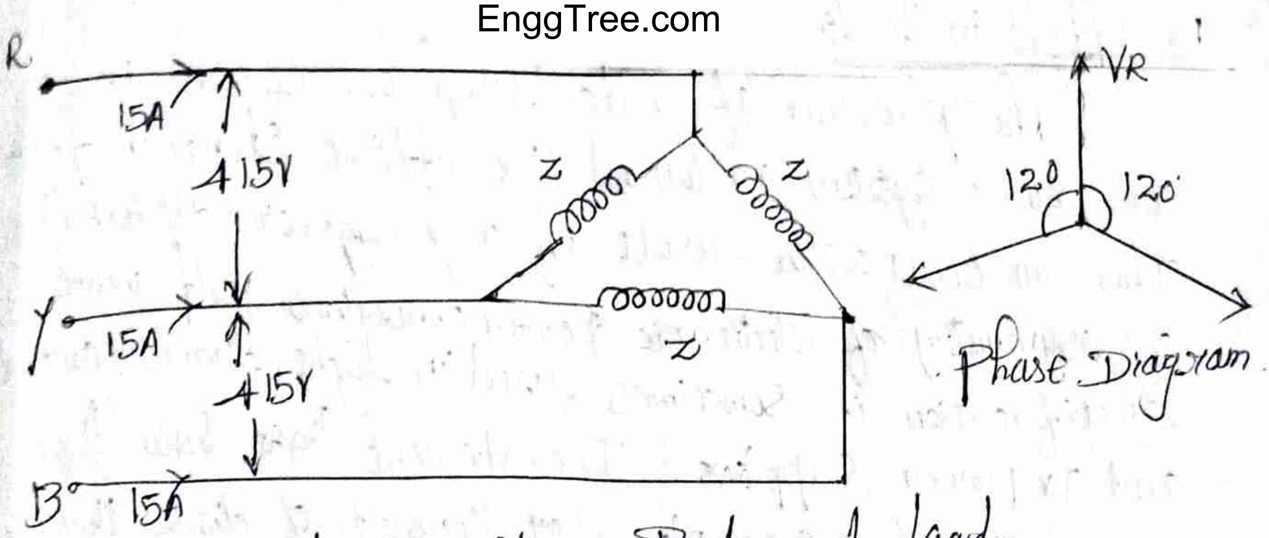
Non linear load waveform:





Balanced load:

Balanced load: In a three-phase System the power factors and the phase current or linear currents of the 3-phase are equal then that load is called Balanced load.



Balanced Circuit or Balanced load.

The main characteristics of balanced circuits are:

1. The magnitude of Voltage in each phase is identical.
2. phase difference in each phase are equal
3. The current in each phase is equal.
4. The algebraic sum of the current in each phase is equal to zero.
5. There is no ground fault or each fault in the balanced circuit
6. Balanced circuit does not have any fault like a symmetrical fault or unsymmetrical fault.

Balanced Load: when a 3ϕ load consumes an equal current in every phase, it will be called a balanced load. The main characteristics of properties of balanced load are.

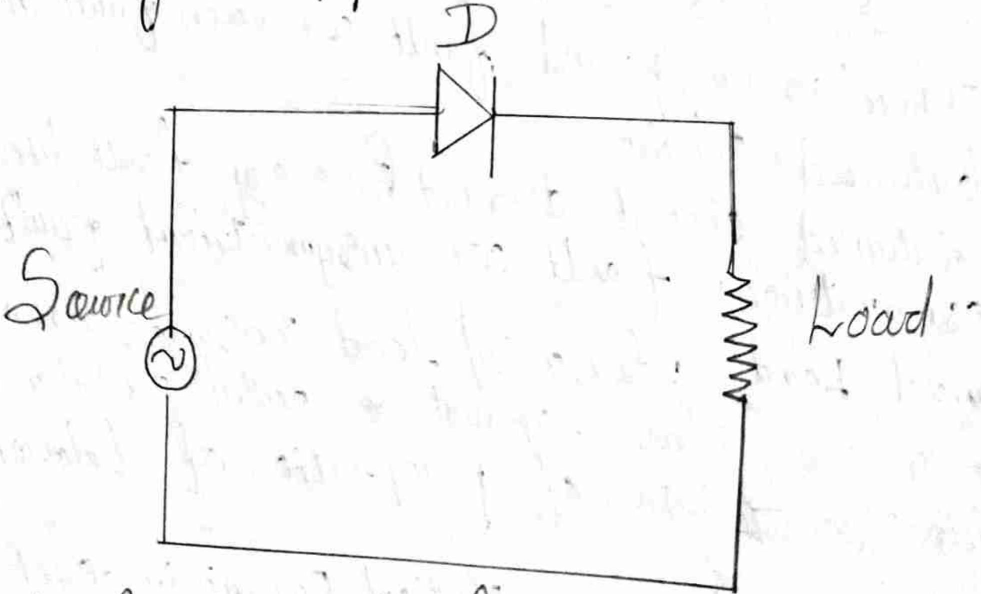
1. They always consume identical current in each phase
2. They always cause a balance of phase differences b/w all three phases.
3. There no leakage current flow from the load.
4. Load performance and Efficiency high.
5. It keeps the overall system healthy.

Dc offset in loads:

The presence of a dc Voltage or current in an ac power system in termed Dc offset shown in figure. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters. Half wave rectification is sometimes used in light dimmer circuits and TV power supplies. Incandescent light bulb life extenders, for example, may consist of diode that reduce the RMS Voltage supplied to the light bulb by half wave rectification is sometimes used in light dimmer circuits and TV power supplies.

Incandescent light bulb by half - wave rectification

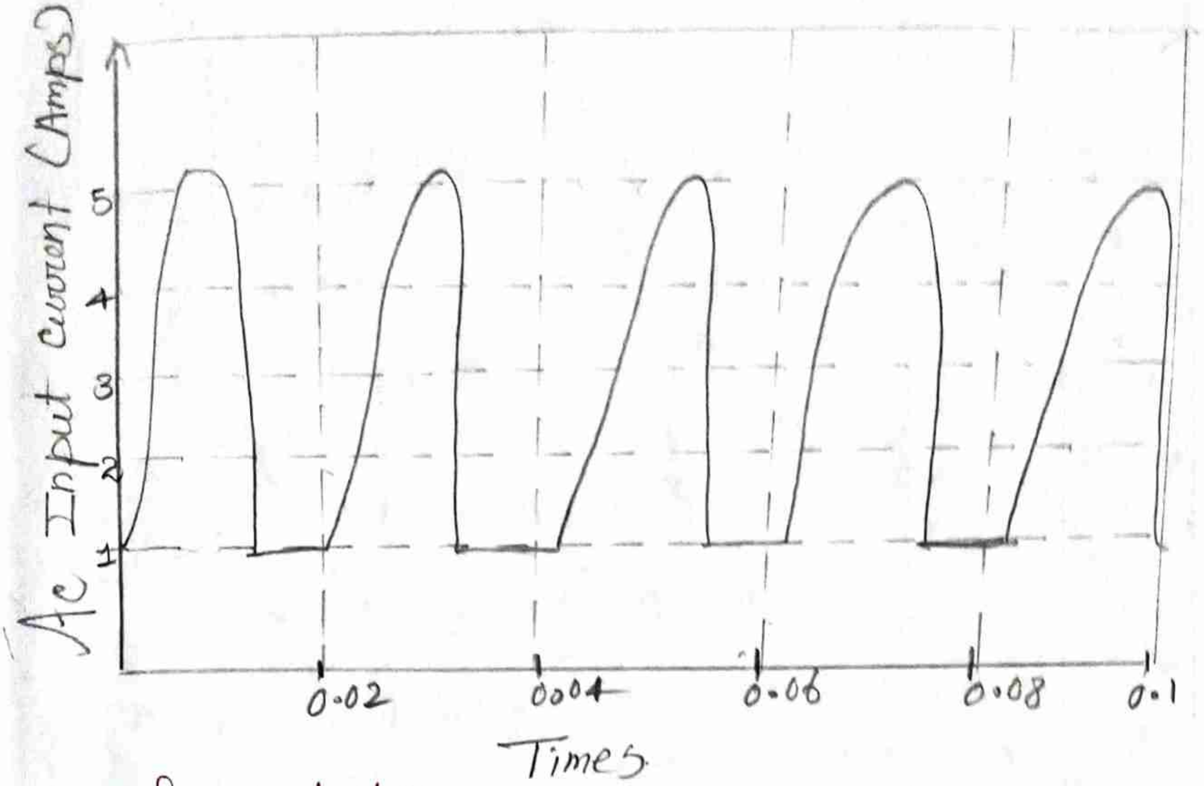
Direct current in ac networks can have a determental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.



Half wave rectifier circuit causing Dc offset in Source Voltage and Source Current.

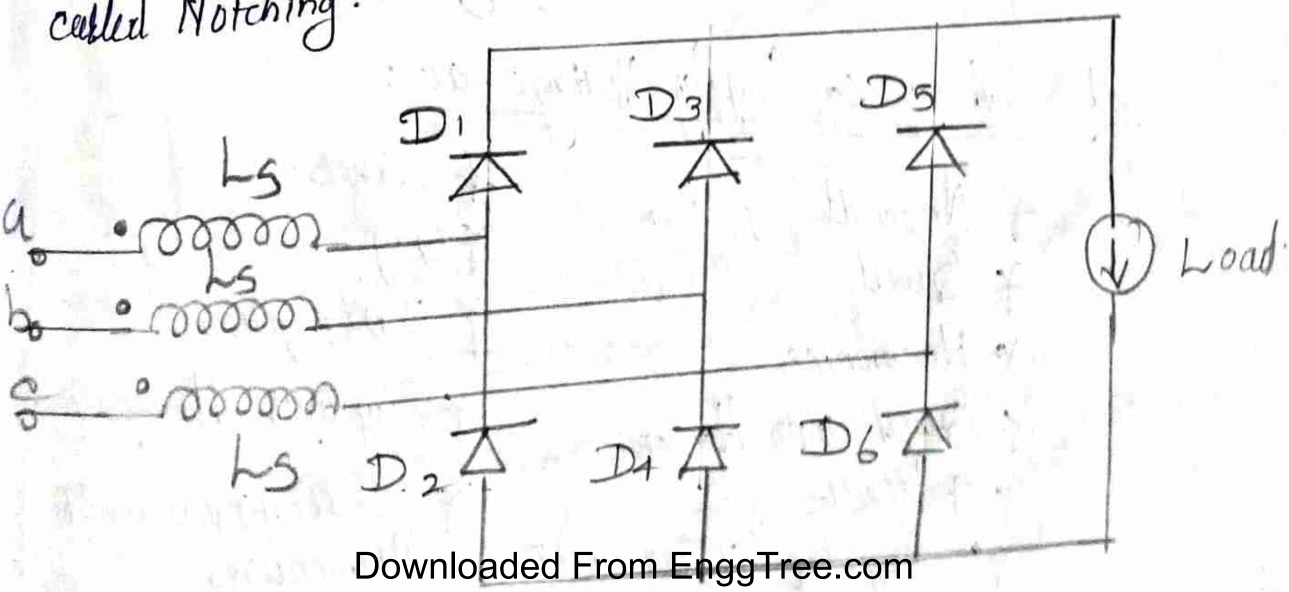
Direct current may also cause the electrolytic errosion of grounding electrode and other connectors.

Input current waveform (example of DC offset due to half wave rectification:

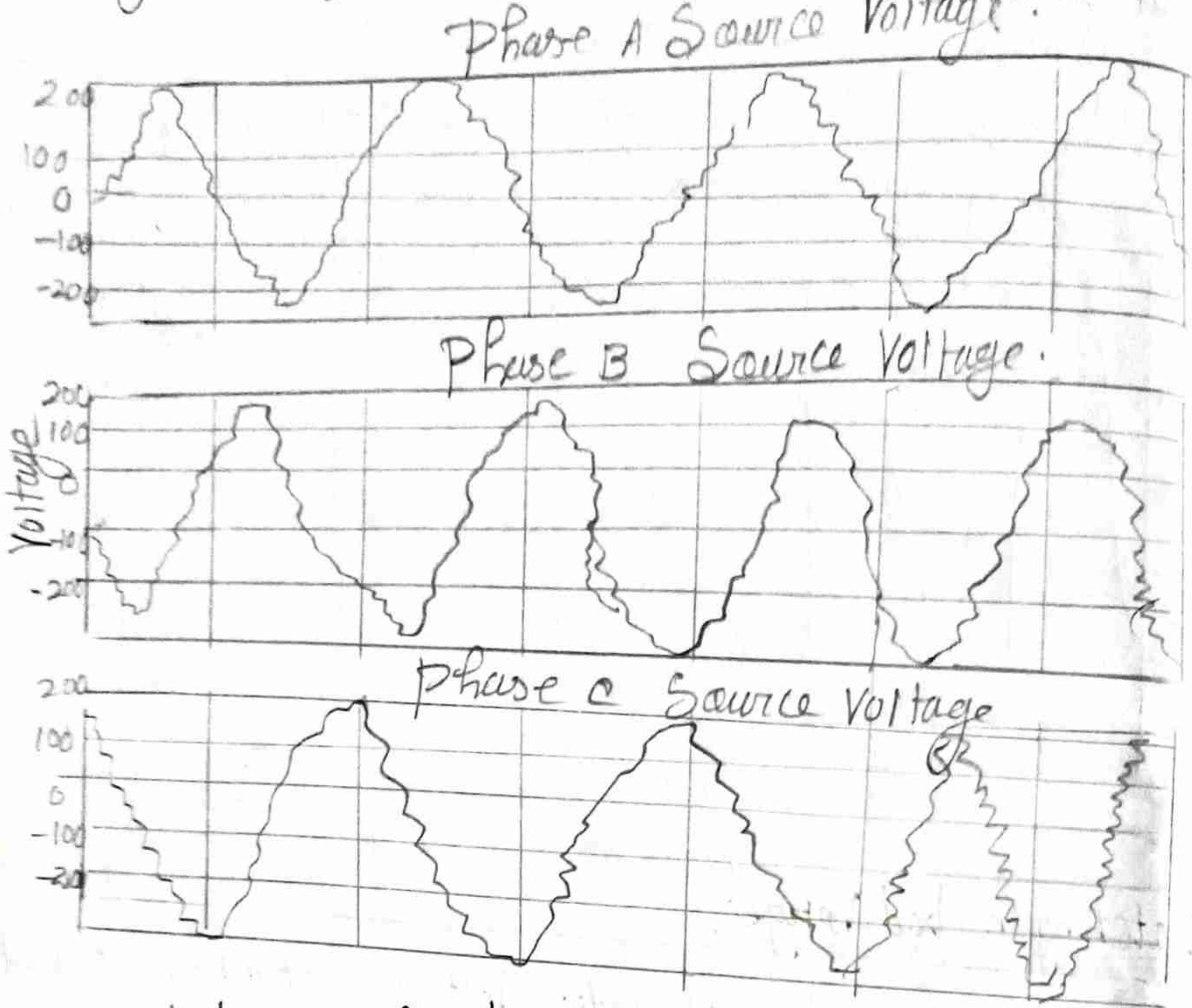


Notching in load Voltage:

Notching is a periodic Voltage disturbance caused by the normal operation of Power electronic devices when current is commutated from one phase to another. Three phase converters that convert ac to dc required commutation of the alternating current from one phase to another. During this period there is momentary short circuit between the two phases which cause a periodic Voltage disturbance called Notching.



Voltage waveform with notching due to Converter operation



Disturbance in Supply Voltage:

In telecommunication, a disturbance voltage is an unwanted voltage is induced in a system by natural or man-made sources. In telecommunication system the disturbance voltage creates currents that limit or interfere with interchanging of information.

Disturbance of Supply Voltages are:

* Normall
* Swell
* Harmonics
* Swell with Harmonics.
* Flicker.
* Impulse Transient
* Spikes.
* Sag
* Interruption.
* Sag with Harmonics
* Interruption with Harmonics

* oscillatary transient
* periodic Notch.
* Flicker with Harmonics

Power Quality Standards:

With the arrival of the computer age and increasing trend towards minimization of electrical and electronic Devices, Power Quality Problems have taken on increasing concern. The design of computers and Microprocessor controllers are not welled in Power Quality Issues.

Power system designers and operators have limited knowledge of operation of sensitivity electronics. This environment has led to a need for power Quality standards and guidlines.

IEEE : Institution of Electrical and Electronics Engineer.

IEC : International Electro technical Comission.

CENELEC : European Comittee for Electro technical Standardization

ANSI : American National Standards Institute.

NER : National Electricity Regulator.

SEMI : Semiconductor Equipment and Material International.

UIE: International Union for Electricity Application

The most universally accepted Standards for power quality are IEC and IEEE Standards.

Both Standards adopt some of the other organization Standards for some specific issues. Also more lists of Power Quality and related Standards for some specific issues.

IEEE Power Quality Standards.

The Institute of Electrical and Electronic Engineer (IEEE) homepage can be visited by at http://www.i...

- IEEE Std 141-1993, IEEE Recommended practice for Electric power Distribution for Industrial plants (IEEE

- IEEE Std 142-1991, IEEE Recommended practice for grounding of industrial and Commercial power System (IEEE Green Book) (ANSI).

- IEEE Std 241-1990, IEEE Recommended practice for Electric power System in commercial building.

- IEEE Std 242-1986, IEEE Recommended practice for protection and coordination of industrial and Commercial power System (IEEE Buff Book) (ANSI.

- IEEE Std 487-1992, IEEE Recommended practice for the Design of Reliable Industrial and Commercial Power System (IEEE Gold Book)(ANSI)

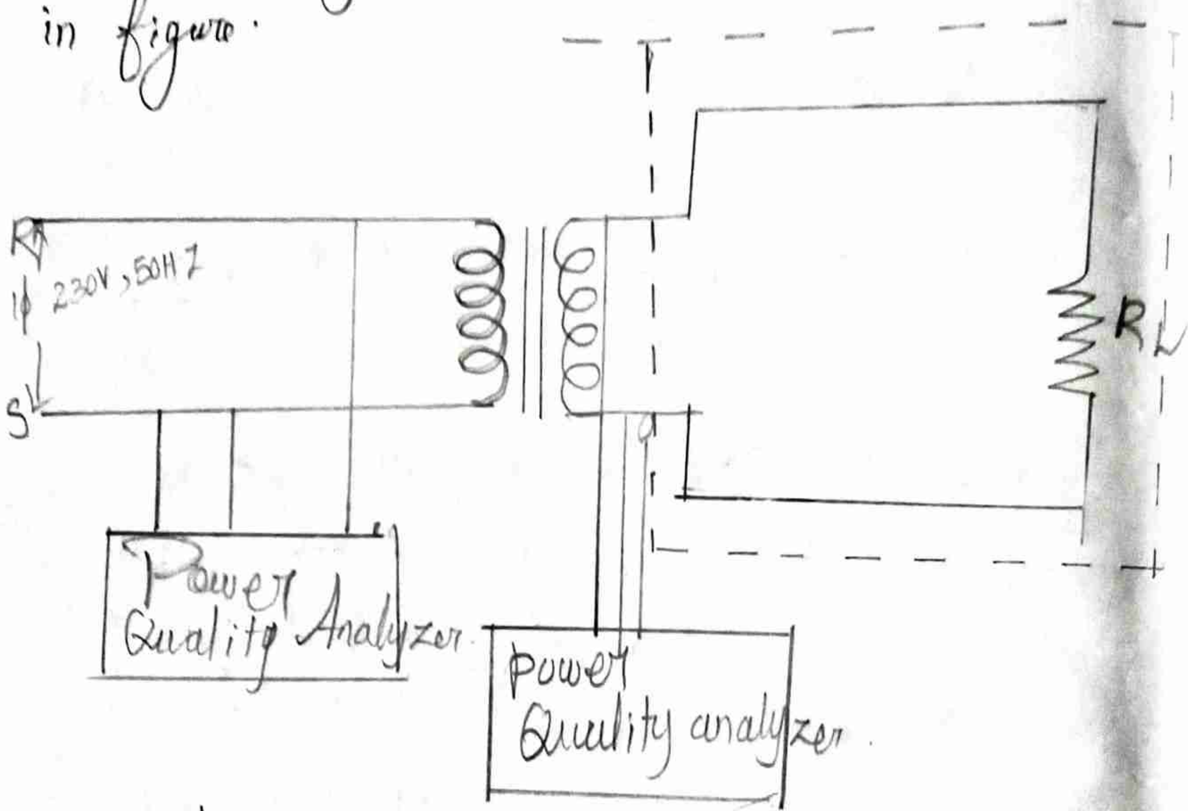
- IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to minimize Noise input to controllers from External Sources. (Reaff 1990) (ANSI).

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 non linear loads - Three phase balanced System - three phase unbalanced System - Three phase - three wire unbalanced and distorted Source Supplying - non-linear loads - concept of power factor - three phase - three wire - three phase - four wire System.

Single Phase Linear and non linear loads:

Single phase Linear Loads Diagram Shown in figure.

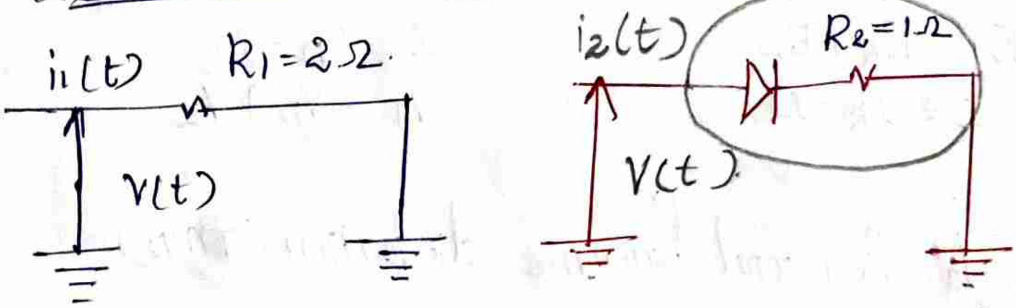


In linear Load, the relationship between the Voltage and current waveform are Sinusoidal and the current at any time is proportional to the Voltage (ohm's law). Example of linear loads would include Motors, Transformer and capacitors.

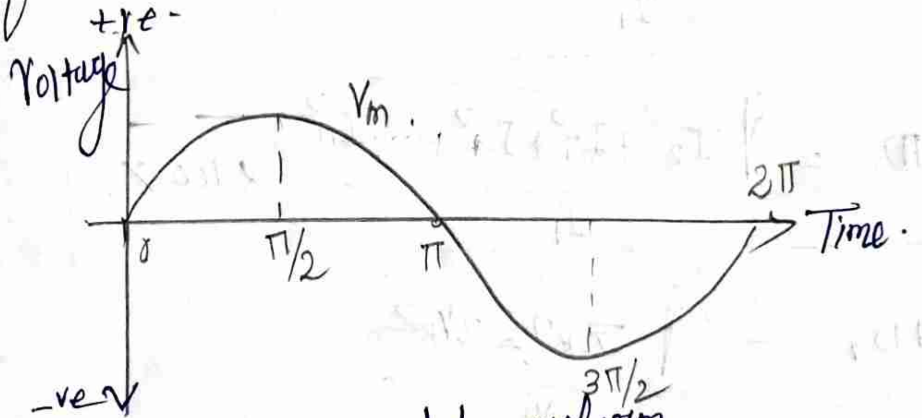
Single phase Ac waveforms.

Sinusoidal Ac supply is given to the input of Transformer and get the output power from the Transformer Secondary.

(a) Linear Load. (b) Non-linear Load.

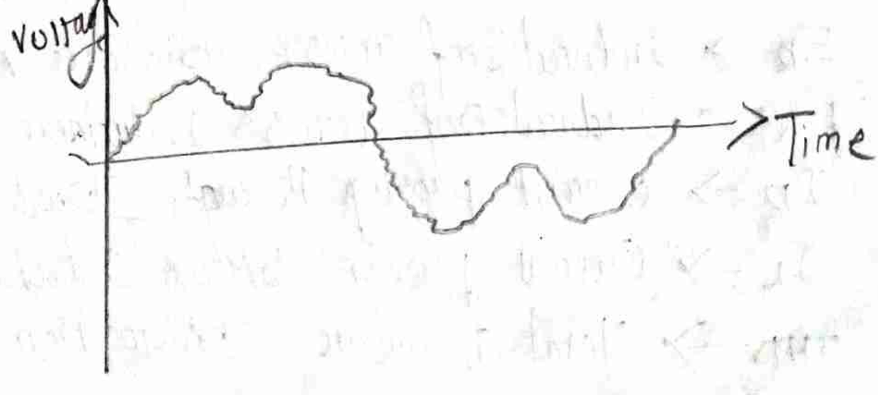


The Sinusoidal Voltage Source Supplies Smooth Sinusoidal waveform. But non linear loads will lead to distorted waveform.



Pure Sinusoidal waveform.

Non linear Load, we get the Distorted output wave form.

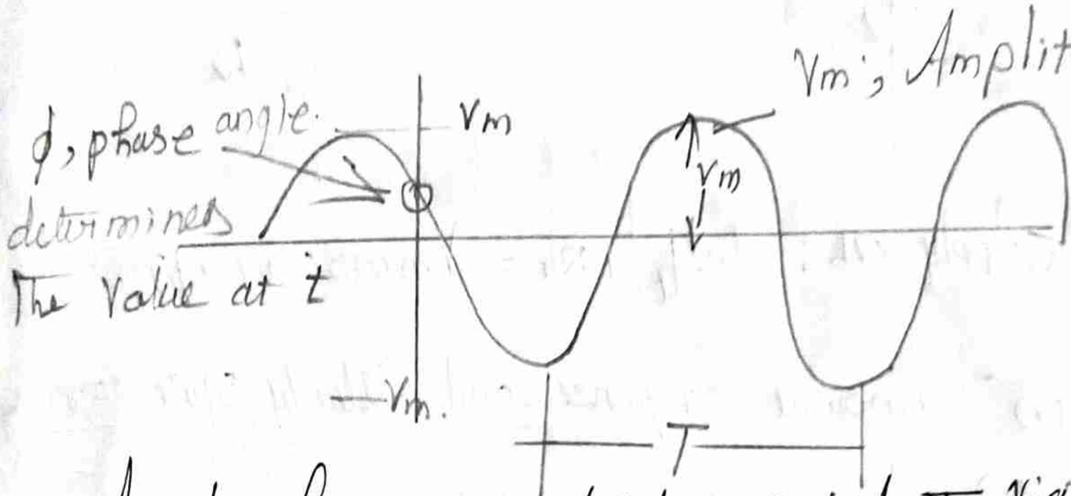


Single phase Sinusoidal and Non-Sinusoidal Sources.

Definition:

A Source Producing a Voltage Varying Sinusoidally with time:

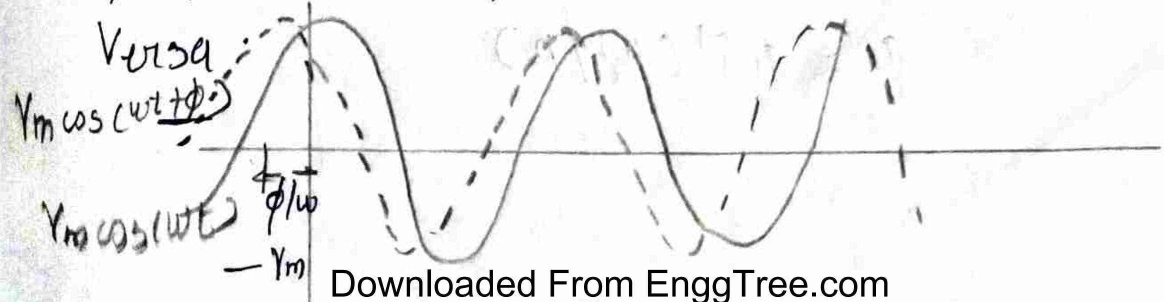
$$v(t) = V_m \cos(\omega t + \phi)$$



ω, Angular frequency, related to period T via $\omega = 2\pi/T$. The argument ωt changes 2π radians (360°) in one period.

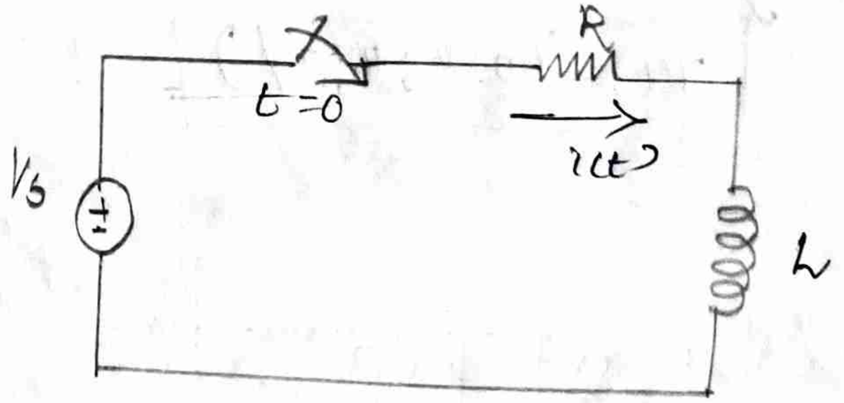
Change of phase angle Shifts the curve along the time axis without changing the Shape (amplitude, angular frequency).

Positive phase ($\phi > 0$) ⟹ the curve is Shifted to the left by ϕ/ω in time, and Vice Versa:



Example RL circuit

Consider an RL circuit with zero initial current $i(t=0^+)=0$ and driven by a sinusoidal voltage source $V_s(t) = V_m \cos(\omega t + \phi)$.



Apply KVL: $L\frac{di}{dt} + Ri = V_m \cos(\omega t + \phi)$

(Tr) Transient response and Steady State response (SS):

$$i(t) = i_{tr}(t) + i_{ss}(t)$$

$$i_{tr}(t) = \frac{V_m \cos(\phi - \theta)}{\sqrt{R^2 + \omega^2 L^2}} e^{-(R/L)t}$$

Transient response. Vanishes as $t \to \infty$.

$$i_{ss}(t) = \frac{V_m}{\sqrt{R^2 + \omega^2 L^2}} \cos(\omega t + \phi - \theta)$$

Steady State response, lasts even $t \to \infty$.

$$\theta = \tan^{-1}(\omega L / R)$$

Analysis of non-Sinusoidal Sources

up to the present, we have been considering direct waveform and Sinusoidal alternating waveform.

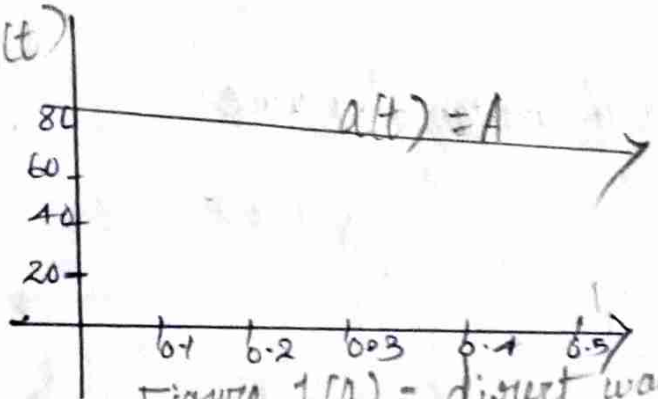
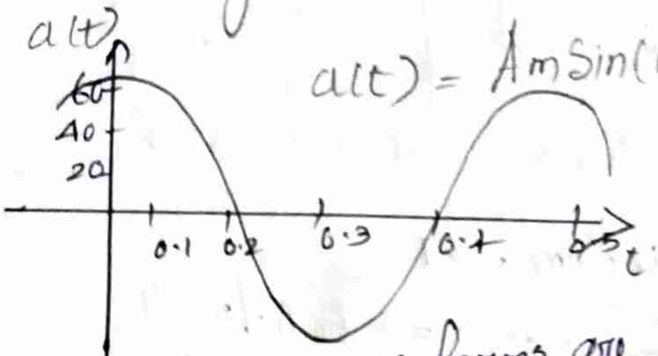
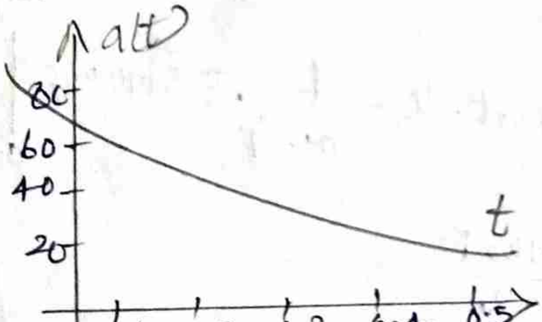
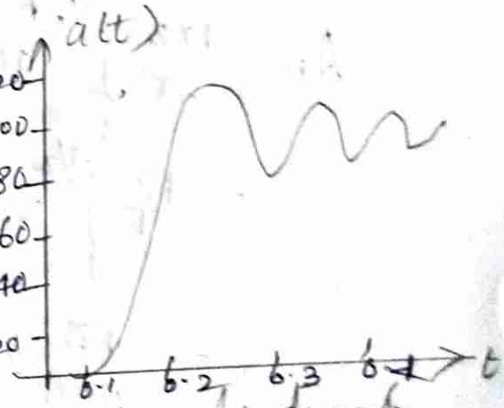


Figure 1(a) = direct waveform.

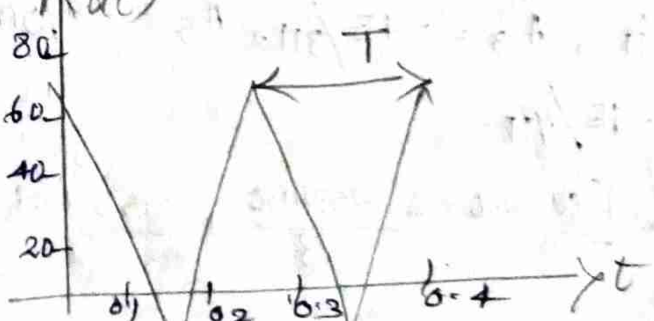


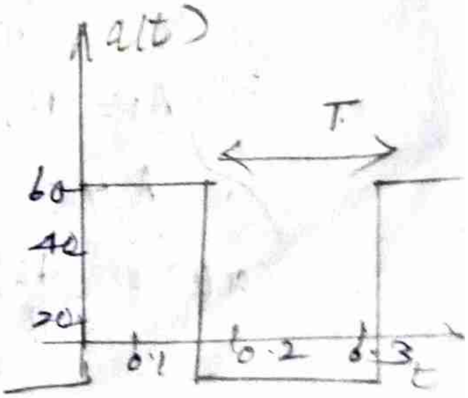
However, Many waveforms are neither direct nor Sinusoidal as seen.





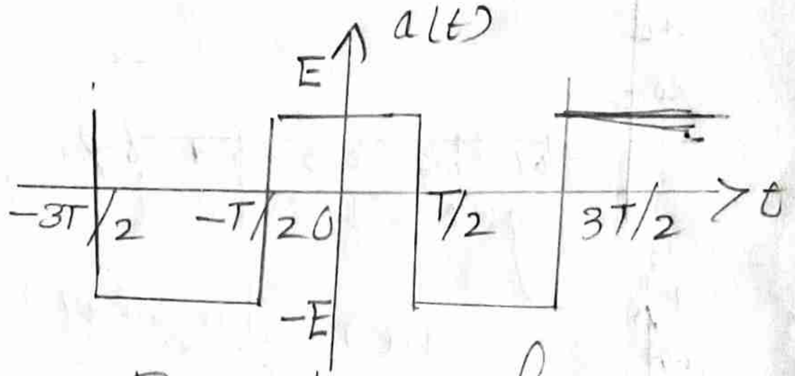
unidirectional but not purely direct





Any waveform that differes from the basic description of the Sinusoidal waveform is referred to as non-Sinusoidal. The most obvious and familiar are the dc, square wave, triangular wave, Saw-tooth and rectified waveform.

Fourier Series of Rectangular wave:



Rectangular waveform

Period of waveform = 2T

Mean Value of waveform = 0 ∴ $A_0/2 = 0$

$$A_n = \frac{4\times 2}{2T}\int_0^{2T/4} a(t)\cos n\omega_0 t \cdot dt \quad \text{for odd } n.$$

$$= 4/T\int_0^{T/2} E\cdot\cos n\omega_0 t\cdot dt = \frac{4}{n\omega_0 T}\cdot E\sin n\omega_0 t\Big|_0^{T/2}$$

$$= \frac{4E}{n\omega_0 T}\sin\frac{n\omega_0 T}{2}$$

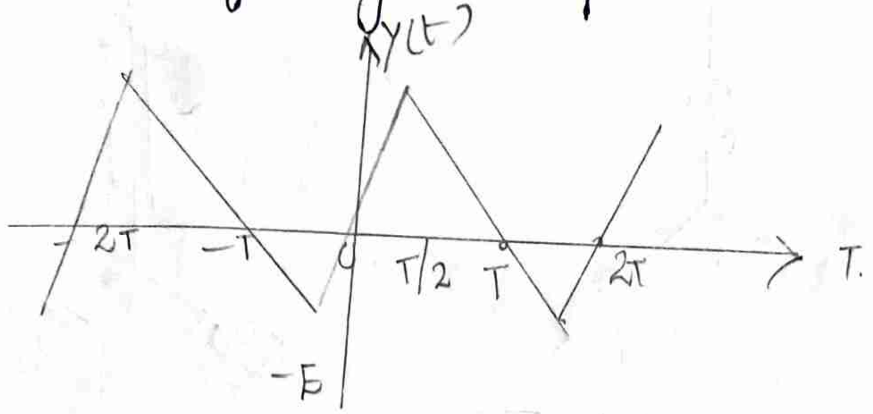
$$= \frac{4E}{n\pi}\sin n\pi/2 \quad \text{for odd } n.$$

∴ $A_1 = 4E/\pi$, $A_3 = -4E/3\pi$, $A_5 = 4E/5\pi$

$A_7 = -4E/7\pi$

$$a(t) = \frac{4E}{\pi}\left[\cos\omega_0 t - \frac{\cos 3\omega_0 t}{3} + \frac{\cos 5\omega_0 t}{5} - \frac{\cos 7}{7}\right.$$

Fourier Series of Triangular waveform:



Triangular waveform.

Period of waveform = 2T, $\omega_0 \cdot 2T = 2\pi$

Mean Value of waveform = 0 ∴ $A_0/2 = 0$

Waveform has odd Symmetry' $A_n, B_n = 0$ for even n

UV Method

$$B_n = \frac{4\times 2}{2T}\int_0^{2T/4} \frac{2E}{T}\cdot t \sin n\omega_0 t \cdot dt$$

$$B_n = \frac{8E}{T^2}\cdot t \cdot \frac{\cos n\omega_0 t}{n\omega_0}\Big|_0^{T/2} - \frac{8E}{T^2}\int_0^{T/2}\frac{\cos n\omega_0 t}{n\omega_0}\cdot dt$$

$$B_n = \frac{8E}{T^2}\cdot\frac{T}{2}\cdot\frac{\cos n\omega_0 T/2}{n\omega_0} + \frac{8E}{T^2}\frac{\sin n\omega_0 T/2}{(n\omega_0)^2}$$

$$B_n = \frac{4E\cdot\cos n\pi/2}{n\pi} + \frac{8E\cdot\sin n\pi/2}{(n\pi)^2}$$

Substituting the values.

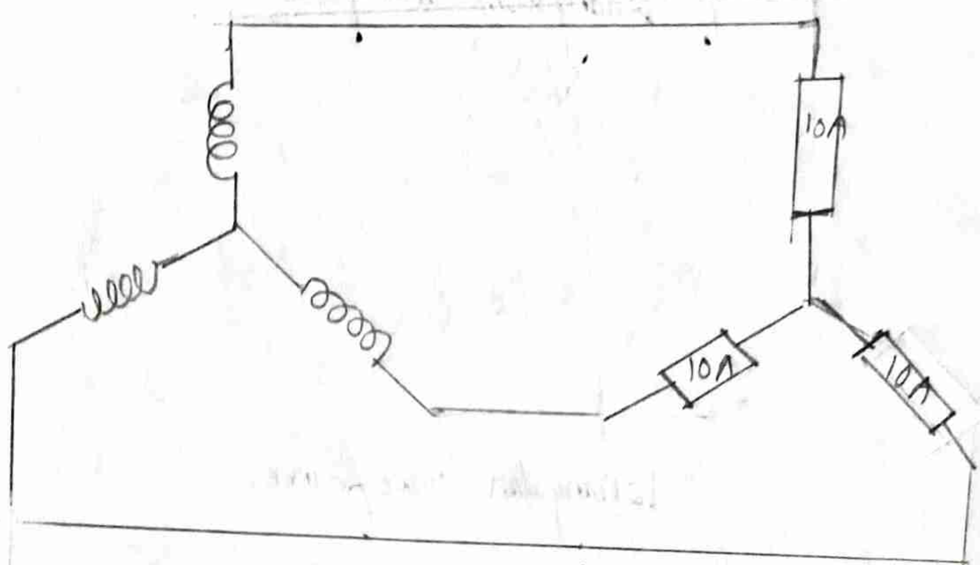
$B_1 = 8E/\pi^2$, $B_3 = -8E/(3\pi)^2$, $B_5 = 8E/(5\pi)^2$

$B_7 = -8E/(7\pi)^2$

$$y(t) = \frac{8E}{\pi^2}\left[\sin\omega_0 t - \frac{\sin 3\omega_0 t}{3} + \frac{\sin 5\omega_0 t}{5^2} - \frac{\sin 7\omega_0 t}{7^2}\right.$$

Three phase Balanced System.

Phase Voltage or Currents are displaced from each other by 120 deg. The windings of a generator are placed 120 deg apart from each other. Consider the Star Connected winding.



Now, if you connected load to it. We can call It is a system. We connected an equal load on each winding. As the load on the system is identical. Current flowing through each phase is same.

* The phase angle b/w Voltage and Current is perfectly 120 deg. as shown in figure.

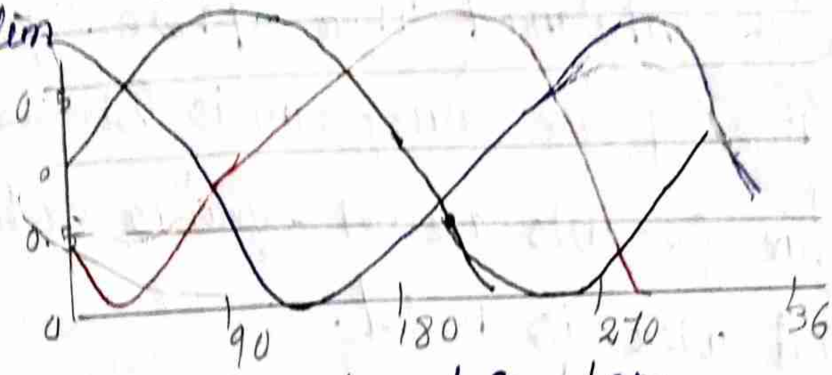
* if your load is perfectly identical on all the 3 phases, current flowing through neutral Conductor is also zero.

* if we add these return currents, we'll get the sum = 0, and this is true for every instance

$I_a + I_b + I_c = (-0.5 I_{max} - 0.5 I_{max}) + I_{max}$

$I_a + I_b + I_c = -I_{max} + I_{max} = 0$

We can therefore, remove the neutral conductor without affecting the voltage or current in the circuit. This is only applicable for perfectly Balanced System.



Properties of Balanced System:-

1. Waveform is perfectly sinusoidal, i.e in terms of Magnitude and phase shift of 120 deg.
2. Current flowing through each phase is identical.
3. No current flows through neutral
4. Power loss is very low or not present

Three phase unbalanced System:

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 impedance are unequal from each other

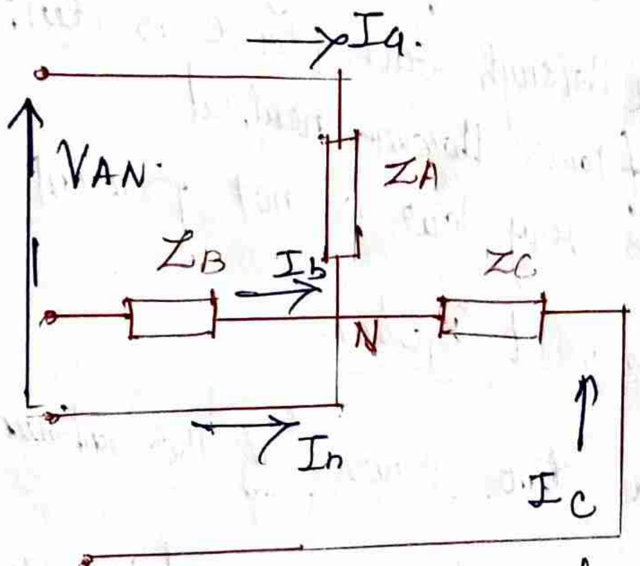
$Z_{AN} \neq Z_{BN} \neq Z_{CN}$

- 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 loss.

unbalanced Star-Connected Load:



unbalanced Star connected load impedances (z_1, z_2 and z_3).
Since we already set the Load impedance are unbalanced, all the Z_A, Z_B and Z_C are un-equal using ohm's law we get the currents as:

$$I_a = \frac{V_{AN}}{Z_A}$$

$$I_b = \frac{V_{BN}}{Z_B}$$

$$I_c = \frac{V_{CN}}{Z_C}$$

The current in the neutral line is not zero.

Applying KCL node N gives the neutral line current as

$$I_n = -(I_a + I_b + I_c)$$

Three phase unbalanced and distorted source supplying non-linear Loads:

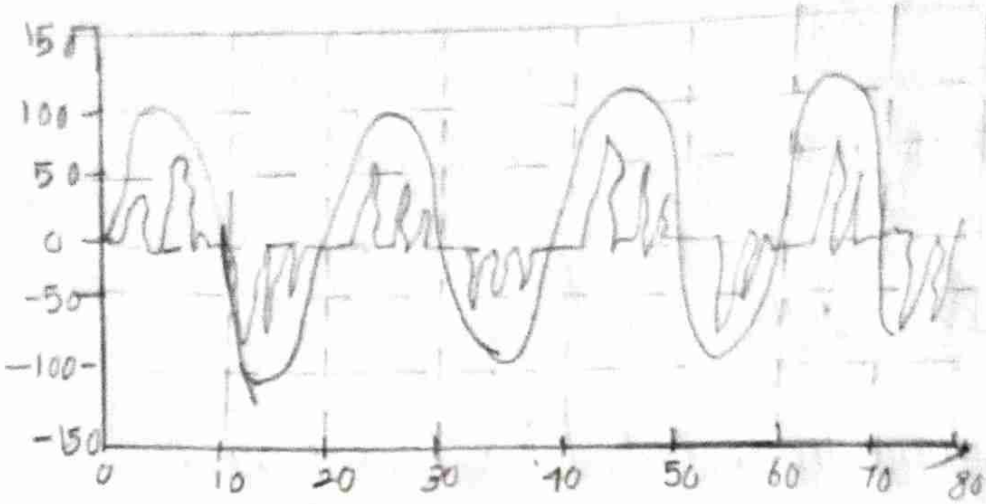
The Three phase unbalanced source system supplying non linear Loads.

Load impedance are unbalanced.

Z_A, Z_B, Z_C are unequal.

$Z_A \neq Z_B \neq Z_C$
$V_{AB} \neq V_{BC} \neq V_{CA}$
$I_A \neq I_B \neq I_C$

We get the o/p from the unbalanced systems are distorted o/p voltages.



Concept of Power factor:

Power factor is the ratio of Active power to the total power (Apparent power)

$$\text{Powerfactor} = \frac{\text{Active power}}{\text{Total power}}$$

$$\text{powerfactor} = \frac{P}{S}$$

S = Total power of Generator (or used)

P = power consumed in the load (active power)

Q = Reactive power stored in Magnetic field. or wasted power.

It is Measure of the degree to which the voltage waveform and the current waveform in phase with one another in an electrical circuit.

Leading Powerfactor:

A circuit in which the Current waveform Precedes ("leads") the Voltage waveform

Lagging Power Factor:

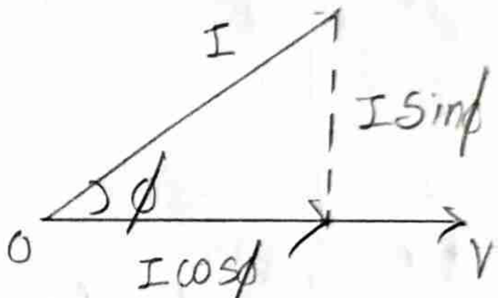
A circuit in which the current waveform follows (lags) the voltage waveform. Motors or transformers can produce circuits with lagging power factor.

$$\text{Power factor} = \frac{\text{Watts}}{\text{Volt-Amperes}}$$

$$= \frac{VI\cos\phi}{VI}$$

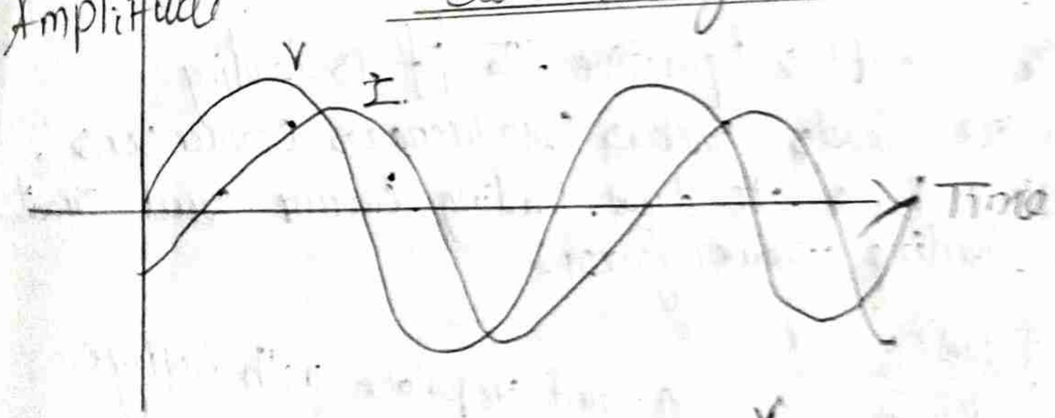
$$= \cos\phi$$

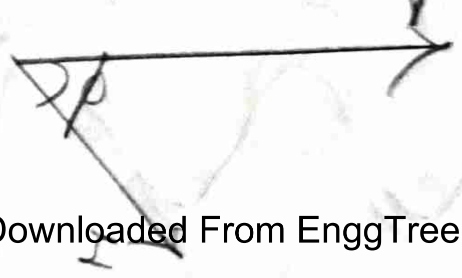
$$\boxed{P/S = \cos\phi.}$$



Power factor

Current lag behind



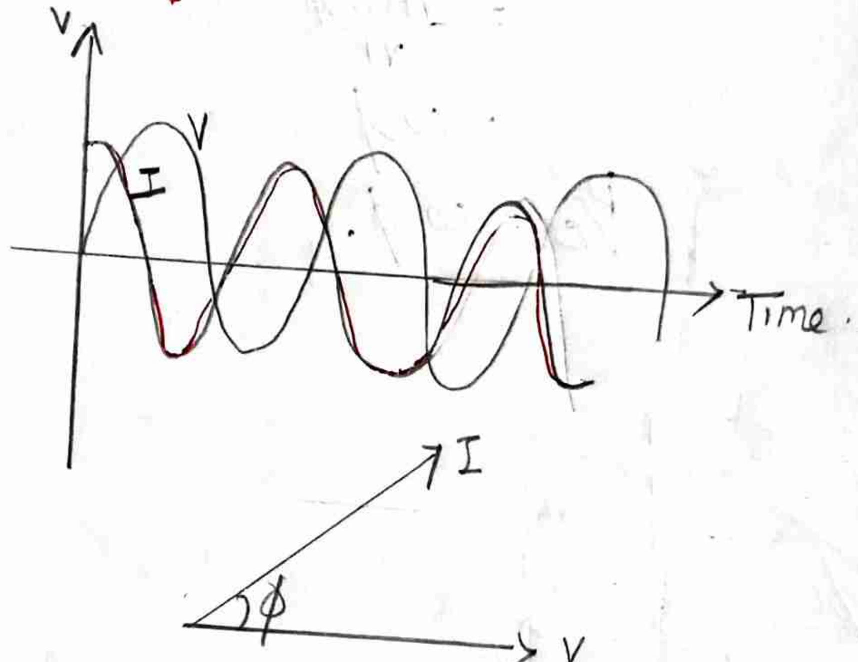


When current lags behind the Voltage, the power factor of the circuit is called Lagging.

* When the circuit is inductive, the pf is lagging

* The loads such as induction motors, coil, lamps, etc. are inductive and have lagging p.f.

Leading Power factor

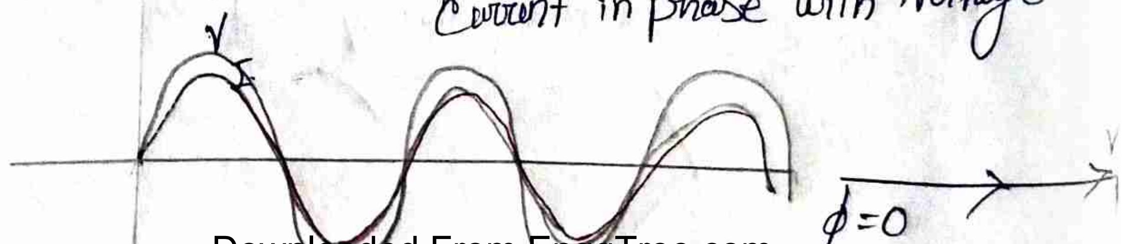


When current leads the Voltage (or Voltage lags behind the Current). The power factor of the circuit is called leading.

- When the circuit is capacitive, the pf is leading.
- Capacitive loads such as synchronous condensers, capacitor bank etc draw leading current. Such circuits have leading power factor.

Unity Power factor

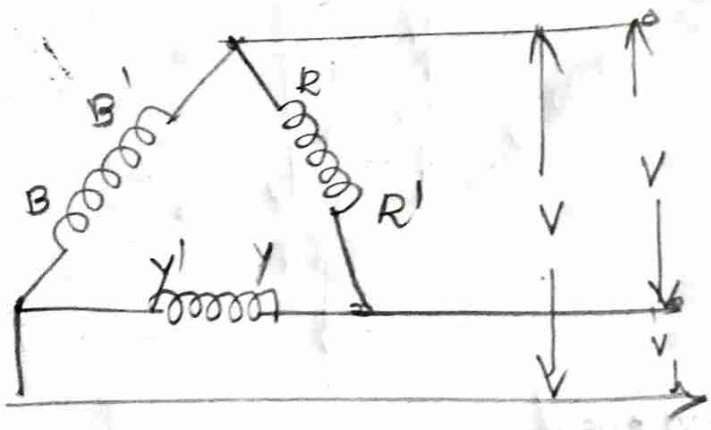
Current in phase with Voltage

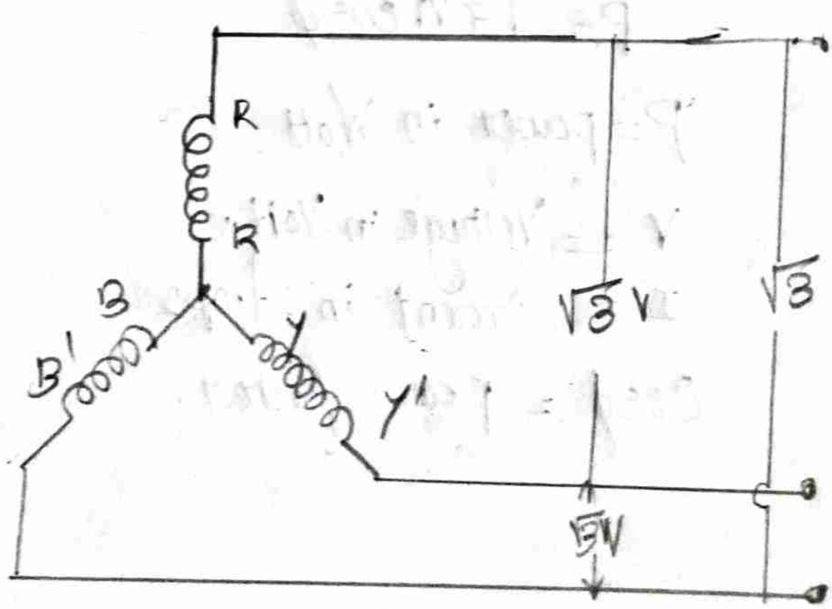


* Power factor is unity for ideal circuit
* when current and Voltage are in phase, PF=1
* power factor cannot be More than unity.
* practically, it Should be as close to unity as possible.

Three phase three wire system

Three-phase Systems are used extensively. The 3-wire System May be delta-connected or Star connected whose Star point is usually earthed. The Voltage between lines is V in delta Connection and $\sqrt{3}$ V in case of Star connection where V is the Voltage of each phase.

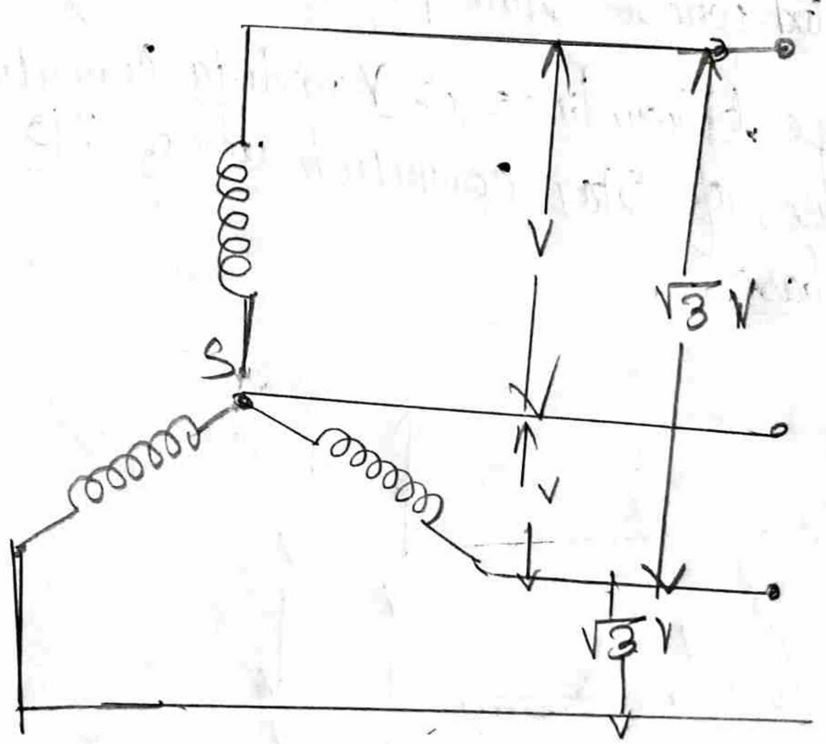




Three phase four wire System.

The 4th or neutral wire is taken from the Star point of the Star-connection as shown in figure. if V is the Voltage of each winding, then line Voltage between any outer and the neutral for Symmetrical System is So that the voltage between any two lines or outer is.

2×230 = ~~44~~0V.



$P = \sqrt{3} VI \cos\phi$

P = power in Watt

V = Voltage in Volt.

I = Current in Amps.

cos φ = power factor.

UNIT-3 : Mitigation of Power System Harmonics:

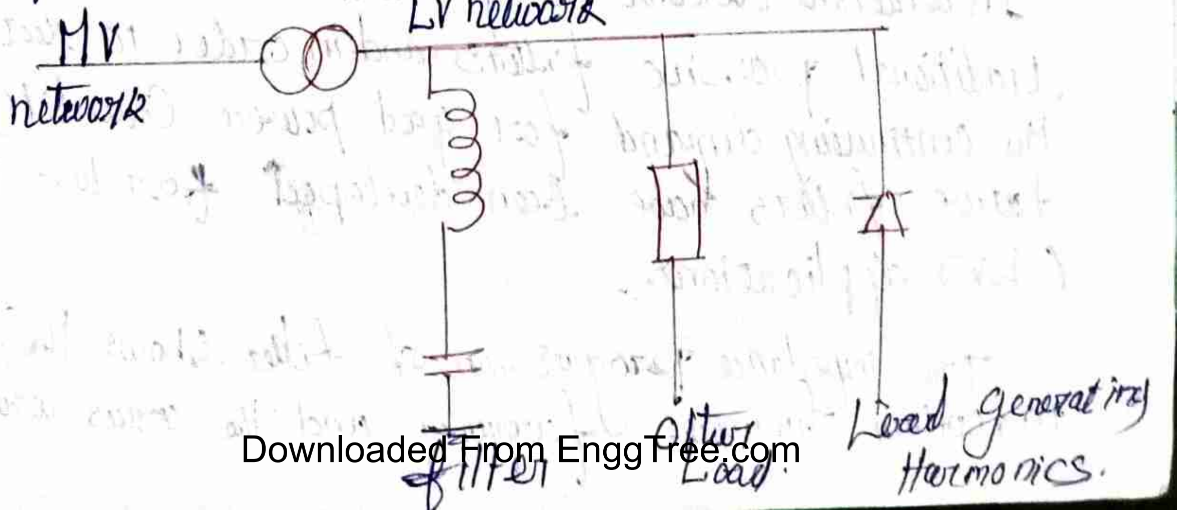
Introduction - principle of Harmonic filter:

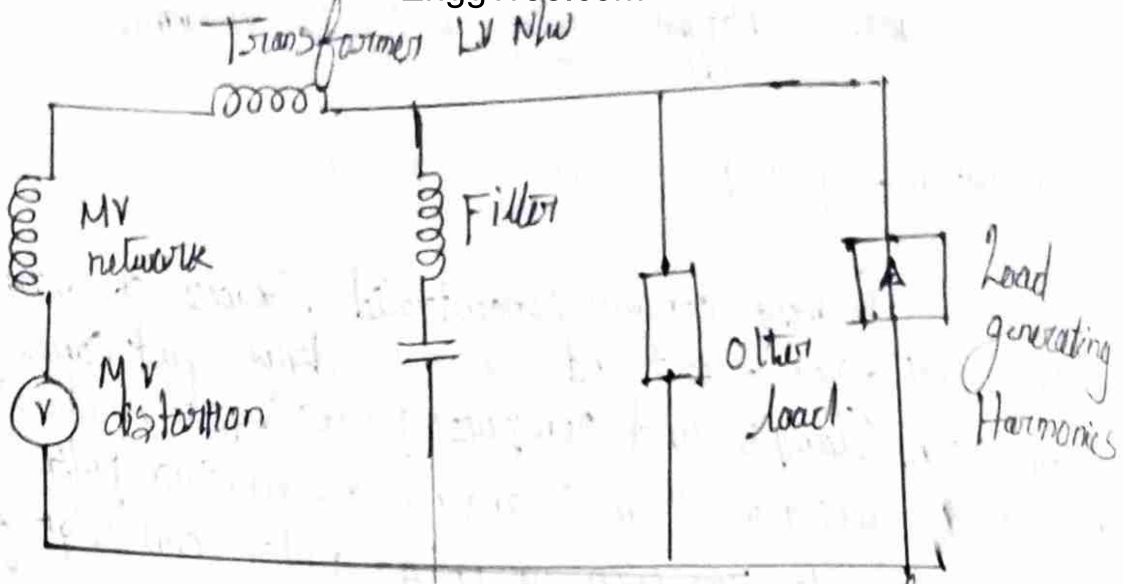
The most common concentrated source of harmonic is the rectifier front end on motor drives and converters, flourescent lamps and computer power supplies. When the load is a large rectifier then changing from six pulse rectifier to twelve pulse or even up to 48 pulse can significantly reduce the strength of low order harmonics.

Harmonic filters reduce distortion by diverting harmonic current 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. $THD = \frac{(V_2^2 + V_3^2 + \cdots + V_n^2)^{1/2}}{V_1}$

Passive filter:

A passive filter consists of a series circuits to reactors and capacitors. Harmonic currents generated by, for example a frequency converter are shunted by this circuit designed to have low impedance at a given frequency compared with the rest of the network.





Equivalent circuit of passive harmonic filtering.

The degree of filtering provided by the passive filter is given by the passive filter is given by its impedance in relation to all other impedance in the network

As a result, the filteration level of a passive filter cannot be controlled and its tuning frequency may change in time due to aging of the components or network modification.

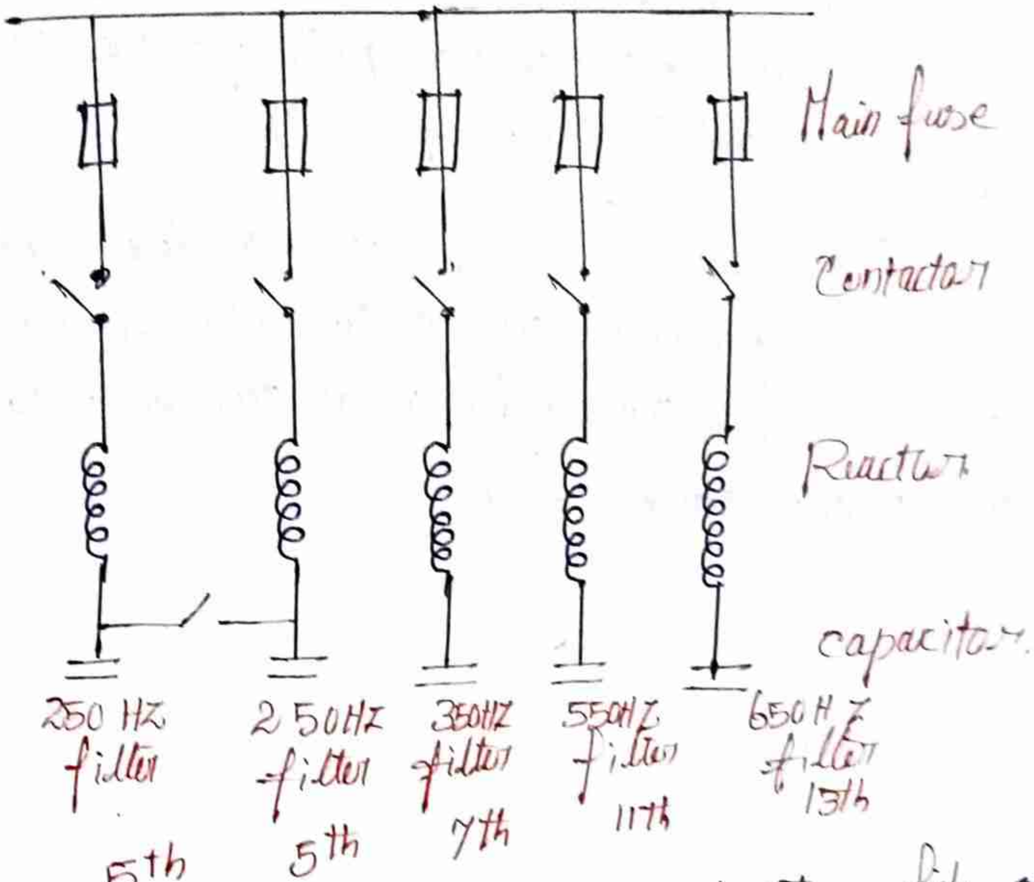
It is also important to note that a passive filter circuit may only filter one harmonic component. A separate filter circuit is required for each harmonic that needs to be filtered.

" In order to overcome the problem associated with traditional passive filters and in order to meet the continuing demand for good power quality, Active filters have been developed for low voltage (LV) applications.

The impedance progression of filter shows the tuning to a certain harmonic frequency and the areas where

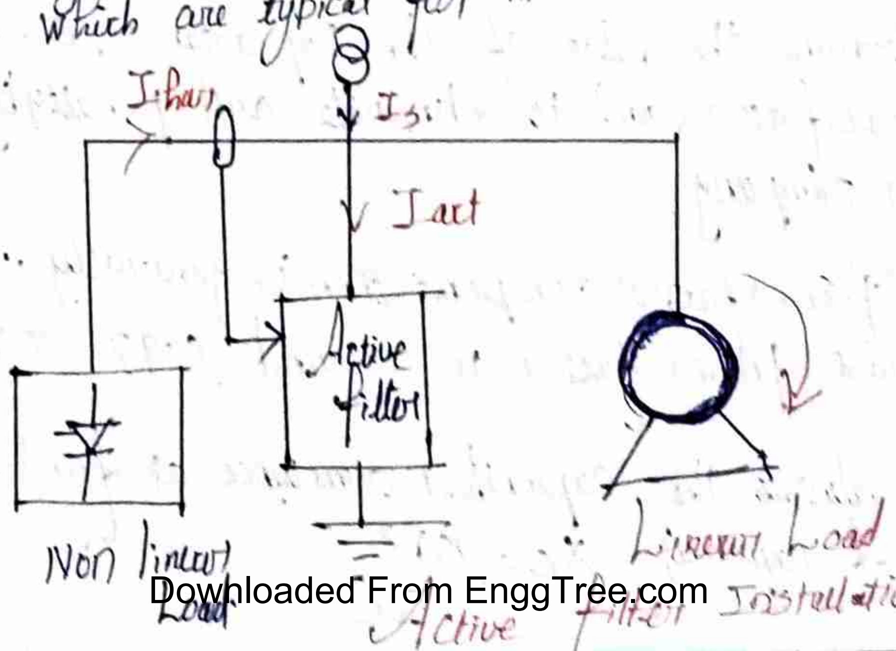
U-3-2

resonance reinforcement may possibly occur.



A passive filter can consist of several steps which are tuned to different frequencies. It can also consist of several steps for a certain frequency. The tuning frequency, capacity and N/w impedance determine effectiveness of the filter.

Passive filters are frequently implemented as tuned filters: are usually tuned to the harmonics of the order V = 5, 7, 11, 13 ... which are typical for inverters.

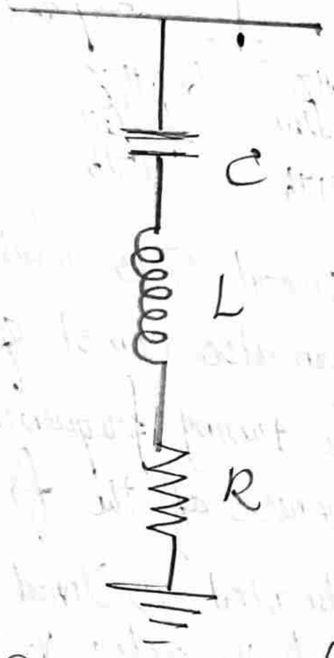


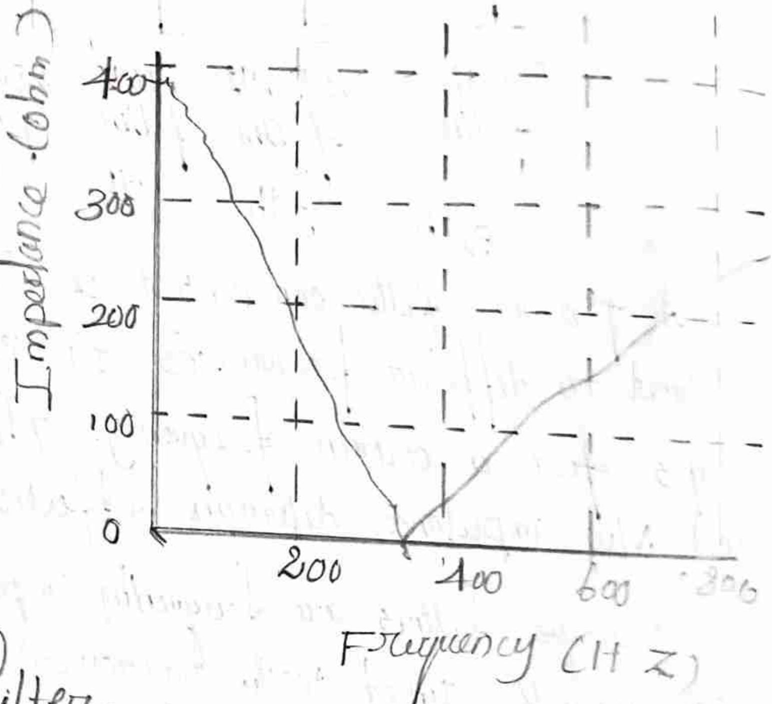
Active filter Installation.

Series Tuned filters:

A tuned filters works on the principle of providing the least impedance path for one or two harmonic frequencies and has tuning frequency.

The tuned filter design has to be done carefully. The tuned filter is forward with a combination of inductance and capacitance so they are bulkier as compared to the de-tuned filter and active filter.





Single tuned filter.

Determine the value of the capacitance, Q_C to improve the powerfactor and to eliminate and penalty by the electric Power company.

Power factor compensation is generally applied to raise power factor to around 0.98 or higher.

* Evaluate the capacitor reactance at fundamental frequency $X_C = \frac{KV^2}{Q_C}$

U3.4

Calculate the reactor size providing the resonance

$$X_L = \frac{X_C}{h_n^2}$$

Calculate the reactor resistance for a specified Quality factor Q. $R = \frac{X_n}{Q}$; $30 < Q < 50$.

The characteristic reactance is

$$X_n = X_{Ln} = X_{Cn} = \sqrt{X_L X_C} = \sqrt{L/C}$$

Filter size $Q_{filter} = \frac{kV^2}{X_C - X_L} = \frac{kV^2}{X_C - X_C/h_n^2}$

$$Q_{filter} = \frac{h_n^2 \cdot kV^2}{h_n^2 - X_C}$$

$$Q_{filter} = \frac{h_n^2}{h_n^2 - X_C} \cdot kV^2$$

$$Q_{filter} = \frac{h_n^2}{X_C\left[\frac{h_n^2}{X_C} - 1\right]} \cdot kV^2$$

$$= \frac{h_n^2}{X\left[\frac{h_n^2}{X_C} - 1\right]} Q_C$$

$X_C << 1$

$$Q_{filter} = \left[\frac{h_n^2}{h_n^2 - 1}\right] Q_C$$

Filter impedance

$$Z_F(h) = R + j(hX_L - X_C/h)$$

$$|Z_F(h)| = \sqrt{R^2 + [hX_L - X_C/h]^2}$$

The voltage across the terminal of the capacitor will be at fundamental frequency

$$V_{C1} = \frac{V_{Bus}}{j[X_L - X_C]} [-jX_C]$$

$$\frac{V_{C1}}{V_{BUS1}} = \frac{-jX_C}{j[X_L - X_C]}$$

$$\frac{V_{C1}}{V_{Bus}} = \frac{X_C/X_L}{X_C/X_L - 1} = \frac{h_n^2}{h_n^2 - 1}$$

at tuned frequency

$$V_{Cn} = \frac{V_{Bus\,n}}{R + j[X_{Ln} - X_{Cn}]} [-jX_{Cn}]$$

$$\frac{V_{Cn}}{V_{BUS}} = \frac{-jX_n}{R}$$

$$\frac{V_{Cn}}{V_{BUS}} = -jQ$$

$$\boxed{V_{BUS1} = \frac{h_n^2 - 1}{h_n^2} \cdot V_{C1}}$$

$$= V_{C1} - \frac{V_{C1}}{h_n^2}$$

$$\boxed{V_{Bus1} = V_{C1} - V_{L1}}$$

The following points summarize the relevant Quality factor aspects in Single - tuned filters:

* Typically, the resistance of single - tuned harmonic filter is the intrinsic resistance of the reactor.

However, R can be favorably used to vary the Quality factor of the filter and provide a way to control the amount of desired harmonic current through it.

* A large Q value implies a prominent valley at the resonant (tuning) frequency of a filter and there force the trapping of the largest amount of harmonic frequency.

* Higher value of Q factor reduce the harmonic content.

* Computer aided harmonic simulation studies to predict the performance of the filters, especially when multiple harmonic source exist.

• Lower Quality factor filters could be used in situation in which harmonic distortion barely exceeds the limits and a small filtering action is all that is needed to bring it into compliance.

Example: A series filter is tuned to the 13^{th} harmonic Given $X_C = 507$ ohm. calculate the filter elements and plot the filter impedance.

$$X_L = \frac{X_C}{h_n^2} = \frac{507}{(13)^2} = 3\Omega$$

$$\boxed{X_L = 3\Omega}$$

$$X_n = X_{Ln} = X_{cn} = \sqrt{X_L X_c}$$

$$= \sqrt{507 * 3}$$

$$\boxed{X_n = 39\,\Omega}$$

$Q = 100$

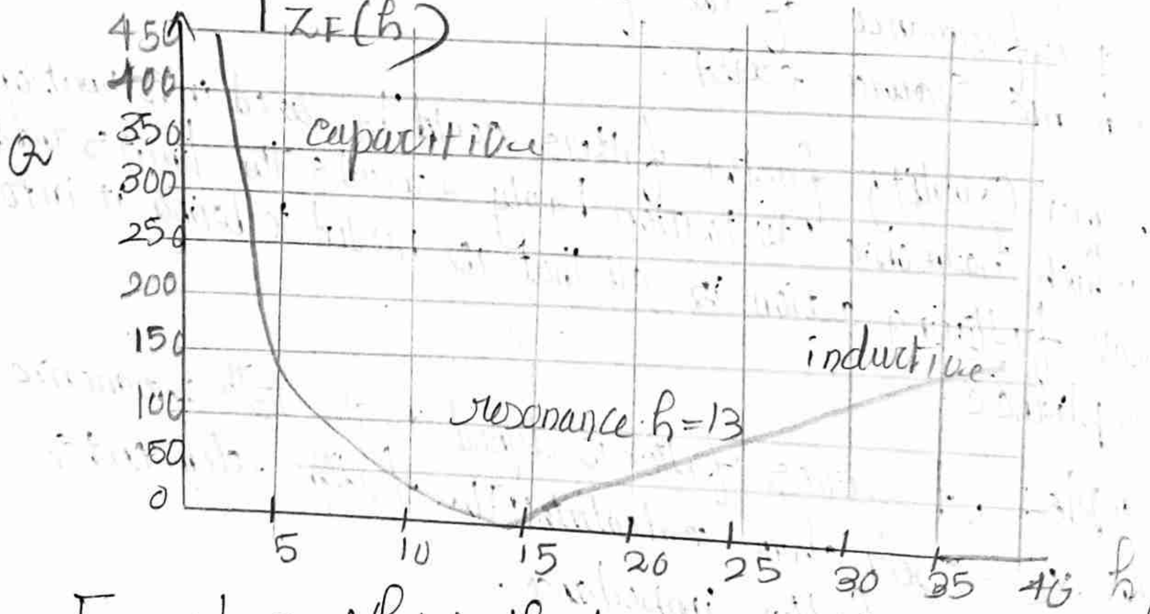
$$R = \frac{X_n}{Q} = \frac{39}{100} = 0.39\,\Omega$$

$$\boxed{R = 0.39\,\Omega}$$

$$Z_F(h) = R + j(hX_L - X_c/h)$$

$$Z_F(h) = 0.39 + j(3h - 507/h)$$

$$|Z_F(h)| = \sqrt{(0.39)^2 + [3h - 507/h]^2}$$



Example 2: What is the tuning order and the Quality factor for a 36KV Series-tuned filter with $X_C = 544.5$ ohm $X_L = 4.5$ ohm and $R = 0.825$ ohm?

$$h_n = \sqrt{X_C / X_L}$$

$$= \sqrt{544.5 / 4.5} = 11$$

$Q = \frac{X_n}{R}$

$Q = \frac{\sqrt{X_C X_L}}{R}$

$Q = \frac{\sqrt{544.5 \times 4.5}}{0.825}$

$Q = 60.$

$Q_C = \frac{KV^2}{X_C} = \frac{36^2}{544.5} \times 10^6$

$Q_C = 2.38\ MVA_r$

$Q_{Filter} = \frac{KV^2}{X_C - X_L}$

$Q_{filter} = \frac{36^2}{544.5 - 4.5} \cdot 10^6$

$Q_{filter} = 2.40\ MVAr$

Example: Which harmonic will be tapped by the filter comprising four series-tuned branches with 3φ, 50Hz, 400V, Y-connected, 1 x 30 + 3* 20 KVAr capacitor bank and 0.779, 0.583, 0.233 and 0.166 mH reactor?

The following table can be constructed for given C and L values:

$X_C = \frac{KV^2}{Q_C}$, $X_L = W_0 L$, $h_0 = \sqrt{X_C / X_L}$

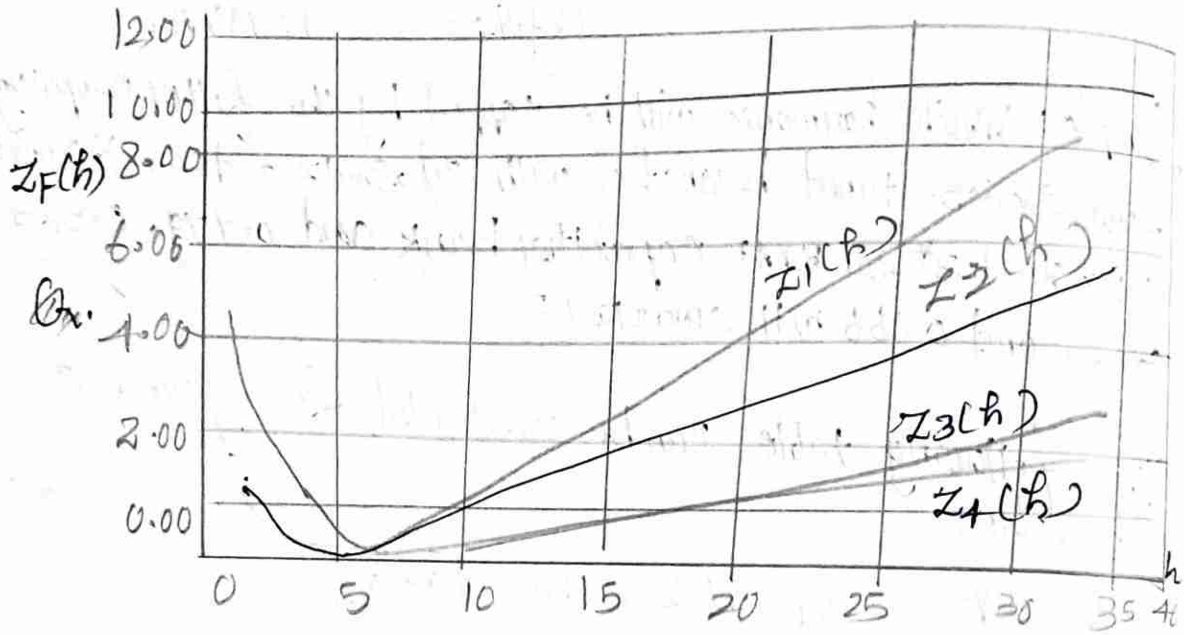
$X_n = \sqrt{X_C X_L}$, Q given $R = X_n / Q$, $R = X_n / Q$.

	Filter-1	Filter-2	Filter-3	Filter-4
Q_C [KVAr]	30	20	20	30
X_C [ohm]	5.33	8.00	8.00	8.00
L [mH]	0.779	0.583	0.233	0.166
h_n	0.2447	0.1832	0.0732	0.0522
X_n [ohm]	1.142	1.210	0.765	0.646
Q	100	100	100	100
R [mohm]	11.42	12.10	7.65	6.46

U3.9

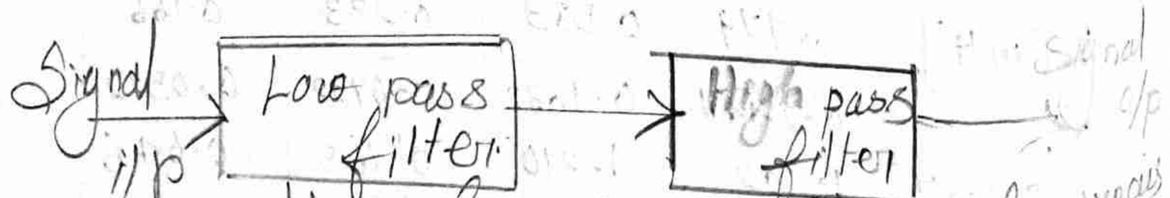
$$\left.\begin{aligned} Z_1(h) &= 0.01142 + j(0.2447h - 5.33/h) \\ Z_2(h) &= 0.01210 + j(0.1832h - 8.00/h) \\ Z_3(h) &= 0.00765 + j(0.0732h - 8.00/h) \\ Z_4(h) &= 0.00646 + j(0.0522h - 8.00/h) \end{aligned}\right\} Z_f(h)$$

$$Z_f(h) = \frac{1}{\frac{1}{Z_1(h)} + \frac{1}{Z_2(h)} + \frac{1}{Z_3(h)} + \frac{1}{Z_4(h)}}$$



Double Band pass filter:

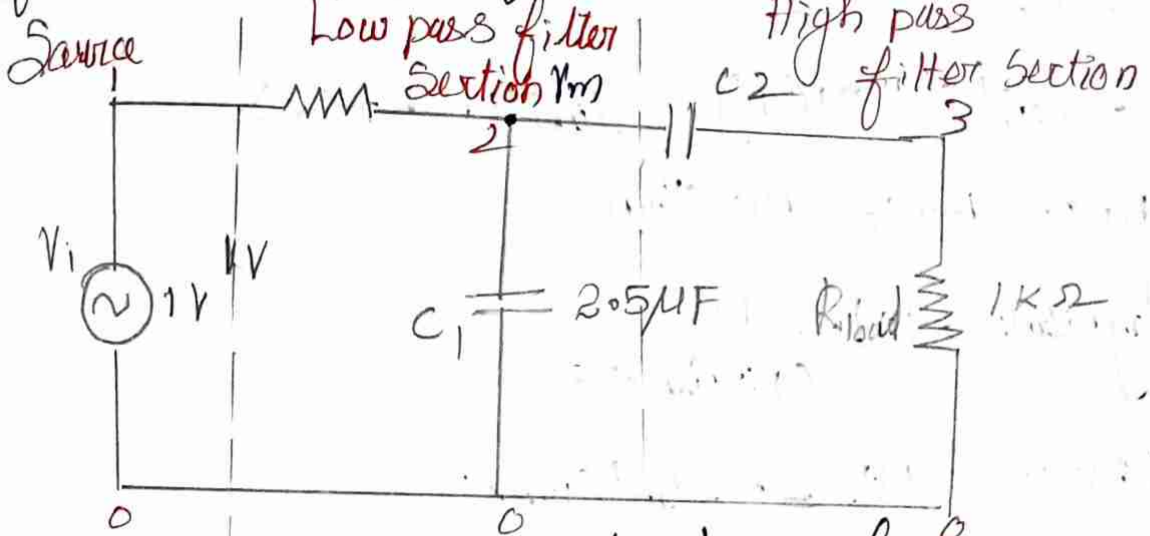
There are applications where a particular band or spread, or frequencies need to be filtered from a wider range of mixed signals. Filter circuits can be designed to accomplish this task by combining the proper of low-pass and high pass into a single filter. The result is called a band-pass filter.



blocks frequencies that are too high   block frequencies that are to low

Design Band-pass filter using Capacitor:

What emerges from the series combination of these two filter circuits is circuit that will only allow passage of those frequencies that are neither too high nor too low. using real components. The response of the band-pass filter shown in figure.



Capacitive bandpass filter.

$$\frac{V_m}{V_{in}} = \frac{ZC_1}{(ZR_1 + ZC_1)} = \frac{1/j\omega C_1}{R_1 + 1/j\omega C_1}$$

$$\boxed{\frac{V_m}{V_{in}} = \frac{1}{(1 + j\omega R_1 C_1)}}$$

$$\frac{V_{out}}{V_m} = \frac{ZC_2}{(ZR_2 + ZC_2)}$$

$$\frac{V_{out}}{V_m} = \frac{1/j\omega C_2}{(R_2 + 1/j\omega C_2)} = \frac{1}{1 + j\omega R_2 C_2}$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + j\omega R_2 C_2}$$

0-3-11

$$\frac{V_{out}}{V_{in}} = \frac{V_{in}}{V_{in}} \times \frac{V_{out}}{V_{in}}$$

$$\frac{V_{out}}{V_{in}} = \left[\frac{1}{1+j\omega R_1 C_1}\right]\left[\frac{1}{1+j\omega R_2 C_2}\right]$$

Magnitude $= |H| = 1/\sqrt{(1+(\omega R_1 C_1)^2)(1+(\omega R_2 C_2)^2)}$

phase $= \angle H = 0 - \angle(1+j\omega R_1 C_1) - \angle(1+j\omega R_2 C_2)$

$= \tan^{-1}[\omega R_1 C_1] - \tan^{-1}(\omega R_2 C_2)$

if $R_1 C_1 = R_2 C_2 = RC$ then

Magnitude $= |H| = \frac{1}{(1+(\omega RC)^2)}$

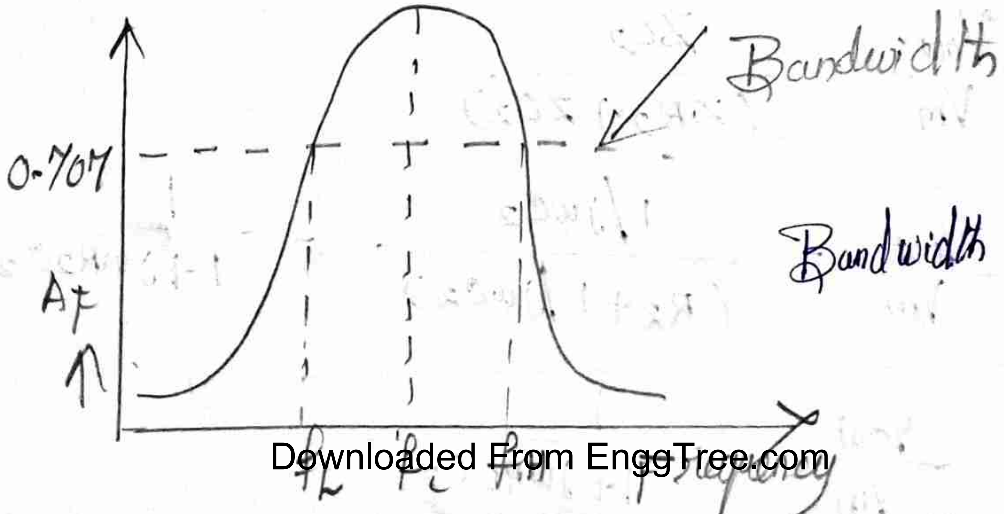
phases $= \angle H = -2\tan^{-1}(\omega RC)$

Quality factor $Q = \frac{f}{B.W} = \frac{f_c}{f_H - f_L}$

wide band filter center frequency

$$f_C = \sqrt{f_H f_L}$$

f_H — higher cut-off-frequency.
f_L - Lower cut-off-frequency

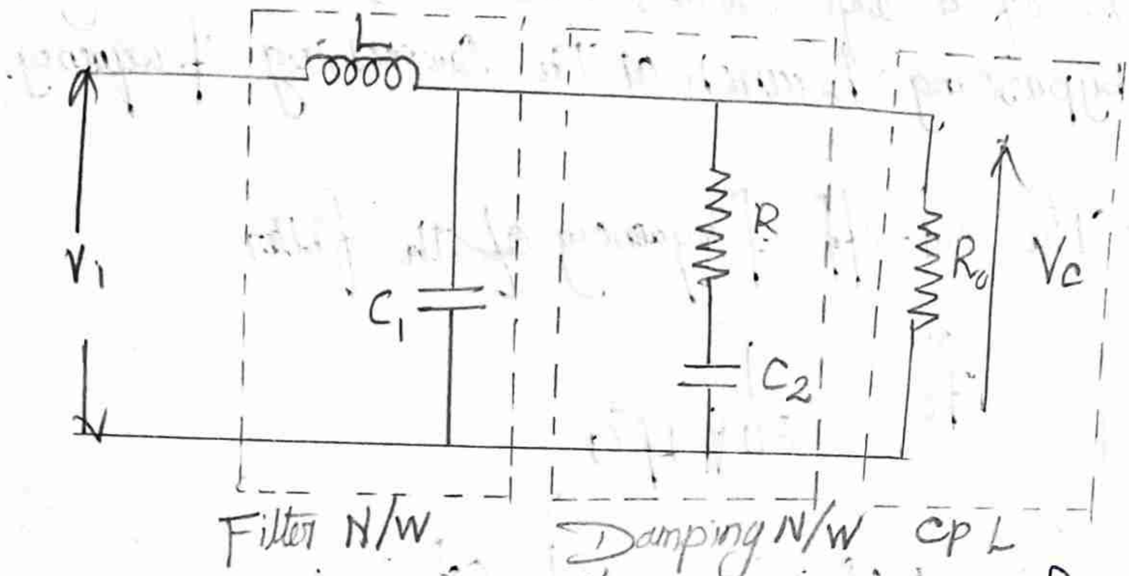


Bandwidth $= f_H - f_L$

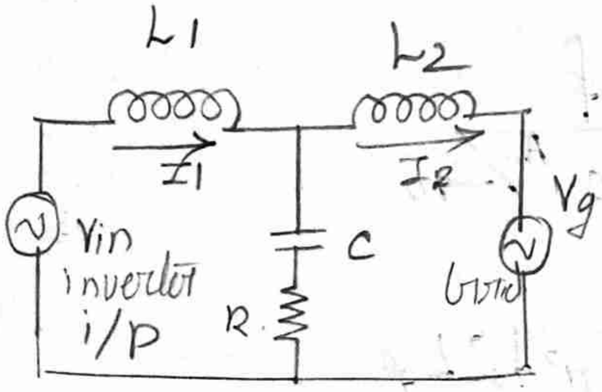
11-3-18

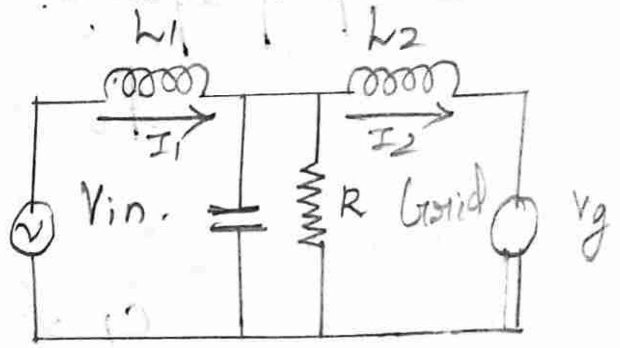
Damped filters:

The damped filter type is mostly used to control higher-order harmonics in the network. It contains higher resistance than single- and double 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.



Series Damped filter | **Parallel Damped filter:**





$$A_{o}\,dB = 20 \log \frac{V_{o,p-p}}{V_{i,p-p}}$$

$V_{1,p-p}$ — peak to peak voltage ripple at the o/p capacitor

$V_{o,p-p}$ — peak to peak o/p voltage.

11-3-23

using phasor analysis, the amplitude of the gain of the LC filter is determined as

$$|H(f)| = \frac{1}{\sqrt{[1-(2\pi f)^2 L_f C_1]^2 + (\omega R_{DC} C_1)^2}}$$

The impedance of the damping branch, which consists of a large series resistor, is much larger than bypassing branch at the switching frequency.

The cut-off frequency of the filter

$$\boxed{f_0 = \frac{1}{2\pi\sqrt{L_f C_1}}}$$

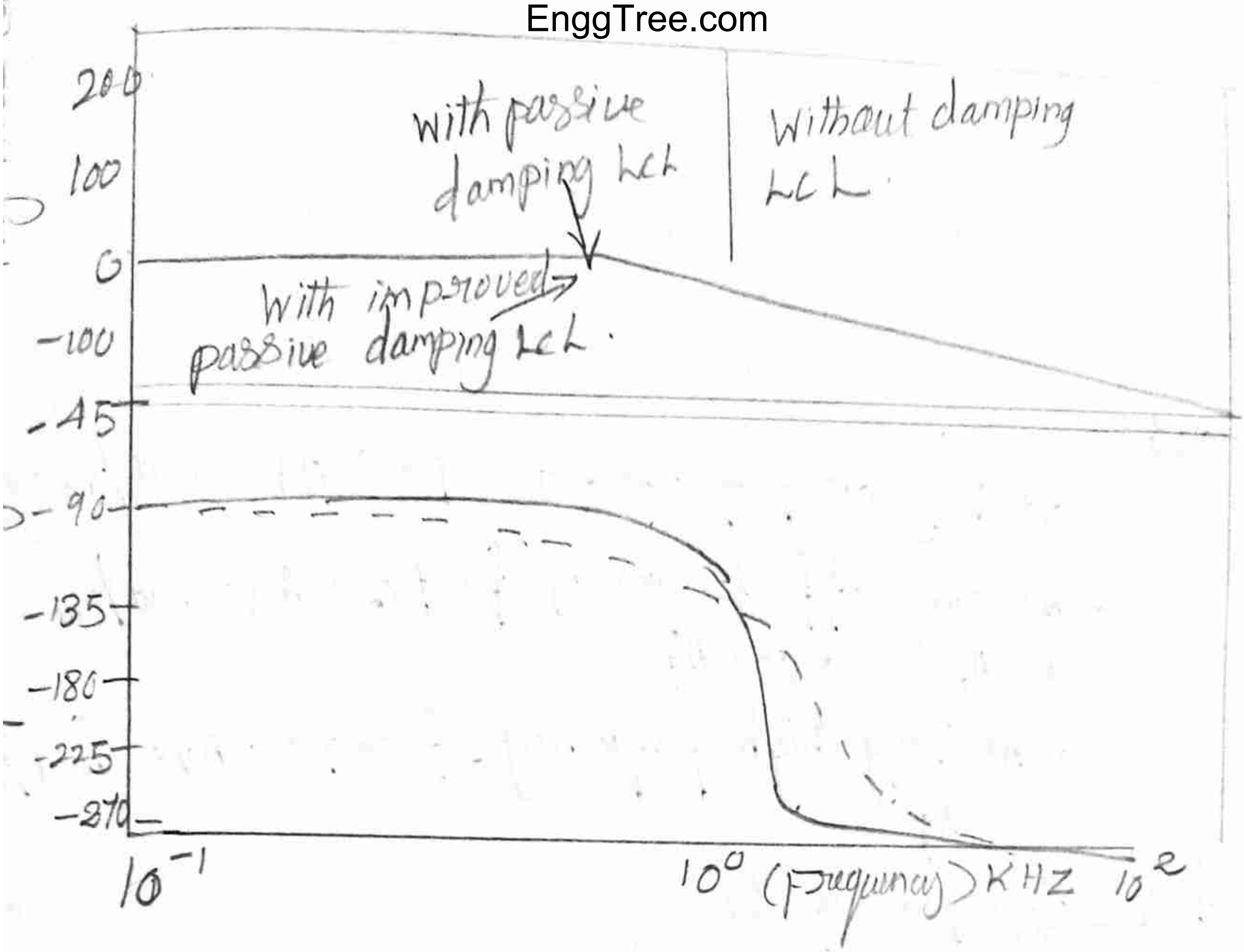
$$A(f) = -40\log\left(\frac{f}{f_0}\right) dB$$

cut-of frequency.

$$f_0 = \frac{f}{10^{A_0/-40}}$$

$$C_1 = \frac{1}{4\pi^2 f_0^2 L_f}$$

Frequency response of LCL filter drawn the graph between phase (deg), Magnitude and dec frequency. with damping & without damping



Active Filters:

The frequency response of Active Low pass filter is same as that of the Passive low pass filter except that the amplitude of output signals. The voltage gain of the non-inverting operational amplifier is given as

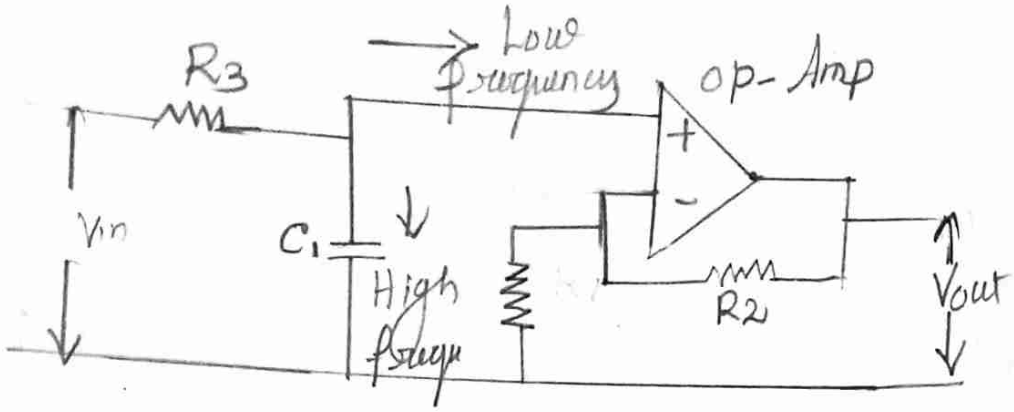
$$A_F = 1 + (R2/R1)$$

The gain of active low pass filter is given as.

$$A_V = V_{out}/V_{in}$$

$$A_V = A_F / \sqrt{(1 + (f/f_c)^2)}.$$

Where
- A_F is the pass band gain $(1 + R2/R1)$
- f is the frequency of input signal.
- f_c is the cut-off frequency.

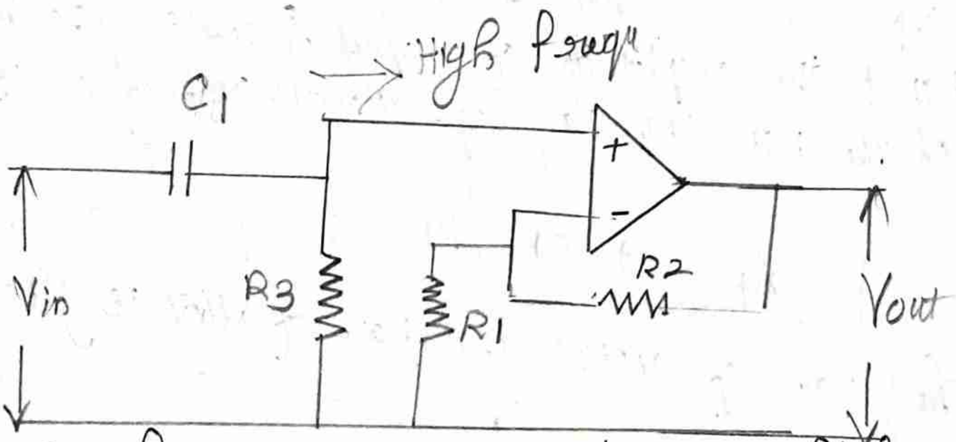


Note:

- At very low frequency, $f < f_c$: $A_V = V_{out}/V_{in} = A_F$
- At cut-off frequency $f = f_c$: $A_V = V_{out}/V_{in} = A_F / = 0.707 A_F$
- At very high frequency, $f > f_c$: $A_V = V_{out}/V_{in} < A_F$.

Active High pass filter:

The simple Active high pass filter can be obtained by connecting a non-inverting or inverting operational amplifier to the passive high pass RC circuit.



The frequency response of active high pass filter is same as that of passive low pass filter, except that the magnitude of the signal is increased by gain of operational amplifier.

In active high pass filter pass band is limited due to the open loop characteristics of operational amplifier.

The gain of active high pass filter is given as.

$$A_V = V_{out}/V_{in}$$

$$A_V = A_F (f/f_c) / (\sqrt{[1+(f/f_c)^2]})$$

A_F is the pass band gain $(1+R_2/R_1)$

f is the frequency of i/p signal

f_c is the cut-off frequency.

$$A_V(dB) = 20\log_{10}(V_{out}/V_{in})$$

$$-3dB = 20\log_{10}(0.707 \times V_{out}/V_{in})$$

For a first order Active high pass filter the frequency response curve increase at a rate of 20dB/decade or 6dB/octave until it reaches the cut-off frequency point same as like passive filter here also cut-off frequency can be calculated using the formula.

$$f_c = 1/2\pi RC$$

In this filter phase shift or phase angle of the output signal leads that of the input signal. At cut-off frequency phase angle value is equal to the +45°. This value can be calculated using the below formula.

$$\text{Phase Angle } \phi = \tan^{-1}(2\pi RC)$$

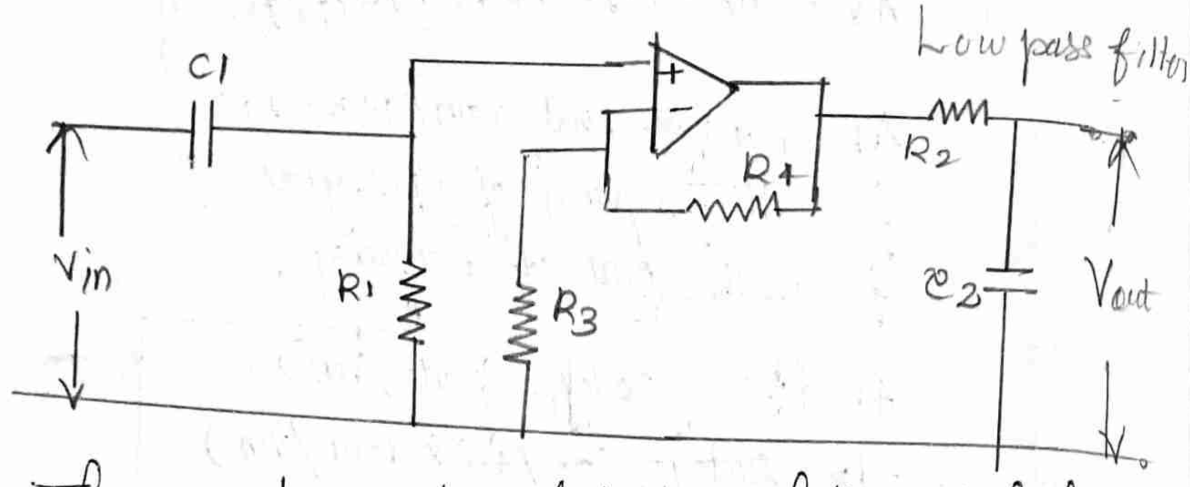
Active Band Pass filter.

Band pass filter is frequency selective filter used in electronic system to allow a particular band or certain range of frequencies. This range of frequencies is set between two cut-off frequency points.

(f_{L}, f_{H})

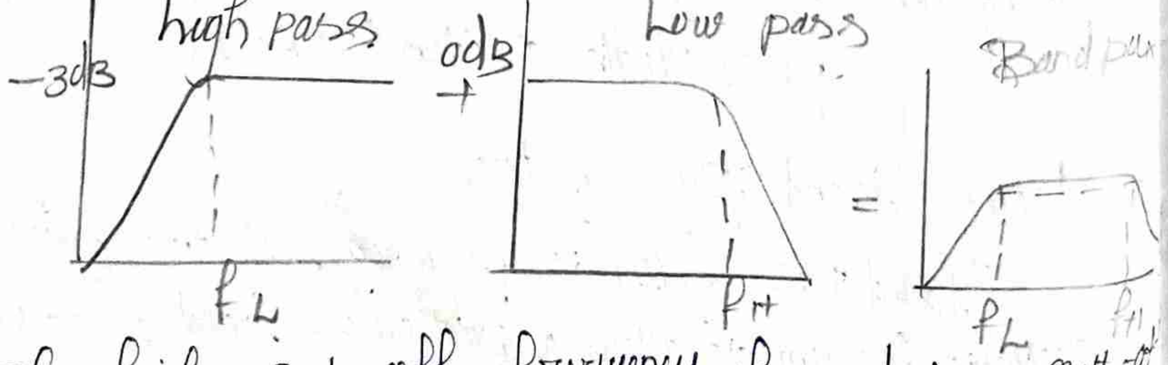
U-3-17

Active pass band filter can be easily designed by Combining or cascading a low pass filter with a high pass filter as shown below.



This cascad connection of low pass filter and high pass filter produces a low "Quality factor" type filter which has wide pass band. The first stage of the circuit (high pass filter stage) blocks the very low frequency signals and low pass filter stage block the very high frequency signals.

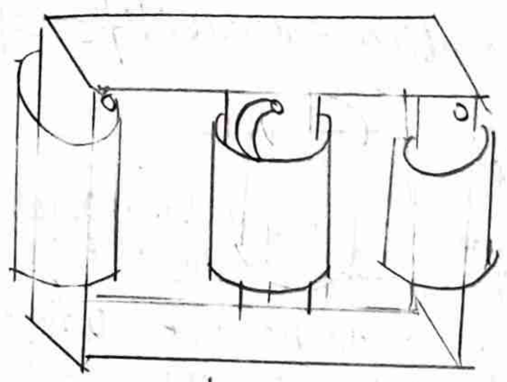
* It produces the relatively flat pass band frequency response in which one half represents high pass stage) blocks the very low frequency signals and low pass filter stage blocks the very high frequency signals.

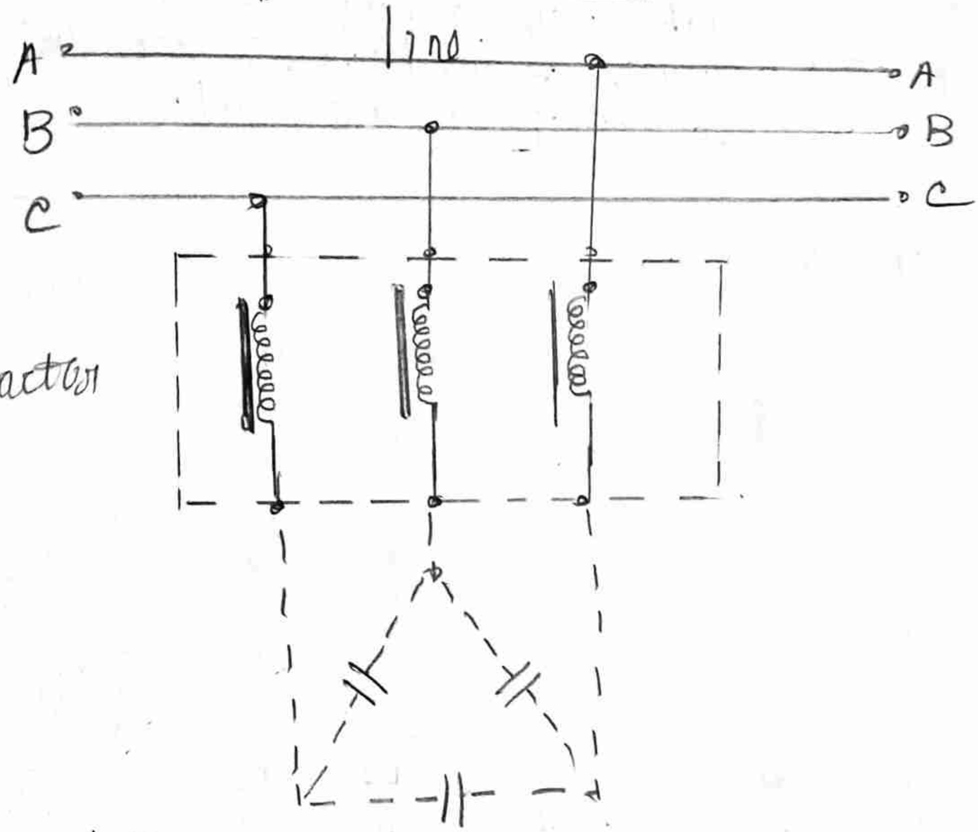


The higher cut-off frequency f_H and lower cut-off frequency f_L are calculated using the first order low pass and high pass filter cut-off frequency equation. The amplifier circuit provides isolation b/w two stages and increase overall gain of the circuit.

Detuned filters:

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





Introduction:

Power disturbance and harmonic distortion in electrical system have proven to be fatal to equipment, cables, Transformers, capacitor bank etc. The Situation has deteriorated further with the use of products such as Variable speed drives, soft starters, rectifiers, UPS, discharge lamp etc. These devices will generate or increase the harmonic distortion and high frequency interference in the power system. These disturbance will cause the overheating to cables.

tranformers and related equipment etc

1) Detuned Harmonic Circuit Filter reactor is used for:

- filtering harmonics and high frequency disturbance
- reduce high inrush current (from parallel switching of capacitor & from power to capacitor banks and thus improve the operating source life span of the capacitor

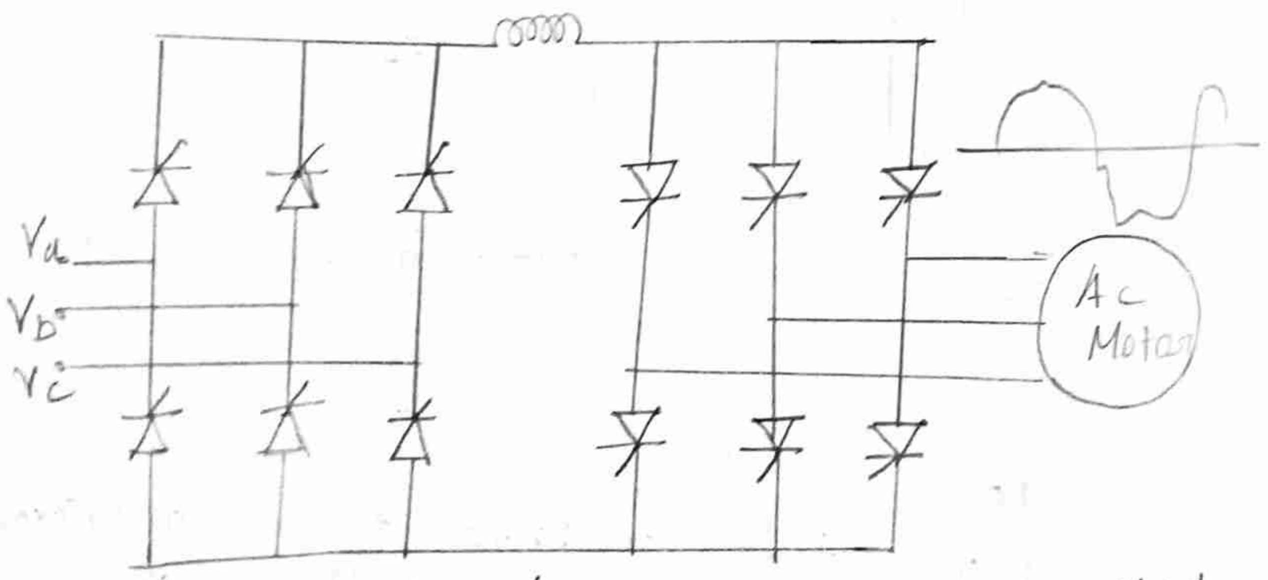
for 50Hz System:

P = 7% = 189 Hz is used when protection to capacitor and harmonic reduction is required.

P = 6% = 204 Hz is to be used where the System is rich in 5th harmonic and above

P = 13% = 139 Hz is used where voltage distortion exceed permissible limit.

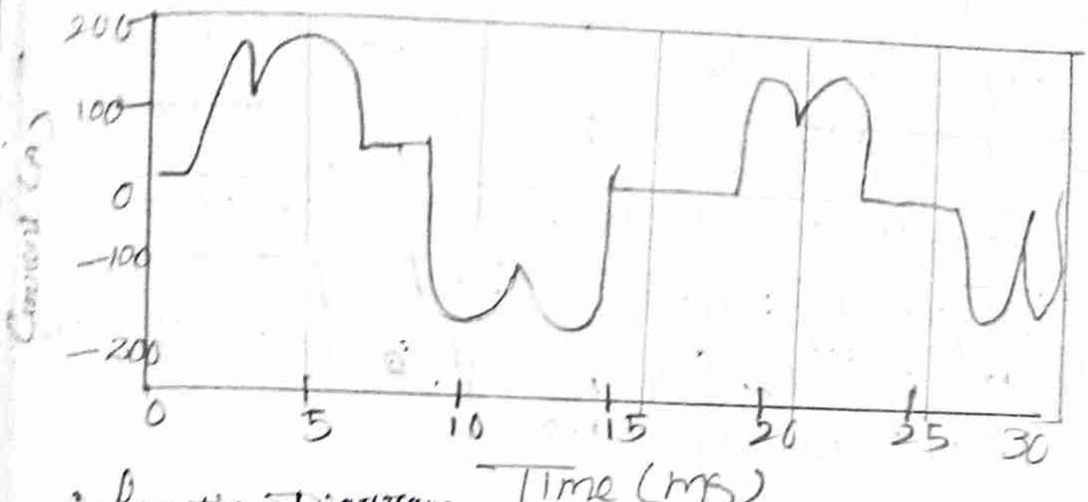
Power Converters:



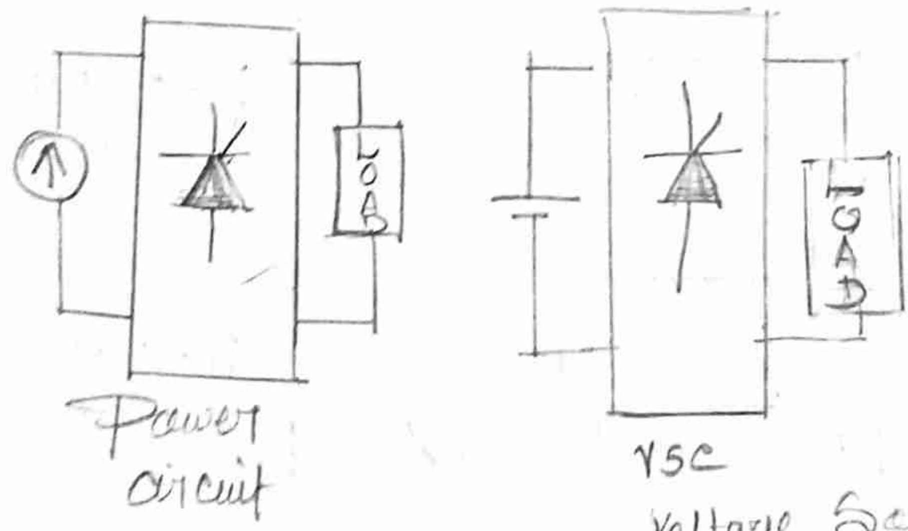
. Current Source Inverts requires a constant current input; hence a Series inductor is placed in the DC link.

* CSI drives have good acceleration/deceleration characteristics.

CSI requires a motor with leading power factor (Synchronous or induction with capacitor) or added control circuitry to commutate the inverter thyristors.



Schematic Diagram of CSC and VSC:

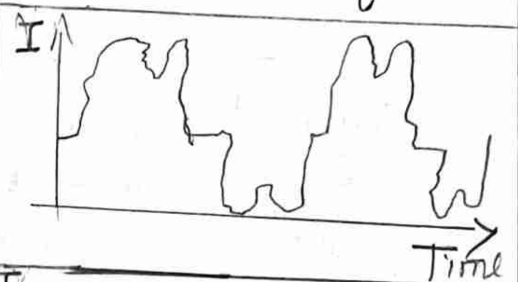
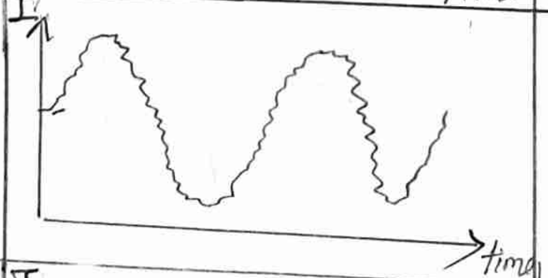
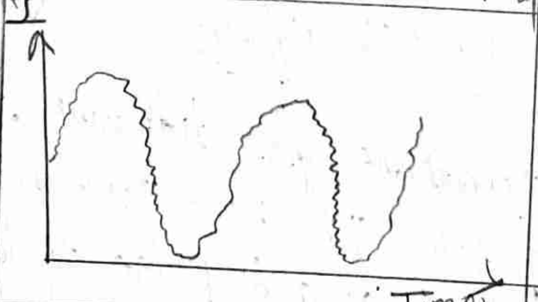


using 6-pulse Diode Rectifier:

The connections for different rectifier solutions are shown in figure. The most common rectifier circuit 3-phase AC drives is a 6-pulse diode bridge. It consists of 6-uncontrollable rectifiers or diodes and an inductor, which together with a DC capacitor forms a low-pass filter for smoothing the DC current. The inductor can be on the DC - or AC - side or it can be left totally out. The 6-pulse rectifier is simple and cheap but it generates high amount of low order harmonics 5th, 7th, 11th especially with small smoothing inductance. The current waveform is shown in figure. If the major part of the load consists of converter with a 6-pulse rectifier, the supply transformer needs to be oversized and meeting the requirements in standards may be difficult. Often some harmonic filtering is needed.

In general the characteristic equation of n-pulse converter is given by : $h = np \pm 1$, where p is the pulse number of the converter say $p = 2, 4, 3, 6, 12$ etc and n is the integer values say $n = 1, 2, 3$

Harmonic in line current with different rectifier Construction

Supply Type	Current waveform	Harmonic order
6-pulse Diode rectifier.		$h = 5, 7, 11, 13$ $17, 19$
12 pulse Diode rectifier		$h = 11, 13, 23$ $25, 35, 37$
24 pulse Diode bridge rectifier.		$h = 23, 25,$ $47, 49$

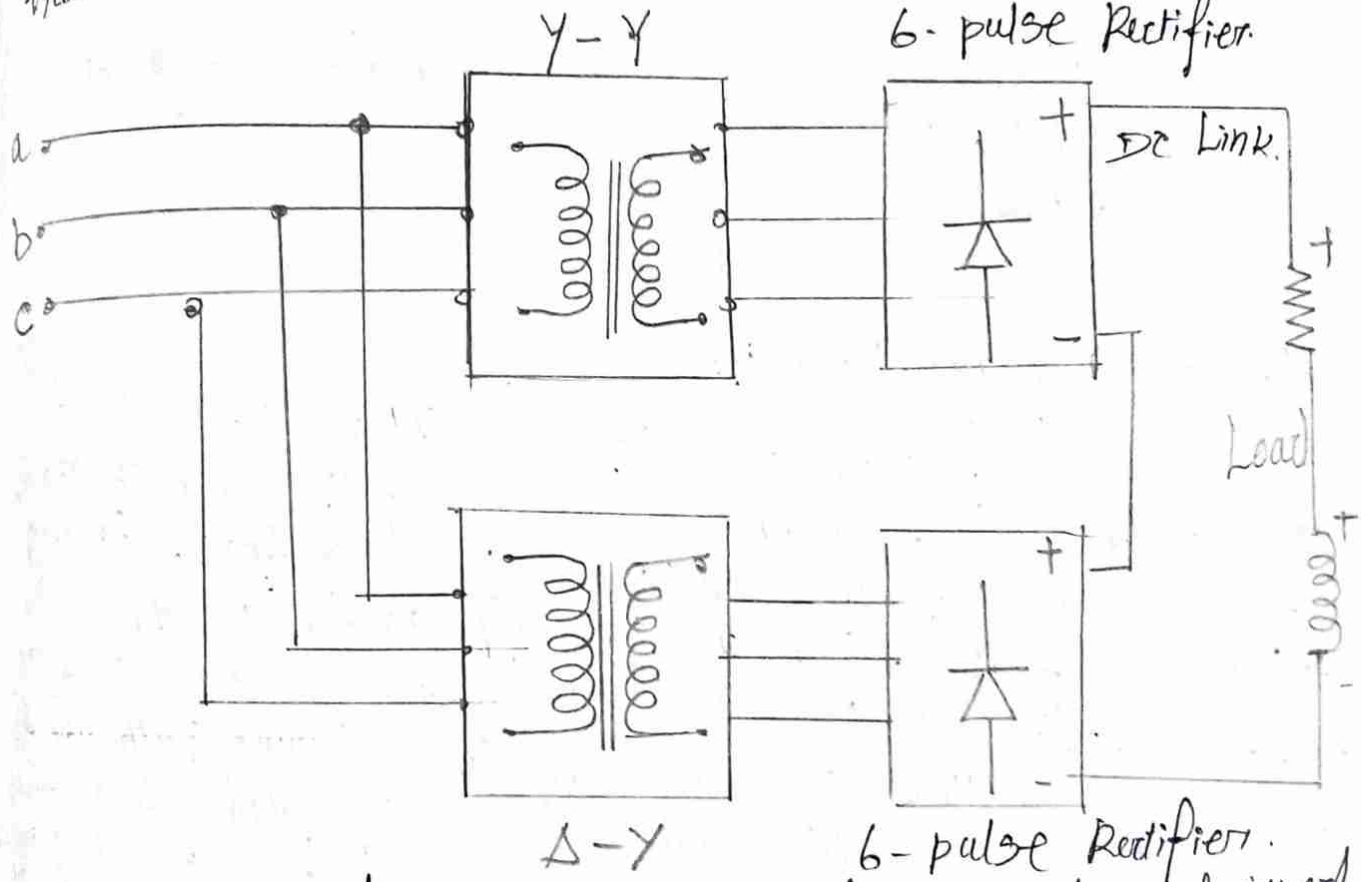
<u>using 12 pulse or 24-pulse Diode Rectifier:</u>

The 12-pulse rectifier is formed by connecting 6-pulse rectifier in parallel to feed a common DC-bus.

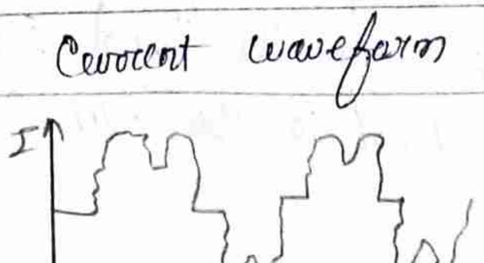
The input to the rectifier is provided with one three winding transformer.

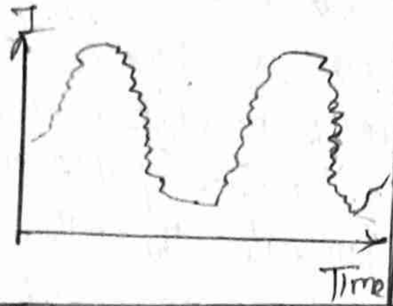
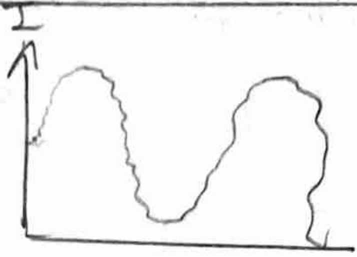
V-3-22

The Transformer Secondary's are in 30° phase shift. The benefit with this arrangement is that in the supply side some of the harmonics are in opposite phase and thus eliminated. The resultant phase current waveform more closely looks like an ideal sine wave than the six-pulse case. This is because the 12-pulse topology eliminates the 5th, 7th, 17th and 19th harmonics, leaving the 11th, 13th, 23rd and 25th harmonics.



The principle of the 24 pulse rectifier is also derived from two 12-pulse rectifiers in parallel with two three winding transformers having 15° phase shift. The benefit is that practically all low frequency harmonics are eliminated but the drawback is the high cost. In case of a high power single drive or large multidrive installation a 24-pulse system may be the most economical solution with lowest harmonic distortion.

Supply type	Current waveform	Harmonic order.
6-pulse Thyristor rectifier.		h = 5, 7, 11, 13, 17, 19 ....

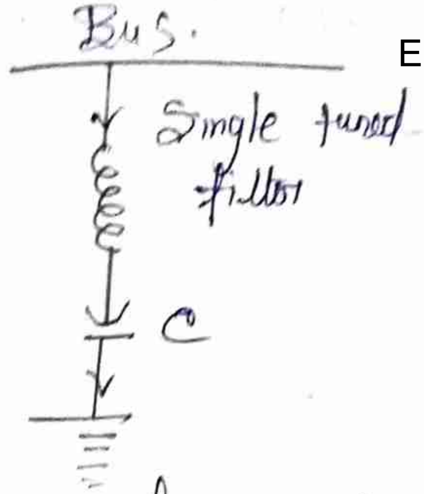
12-pulse Thyristor rectifier.		h = 11, 13, 23, 25 35, 37
IGBTs Supply unit		h = 23, 25, 47, 49 ...

Harmonic filter Design:

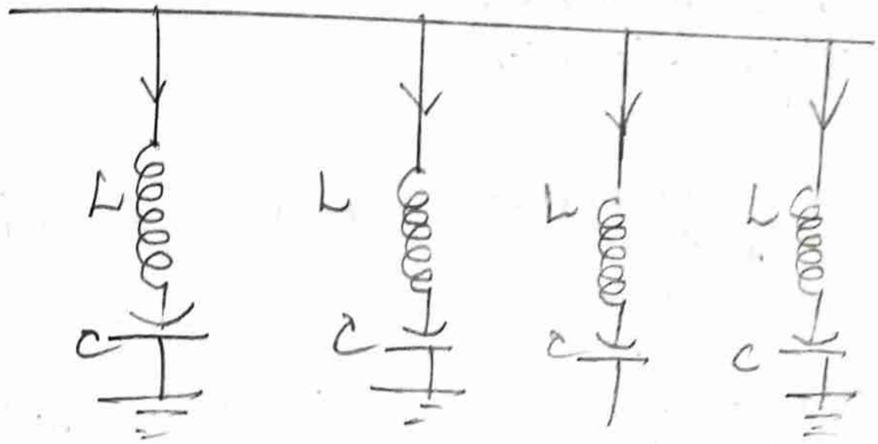
Harmonic filtering is one of the Solutions to prevent the troublesome harmonics from entering the rest of the system. They are passive filters and active power filters. Among the passive filters, there are two approaches to suppress undesired harmonic currents; using a Series impedance to block them by Means of a low impedance Shunt path. The former is called series filters and the latter is called Shunt filters. Series filters are not commonly used because they must carry full load Current and be insulated for full line Voltages. These factors make a series filter more expensive than Shunt filters

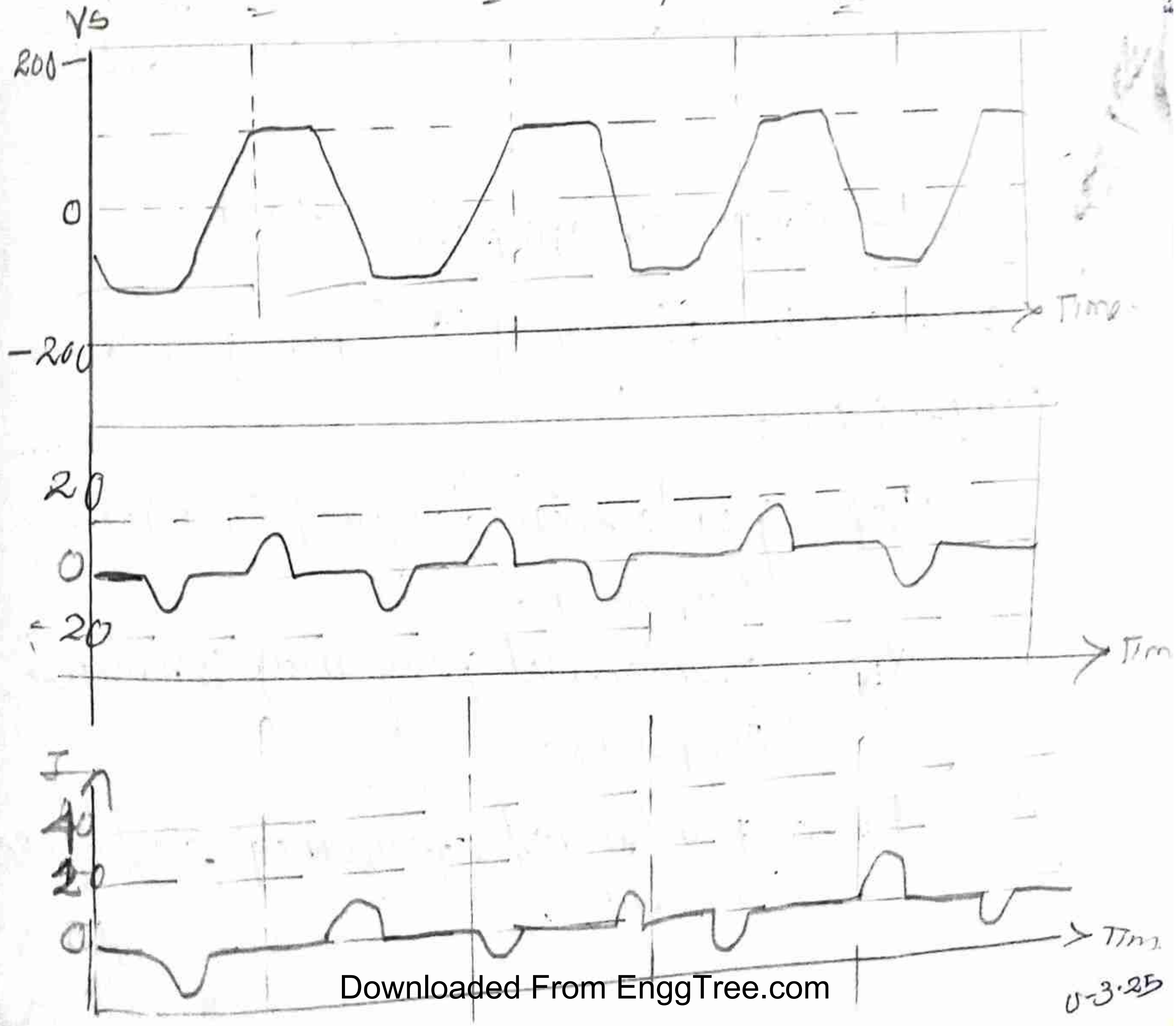
Passive filtering:

A Shunt filter is required to trap the harmonic Current to Correct the power factor of load and properly filter the harmonics of the load. Shunt filters are usually more practical to use than series filters.



Single frequency tuned filter.





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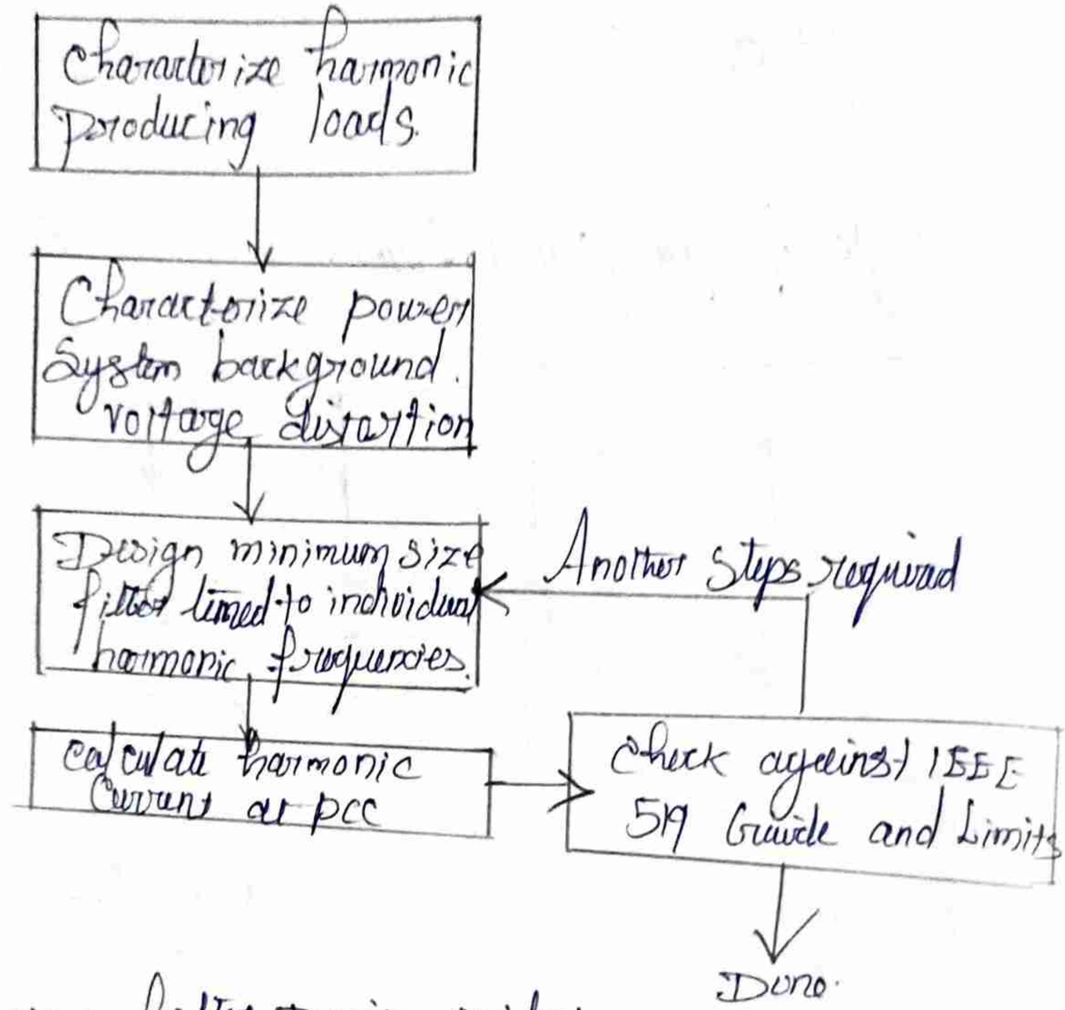
General procedure for designing individually tuned filters.



Passive filter Design criteria:

Fundamental frequency Reactive power Compensation:

X_{cf} = Fundamental frequency Capacitive Component.

X_{Lf} = Fundamental frequency Inductive Component.

R_f = Fundamental frequency resistive Component, Total reactive power supplied to the filter is given by

$$Q_F = 2\times\pi\times f h.$$

$$= 2\times\pi\times f\times h.$$

f = power System fundamental frequency.

fh = power System harmonic Tuning frequency.

h = harmonic order.

At the tuning frequency, The capacitive and inductive component of the filter becomes equal

$$\boxed{\frac{1}{2\pi h f C_f} = 2\pi h f L_1}$$

$$\frac{X_{cf}}{h} = h \times X_{Lf}$$

Thus the tuning frequency, The capacitive and inductive component of the filter becomes equal.

$$\boxed{f_h = \frac{1}{2\pi\sqrt{L_H C_h}}}$$

Assume resistance of coil is small, and then the fundamental frequency reactive power can be given as.

$$Q_1 = \frac{V^2}{X_{Lf} - X_{cf}}$$

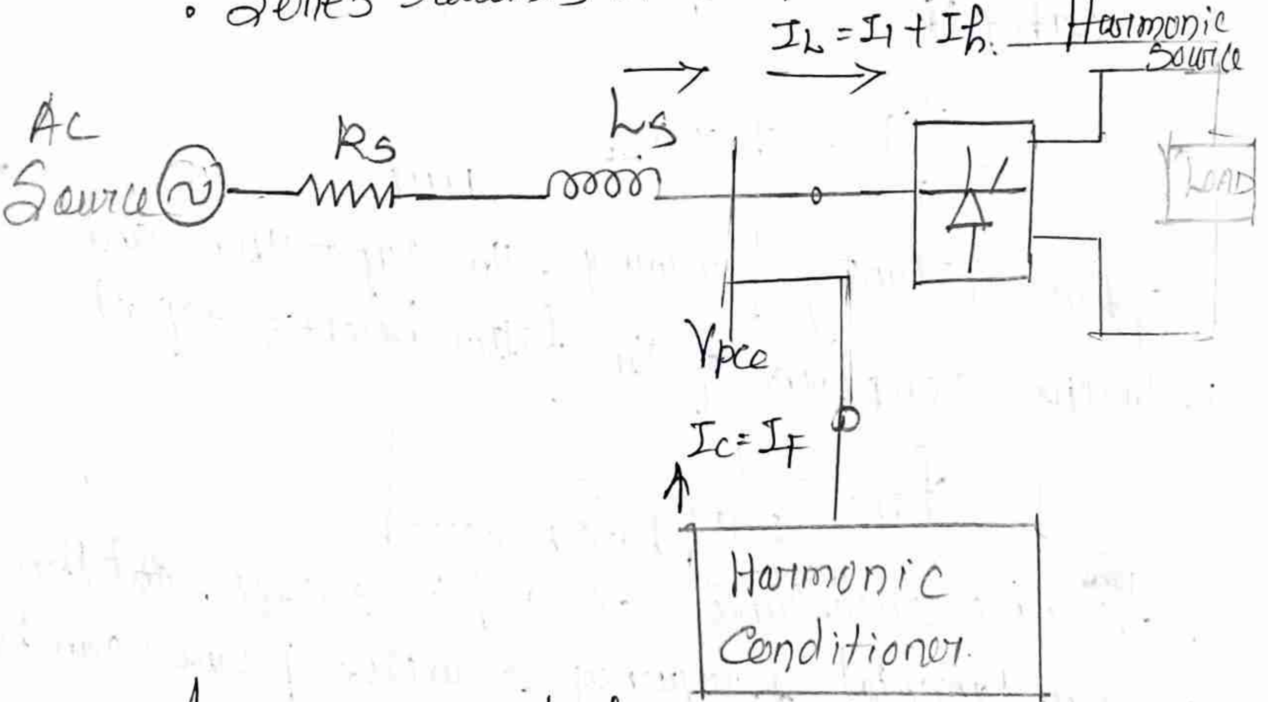
V is the Magnitude of the fundamental Voltage at the bus where filter is located. Also Quality factor of the coil is taken into account Thus

$$Q = 2\pi h f L_H / R_f$$

Active power Filtering:

Industrial and commercial power System usually incorporate power capacitors to improve the power factor and provide reactive power for voltage Support. when the System includes Sources of harmonic current, Such as power electronic converters or adjustable Speed drives (ASD), the capacitors May be used in power harmonic filter to minimize the harmonic Voltage applied to the System load at the point of common coupling (pcc). The current harmonics produced by power converters, usually polyphone rectifiers. can be reduced in one of three ways:

- Series reactors in the input line:



A passive tuned filter introduces new resonance that can cause additional harmonic problems. New power electronic technologies are resulting in products that can control harmonic distortion with active control. These active filters provide Compensation for harmonic components on the utility System based on existing.

harmonic generation at any given moment in time. A typical distribution system showing a possible location for a harmonic filter shown in figure.

Topologies of Active harmonic conditioner: (Active power filters)

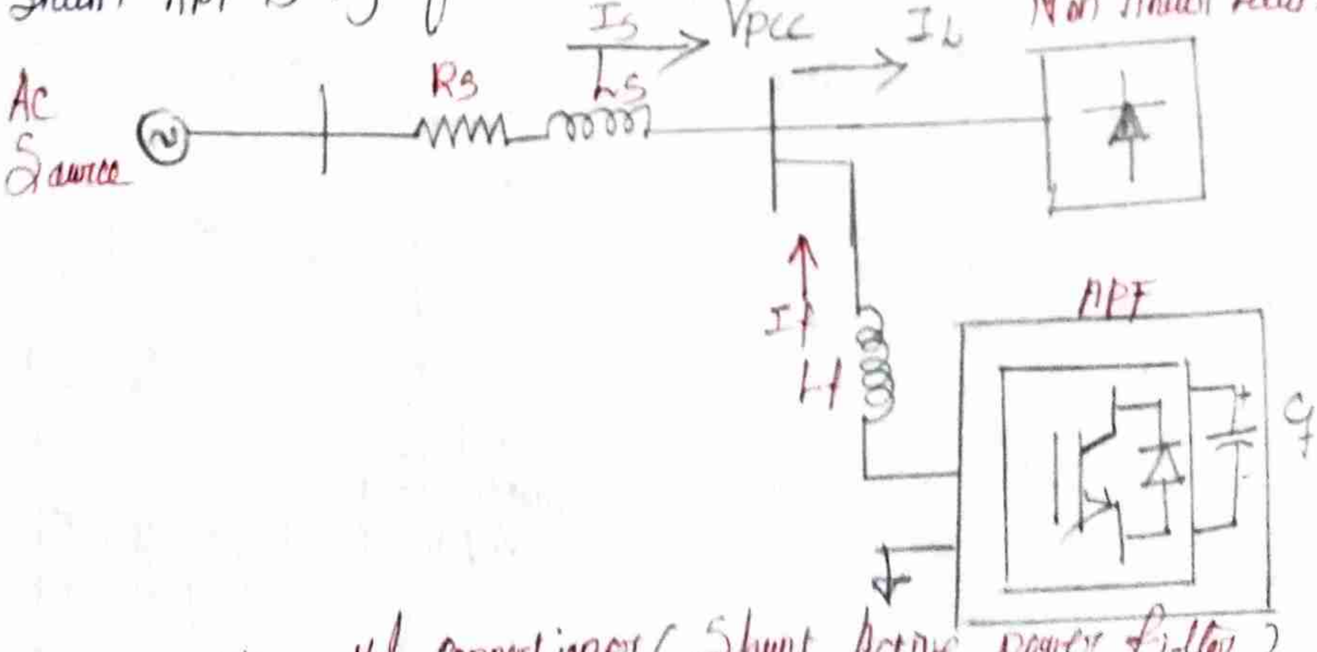
Active harmonic conditions (filters) can be broadly classified into three categories:

- parallel conditioners (Shunt APF)
- Series Conditioners (Series APF)
- Hybrid conditioners (Hybrid APF)

Parallel conditioners (Shunt Active power filters)

Shunt Conditioners They are connected in parallel with AC line and need to be sized only for the harmonic power (harmonic current) drawn by the nonlinear loads. This is the most important configuration and widely used in active filtering applications. A Shunt APF consists of a controllable voltage or current source applications.

A Shunt APF consists of a controllable voltage or current source. The voltage source inverter (VSI) based Shunt APF is by far the most common type used today.

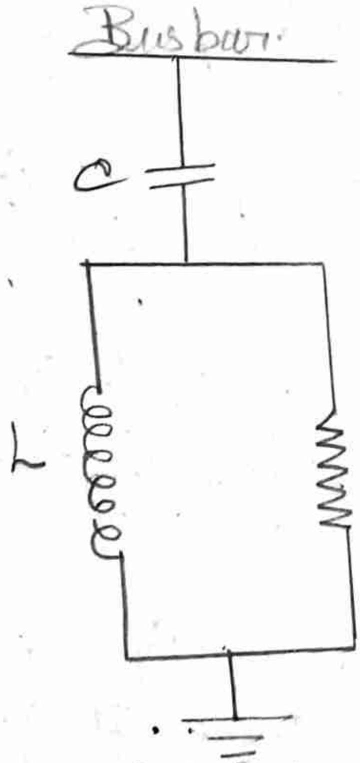


Parallel connectioner (Shunt Active power filter)

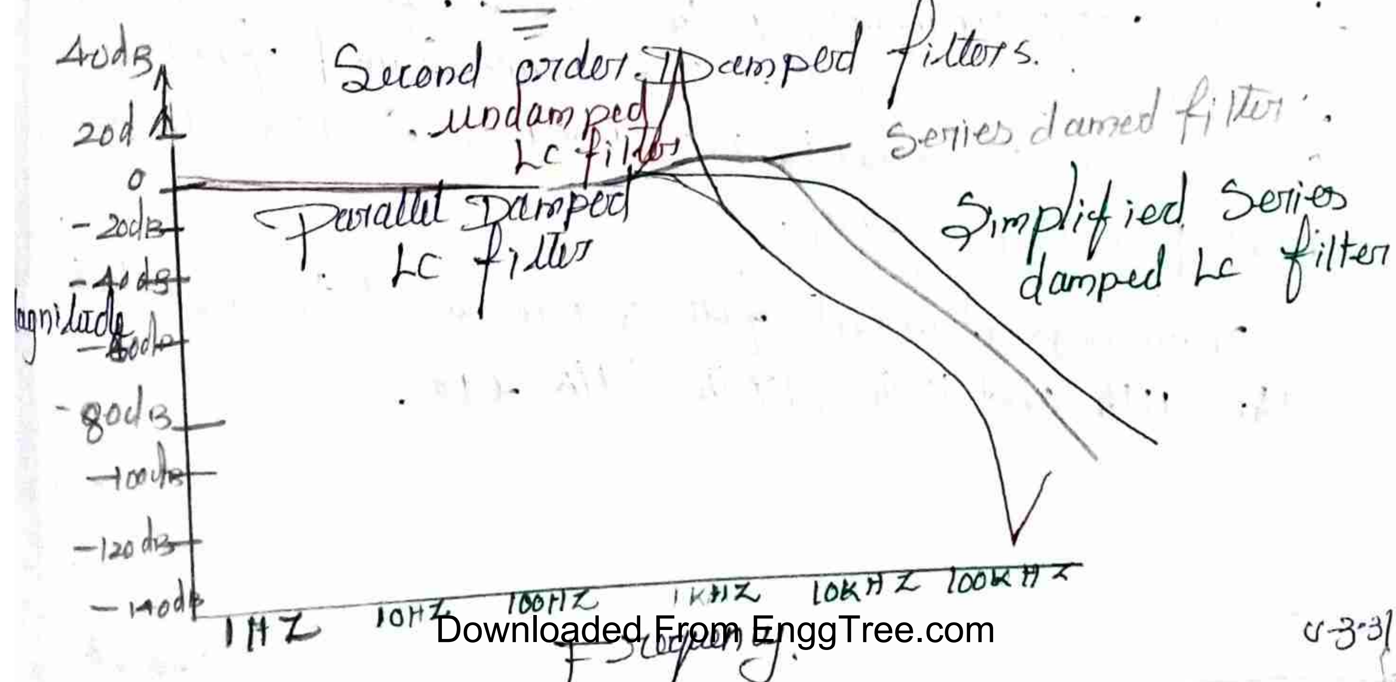
Hybrid APFs, inheriting the advantages of both passive filters and APF, Hybrid APF, inheriting the advantages of both passive filters and APF provide improved performance and co-efficient Solution.

Second order Damped filter:

Second order (or two-pole) filters consist of two RC filter sections connected together to provide a -40dB/decade roll-off rate.



A second order filter provides better attenuation of higher frequencies resulting in a more effective filtering of unwanted noise or signals.



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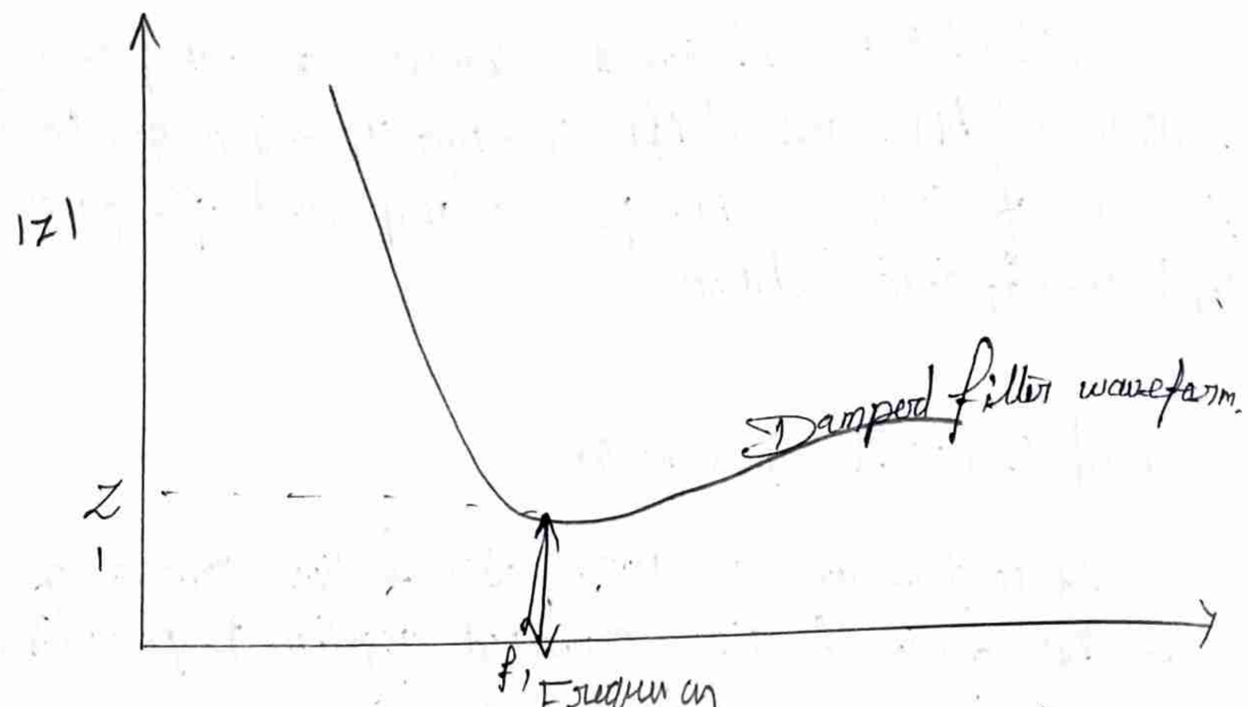


A Second order filter can be obtained by the use of single op amp first order low pass filter by simply using an additional RC network

The second order filter block implements different types of second-order filters. Filters are useful for attenuating noise in measurements signals.

first order, it might has either an single (inductor or capacitor). If its 2nd order, they might have two component (inductors or capacitor)

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 power frequency.

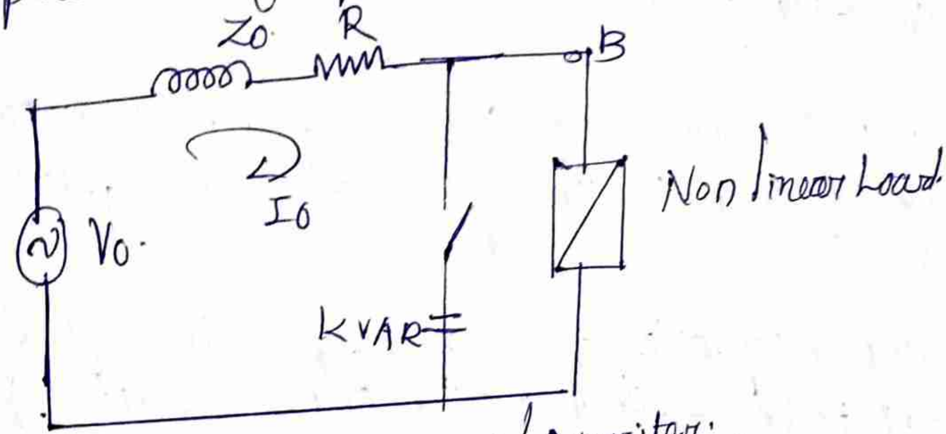
commonly, damped filters are used to reduce the 11th and 13th, 17th 19th etc.

Impedance plots for filter Banks

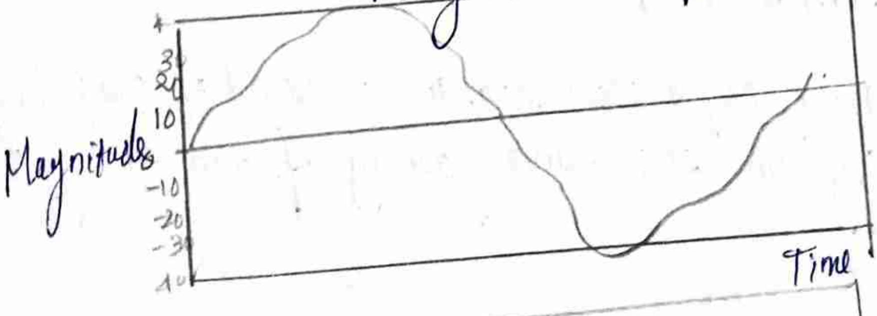
The protection of a harmonic filter is different than that of a Shunt capacitor bank. Typically Shunt capacitor Banks are protected for case rupture by expulsion or current limiting fuses.

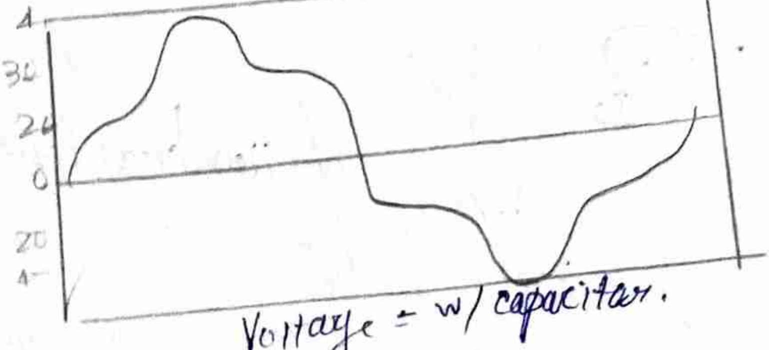
As described earlier, harmonic Voltages are usually caused by the interaction between harmonic Currents and the power System impedance. under normal Condition, this relationship does not result in Significant Voltage distortion.

However, when power factor Correction capacitors are applied to a power System where harmonic Currents are present, the capacitor and System impedance (inductive) will resonate at a particular frequency.



Voltage - w/o capacitor.





Voltage - w/ capacitor.

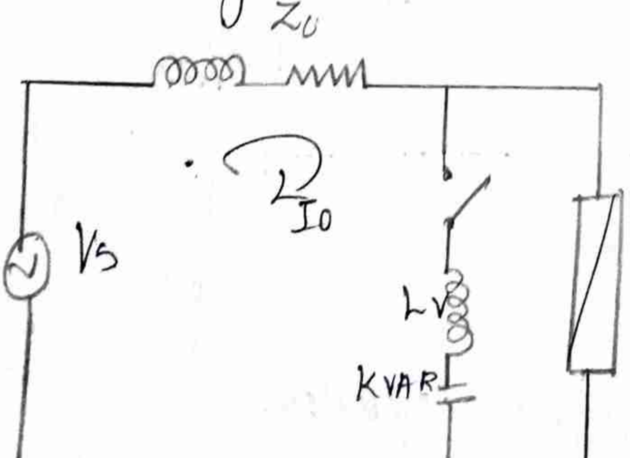
the System without capacitors results in minimal Voltage distortion. However, the Same System with the addition of capacitor result in parallel resonance near the fifth harmonic and Significant increase in harmonic distortion created. Notice the Sharp increase in peak Voltage.

Method for Solving harmonic Distortion Problems:

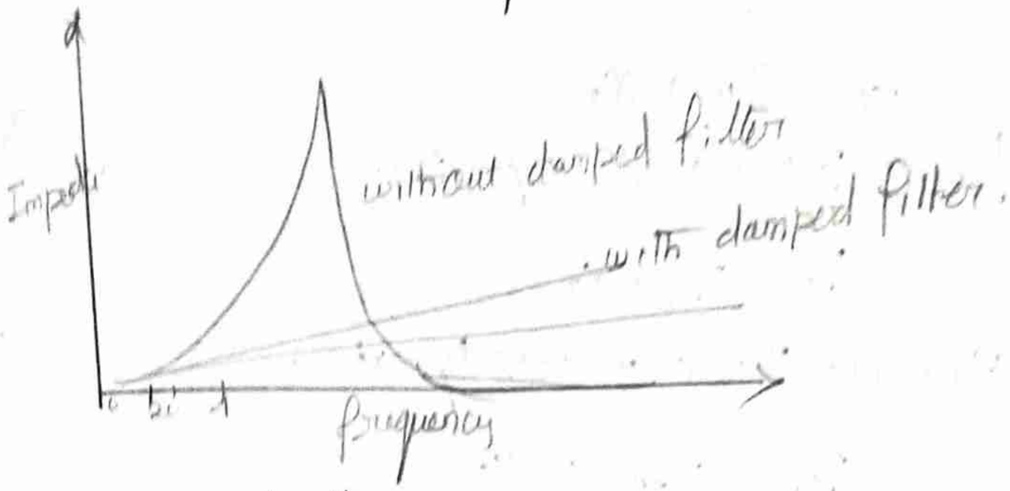
The application of an LC tuned or 'notch' filter is to simply short circuit a particular harmonic current. This filter may also be used to move the resonant frequency of the System Safely away from troublesome harmonic. This is useful in instances when a power System is capable of absorbing the harmonic currents produced by a load except when resonance exists. The fundamental approach to the filter design is.

1. Determination of amount of harmonic current to be filtered and the required harmonic frequency (2fn, fn).
2. Select a capacitor size based upon the required harmonic current to be filtered and the 60Hz reactive power required. (MVAR, Xc)

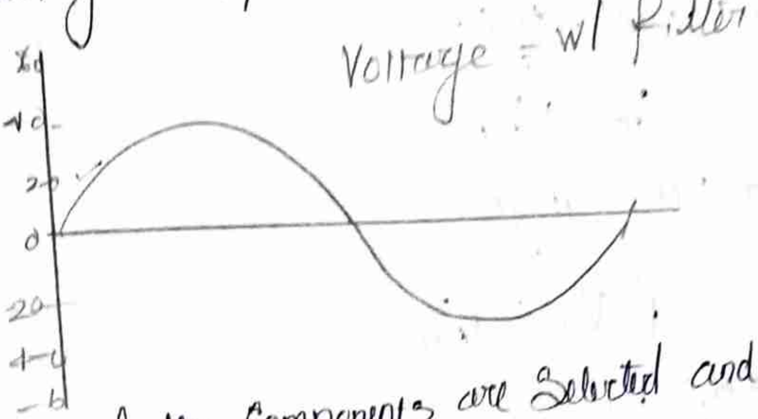
The existing capacitor bank is used to safely detune the System resonance away from the fifth



Impedance vs Frequency



Voltage - w/o filter



Once the filter components are selected and they are checked to insure that they will operate within their ratings, the expected system results are reviewed.

Resonance Frequency

$$f_r = 60 \times \sqrt{\frac{KVA_{sc}}{KVAR_{cap}}}$$

Filter Design Given Capacitor size & filter frequency

Reactor Impedance.

$$X_L = \frac{kV^2}{KVAR \times n^2 \times 1000}$$

Filter Duty

$$I_n = \frac{V_{in}}{X_C - X_L}$$

Total RMS Current

$$I_{rms} = \sqrt{I_h^2 + I_{fn}^2}$$

Fundamental Voltage across Capacitor.

$$V_{C1} = I_n \times X_c$$

Harmonic Voltage across capacitor.

$$V_{C1} = I_{fn} \times X_c$$

Harmonic Voltage across Capacitor.

$$V_{cn} = I_{fn} \times \frac{X_c}{n}.$$

Approximate peak Voltage.

$$V_{peak} = V_{cl} + V_{cn}$$

Approximate RMS Voltage.

$$V_{rms} = \sqrt{V_n^2 + V_{En}^2}.$$

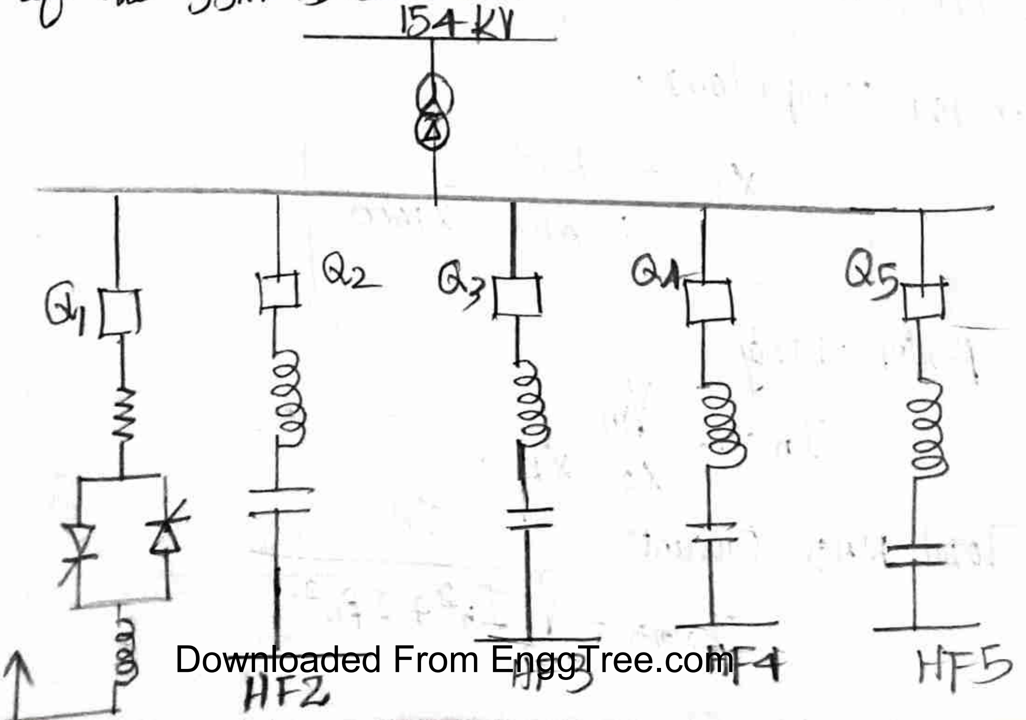
Approximate RMS Voltage

Approximate Reactive power of filter.

$$KVAR = 3 \times \sqrt{V_{rms}^2 \times I_{rms}^2}$$

Impedance plot for a Three phase 33 kV Filter:

A 33 kV distribution network of island Business District. Eco Electricity Distribution plc, from which one of the 33kV Distribution lines

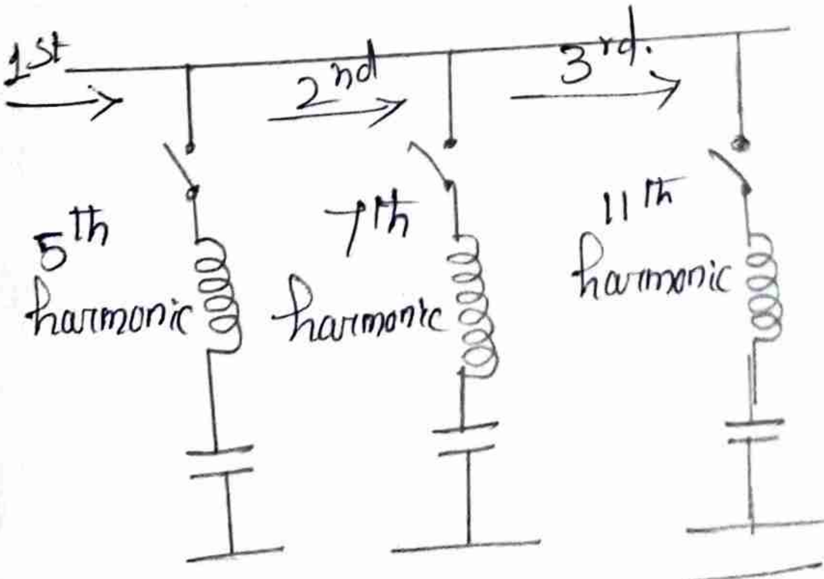


capacitor banks, which are normally used for reactive power compensation, are composed of series and parallel capacitor units.

In addition inductors, often called current limiting reactors are placed b/w the main bus and the capacitor bank to mitigate transient inrush currents for a short-circuit near to the capacitor banks. The equivalent circuit of the capacitor banks are therefore: the combination of the inductance and capacitance in series similar to the single-tuned and de-tuned filter.

A high magnitude and frequency inrush current and voltage occur during back-to-back switching in capacitor banks. Numerous studies have been conducted on how to reduce these switching transient currents and voltages, which can affect equipment damage, system reliability and power quality.

Energization Sequence:



The resonance current between two banks, and it expressed as follows.

$i_{2h}(t)$

$$I_{2h}(t) = V_m \sqrt{\frac{C_{eq}}{L_{eq}}} \sin\left(\frac{1}{\sqrt{C_{eq} L_{eq}}} t\right)$$

$$L_{eq} = \frac{C_1 C_2}{C_1 + C_2} \qquad L_{eq} = L_1 + L_2$$

Compensating — Single phase loads:

The single phase compensator shown in below. In this Diagram a voltage Source is Supplying a load compensator is shown in figure.

In this diagram a voltage source is supplying a load and the source is the point of common coupling (pcc). Since there is no feeder joining the source and the load. Here the compensator consists of an H-bridge inverter and 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 compensator is connected with load ground. The dc capacitor Cdc The inverter is expected to be controlled to maintain a voltage Vdc across this capacitor.

Let us assume that the load is non linear and draws a current that has a poor power factor. The instantaneous load current then can be decomposed as.

$$i_l = i_{lp} + i_{lq} + i_{lh}$$

i_{lp} → Real current

i_{lq} → Reactive current

i_{lh} → harmonic current.

The purpose of the compensator is to inject current i_f Such that it cancels out the reactive and harmonic parts of load current.

Now applying KCL at the pcc we get

$$i_l = i_s + i_f \Rightarrow i_s = i_l - i_f$$

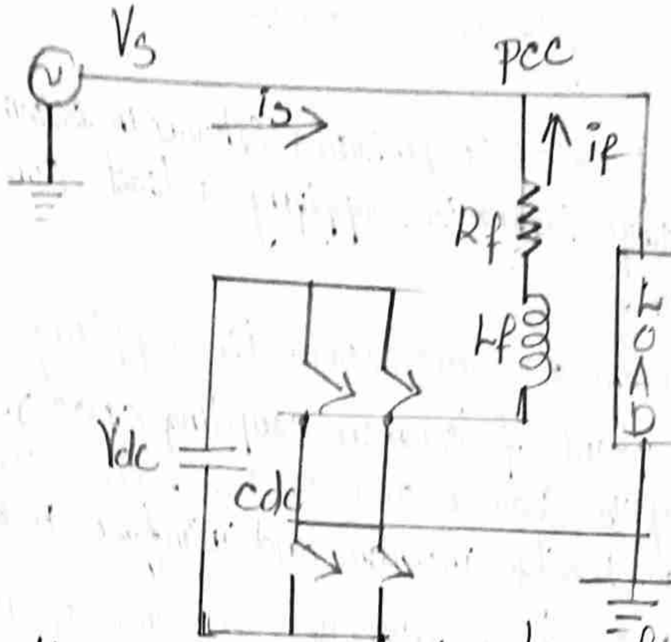


Fig: Schematic Diagram of Single-phase compensator

We assume that the compensator operates in a hysteresis current control loop in which the compensator current track a reference current i_f^*. Let us know 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.

Let us assume that a 240V (rms), 50Hz 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 15A at a power factor of 0.5 lagging and the harmonic parts contains 5th and 7th harmonic

The instantaneous Source voltage and the load current are given by.

$V_s = \sqrt{2} \times 240 \sin(\omega t)$

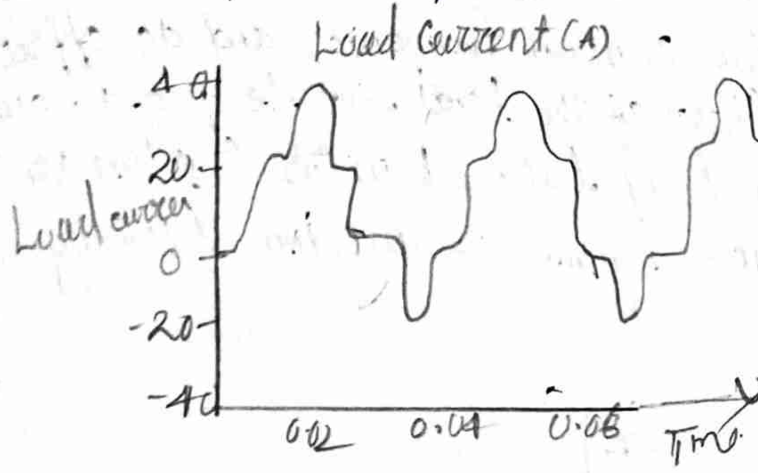
$i_l = \sqrt{2} \times 15 \sin(\omega t - 60^\circ) + \frac{1}{5} \sin(5\omega t - 60^\circ) + \frac{1}{7} \sin 7(\omega t - 60)$

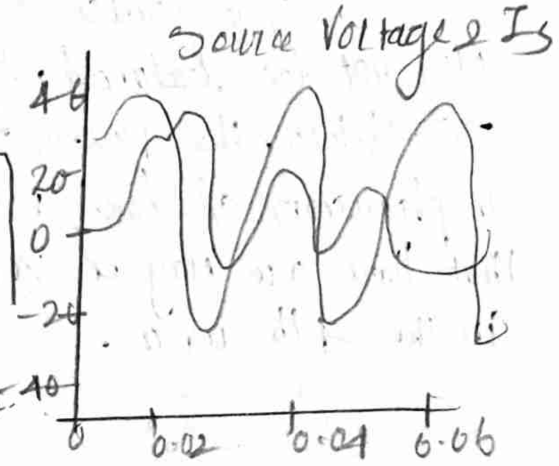
where $\omega = 100\pi$. The load current is shown in figure

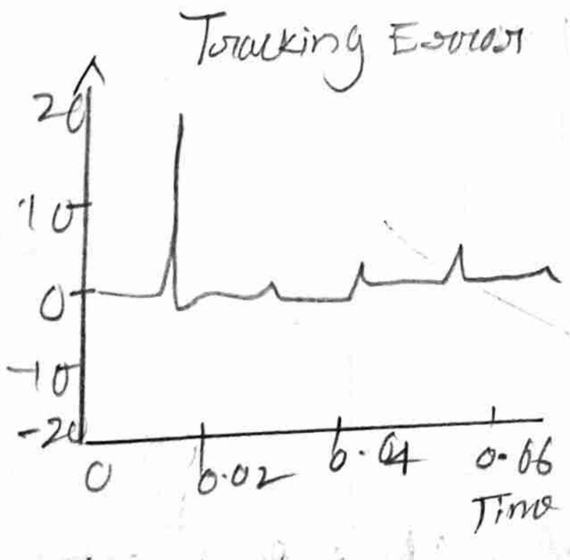
$i_s^* = \sqrt{2} \times \frac{P}{240} \sin \omega t$

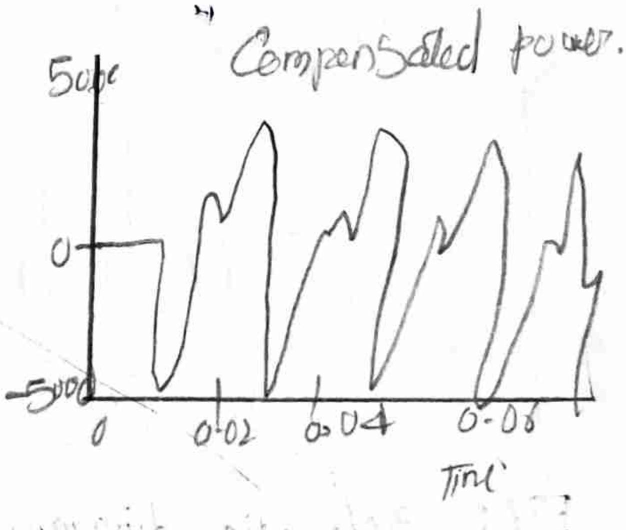
In this system parameters chosen are

$R_f = 0, \; L_f = 20mH, \; V_{dc} = 600V$









Single-phase Compensator cancel the reactive power in the line. It will improve real power Distribution in Transmission line.

Ideal Three-phase Shunt Compensator Structure

To illustrate the functioning of Shunt compensator Consider the three phase, four wire ($3\phi 4w$) distribution System. All the currents and Voltage that are indicated in this figure as 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_a, i_b, i_c) 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 are May be zero-sequence current inn flowing in the 4th wire.

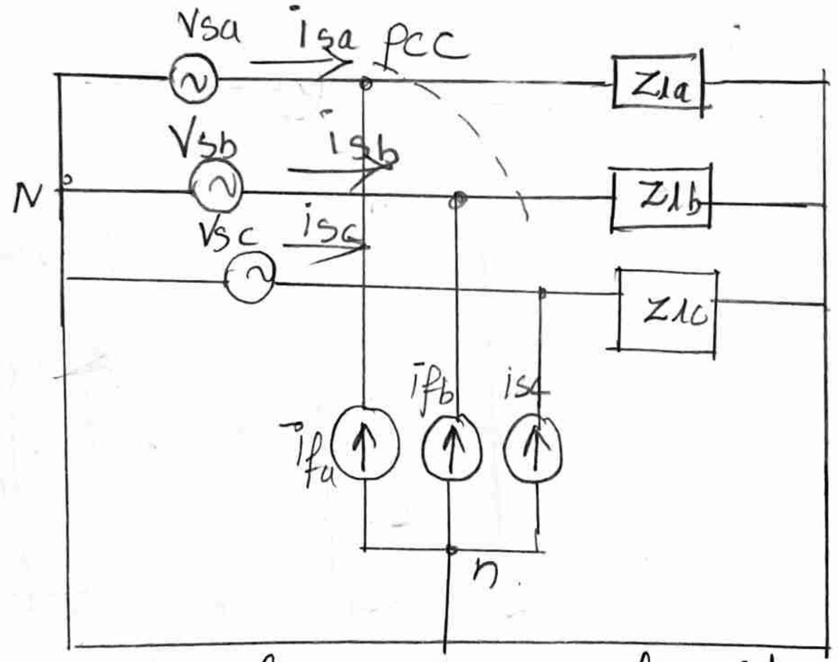


Fig: Schematic diagram of a Shunt Compensator for 3-ph4w Distribution System that is Supplying a Y Connected Load.

The Shunt compensator is represented by three ideal current i_{fa}, i_{fb} and I_{fc}. The Common coupling (PCC) is encircled. The current Sources are Connected in Y with their neutral n being connected to the 4th wire. The purpose of shunt compensator is to inject currents in such a way that the source current (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 desired value.

Example: Let us three phase instantaneous source voltage be given per unit by

$$V_{sa} = \sqrt{2}\sin\omega t, \quad V_{sb} = \sqrt{2}\sin(\omega t - 120°) \text{ and}$$

$$V_{sc} = \sqrt{2}\sin(\omega t + 120°)$$

with $\omega = 100\pi$. Three unbalanced RL loads are connected across the supply.

They are given in per unit as

$$Z_{la} = 6.0 + j3.0$$

$$Z_{lb} = 3.0 + j1.5$$

$$Z_{lc} = 7.5 + j1.5$$

Assume that load is drawing 5th harmonic current of magnitude 0.05 per unit. The load current are then given in per unit by.

$$i_{la} = 0.2108\sin(\omega t - 26.57°) + 0.05\sin 5\omega t$$

$$i_{lb} = 0.4216\sin(\omega t - 146.57°) + 0.05\sin 5(\omega t - 120°)$$

$$i_{lc} = 0.1849\sin(\omega t + 108.69°) + 0.05\sin 5(\omega t + 120°)$$

power level power factor given per unit by

$$i_{sa} = \sqrt{2} \times 0.176\sin\omega t = 0.249\sin\omega t$$

$$i_{sb} = 0.249\sin(\omega t - 120°)$$

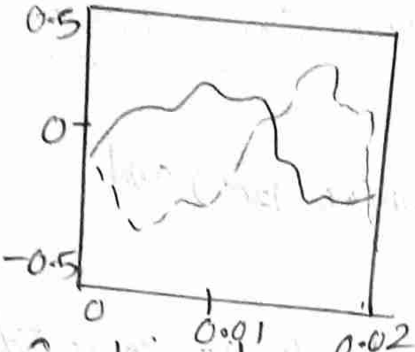
$$i_{sc} = 0.249\sin(\omega t + 120°)$$

Applying KCL at the PCC we can write the following expression for the compensator currents.

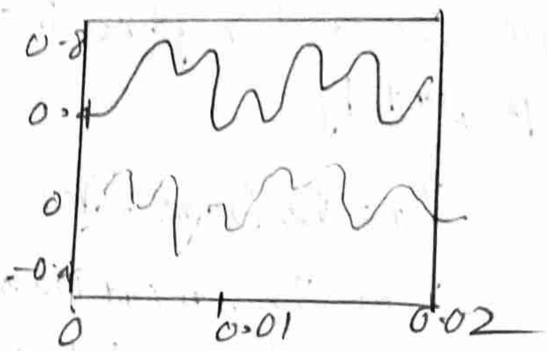
$$i_{f\beta} = i_{l\beta} - i_{s\beta}$$

$$\beta = a, b, c$$

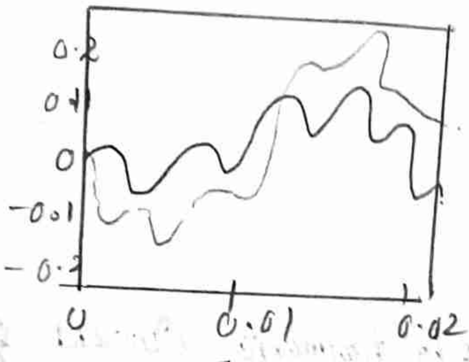
Instantaneous power(p_L)



Load current

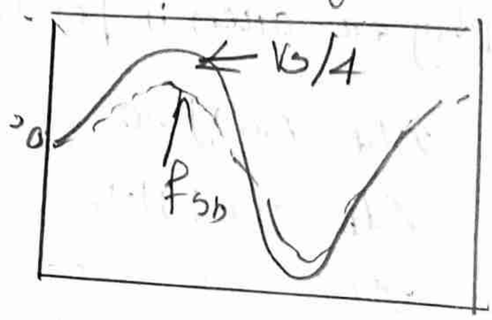


Source Voltage & Current

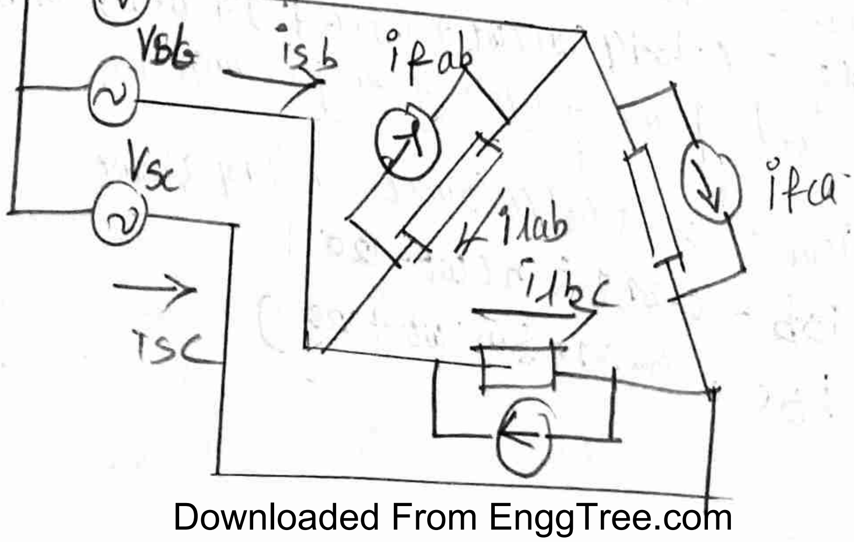


Time

Compensator current



The System performance with the Shunt compensator of Example 7.2



Generating Reference current using Instantaneous PQ Theory:

Hirofumi Akagi and his coworkers have described an Instantaneous Method of generating reference currents for shunt compensator. We transform the three phase voltages from a-b-c frame 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 given by

$$P_{3\phi} = V_a i_a + V_b i_b + V_c i_c$$
$$= V_\alpha i_\alpha + V_\beta i_\beta + V_0 i_p$$

$$P_{3\phi} = P + P_0$$

$P \rightarrow$ Total instantaneous real power in the 3ϕ wires

$P_0 = V_0 I_0 \rightarrow$ instantaneous power in zero-sequence.

$$q = V_\alpha i_\beta - V_\beta i_\alpha$$

$$q = \frac{1}{\sqrt{3}} \{ i_a (V_c - V_b) + i_b (V_a - V_c) + i_c (V_b - V_a) \}$$

We have discussed the theory of the Instantaneous Symmetrical components. In this section we shall utilize the theo for generating instantaneous reference currents.

The compensation scheme presented here can be applie to either a three phase three wire system or a three phase four wire system.

The load can be connected in Y or in Δ. We shall discuss the compensation of Y connected load first.

The objective in either three or four wire system compensation is to provide balanced supply current such that its zero-sequence component is zero.

$$i_{sa} + i_{sb} + i_{sc} = 0$$

The unity power factor. Let us assume that the source voltages are balanced and are given by

$$V_{sa} = \sin\omega t$$

$$V_{sb} = \sin(\omega t - 120^\circ)$$

$$V_{sc} = \sin(\omega t + 120^\circ)$$

$$V_{sa1} = \frac{1}{\sqrt{3}}\left\{V_{sa} + aV_{sb} + a^2 V_{sc}\right\}$$

The angle of the vector is given by

$$\phi = \angle V_{sa1} = \tan^{-1}\left[\frac{\frac{\sqrt{3}}{2}V_{sb} - \frac{\sqrt{3}}{2}V_{sc}}{V_{sa} - \frac{1}{2}V_{sb} - \frac{1}{2}V_{sc}}\right]$$

$$\phi = \tan^{-1}\left[\frac{\frac{\sqrt{3}}{2}(V_{sb} - V_{sc})}{\frac{3}{2}V_{sa}}\right]$$

Substituting Values of the Instantaneous Voltages.

$$\phi = \tan^{-1}\left\{\frac{-\cos\omega t}{\sin\omega t}\right\} = \omega t - \pi/2$$

The angle of the vector V_{sat} will change linearly at t changes. We can then easily force another vector to follow (or lead) this vector by an arbitrary angle.

If we assume that phase of the vector i_{sat} lags that of V_{sat} by an angle ϕ, We get

$$\angle\{V_{sa} + aV_{sb} + a^2 V_{sc}\}$$

$$= \angle\{i_{sa} + a i_{sb} + a^2 i_{sc}\} + \phi$$

equating the angles, We can Write from the above equation.

$$\tan^{-1}(K_1/K_2) = \tan^{-1}(K_3/K_4) + \phi$$

- $$K_1 = \frac{\sqrt{3}}{2}(V_{sb} - V_{sc}), \quad K_2 = V_{sa} - \frac{1}{2}V_{sb} - \frac{1}{2}V_{sc}$$

$$K_3 = \frac{\sqrt{3}}{2}(i_{sb} - i_{sc}) \text{ and}$$

$$K_4 = i_{sa} - \frac{i_{sb}}{2} - \frac{i_{sc}}{2}$$

using formula.

$$\tan(\alpha + \beta) = \frac{\tan\alpha + \tan\beta}{1 - \tan\alpha \tan\beta}.$$

We can expanded as.,

$$\frac{K_1}{K_2} = \tan\{\tan^{-1}(K_3/K_4) + \phi\}$$

$$\boxed{\frac{K_1}{K_2} = \frac{K_3/K_4 + \tan\phi}{1 - (K_3/K_4)\tan\phi}}$$

Solving the above equation we get

$$(V_{sb} - V_{sc} - 3\beta V_{sa}) i_{sa} + (V_{sc} - V_{sa} - 3\beta V_{sb}) i_{sb} + (V_{sa} - V_{sb} - 3\beta V_{sc}) i_{sc}$$

Where

$$\beta = \tan^{-1}(\phi/\sqrt{3})$$

The objective of the compensator is to supply the oscillating component such that the source supplies the average value of the load power, Therefore

$$V_{sa} i_{sa} + V_{sb} i_{sb} + V_{sc} i_{sc} = P_{lav}.$$

P_{lav} = average power drawn by the load. Since the harmonic component in the load does not require any real power, Since the supplies of real power required by the load.

$$\begin{bmatrix} 1 & 1 & 1 \\ V_{sb} - V_{sc} - 3\beta V_{sa} & V_{sc} - V_{sa} - 3\beta V_{sb} & V_{sa} - V_{sb} - 3\beta V_{sc} \\ V_{sa} & V_{sb} & V_{sc} \end{bmatrix}$$

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

$$i_{fa}^{*} = i_{la} - \frac{V_{sa} + (V_{sb} - V_{sc})\beta}{V_{sa}^2 + V_{sb}^2 + V_{sc}^2} P_{lav}$$

$$i_{fb}^{*} = i_{lb} - \frac{V_{sb} + (V_{sc} - V_{sa})\beta}{V_{sa}^2 + V_{sb}^2 + V_{sc}^2} P_{lav}.$$

$$i_{fc}^{*} = i_{lc} - \frac{V_{sc} - q(V_{sa} - V_{sb})\beta}{V_{sa}^2 + V_{sb}^2 + V_{sc}^2} P_{lav}.$$

Generating the reference current when the Source is unbalanced:

The instantaneous real and reactive power in Section Instantanous Vector of the filter reference currents in terms of its active and reactive Components as

$$i_f^* = i_{fp}^* + i_{fq}^* = \frac{P_f V_s}{V_s \cdot V_s} + \frac{q_f \times V_s}{V_s \cdot V_s}$$

Where P_f is the instantaneous Solar power drawn by the filter are Vectors defined by

$$V_s = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}, \quad q_f = \begin{bmatrix} q_{fa} \\ q_{fb} \\ q_{fc} \end{bmatrix}, \quad i_f^* = \begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix}$$

Similarly the instantaneous Power drawn from the Source can also be Written in terms Source real and reactive power as

$$i_s^* = i_{sp}^* + i_{sq}^* = \frac{P_s V_s}{V_s \cdot V_s} + \frac{q_s \times V_s}{V_s \cdot V_s}$$

Where P_s is The Scalar power Supplied by the Source and the Vector Source reactive power as is given by

$$q_s = [q_{sa} \; q_{sb} \; q_{sc}]^T$$

Differentiating p and q and noting that $i_f^* = i_l - i_s$,

We get the following general algorithm

$$i_{fa}^* = i_{la} - i_{sa} = i_{la} - \frac{1}{\sum_{k=a,b,c} V_{sk}^2} (P_s V_{sa} + q_{sb} V_{sc} - q_{sc} V_{sb})$$

$$i_{fb}^{*} = i_{lb} - i_{sb} = i_{lb} - \frac{1}{\sum_{k=a,b,c} v_{sk}^2}(P_s v_{sb} + q_{sc} v_{sc} - q_{sa} v_{sa})$$

$$i_{fc} = i_{lc} - i_{sc} = i_{lc} - \frac{1}{\sum_{k=a,b,c} v_{sk}^2}(P_s v_{sc} + q_{sa} v_{sb} - q_{sb} v_{sa})$$

The appropriate selection of source yields different kinds of compensation scheme

Appropriate sources are.

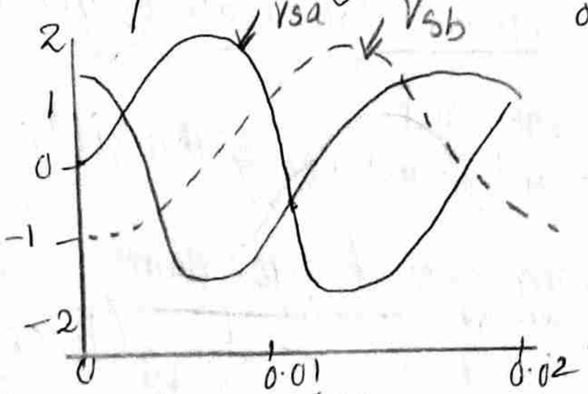
P_s, q_{sa}, q_{sb} and q_{sc}

The implementation of these scheme involves continuous measurement of system voltage and load current and real time calculation of various active and reactive load power components.

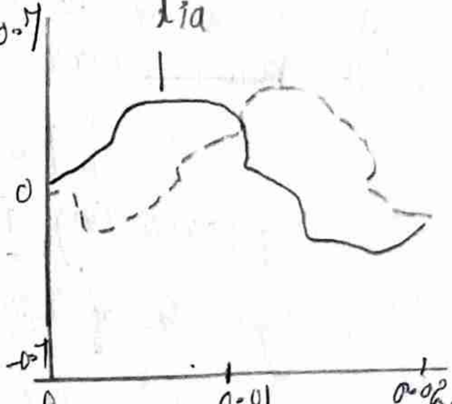
The source voltages are unbalanced and are given per unit by

$$v_{sa} = \sqrt{2}\sin\omega t$$
$$v_{sb} = 0.8 \times \sqrt{2}\sin(\omega t - 120^\circ)$$
$$v_{sc} = 1.2 \times \sqrt{2}\sin(\omega t + 120^\circ)$$

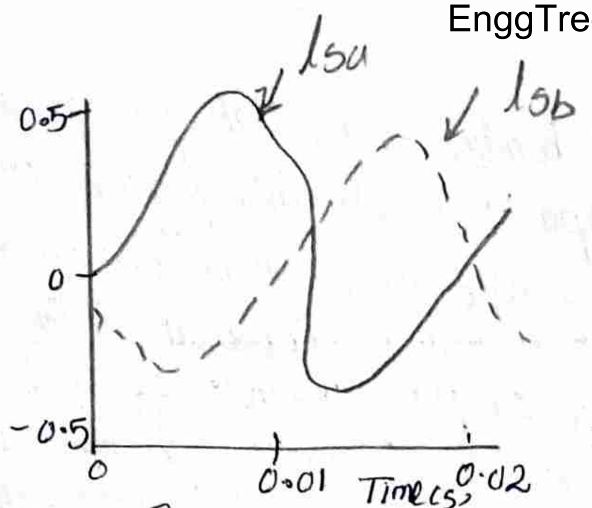
Voltage and current are unbalanced. So the power drawn from the source is not a steady dc value. The imaginary power drawn from the source however remain zero. Thus the compensator supplies the entire imaginary power requirement of the load.



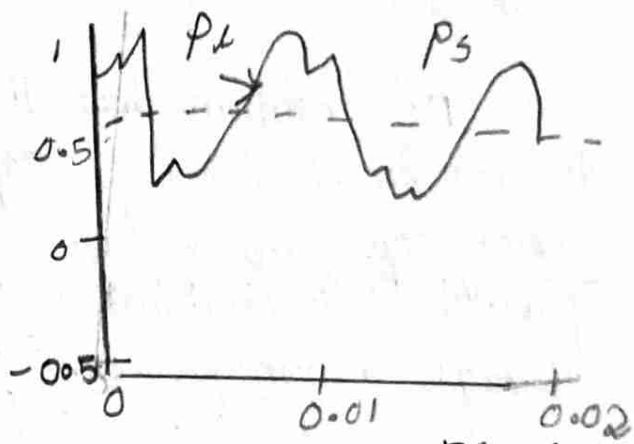
Source Voltage



Load current



Source Current



Instantaneous power.

System response with unbalanced nonlinear load and unbalanced source when both q and P_{osc} are compensated along with the zero-sequence compensation

unity powerfactor operation these equations are:

$$i_{fa}^{*} = i_{la} - i_{sa} = i_{la} - \frac{V_{sa} - V_0}{\Delta} P_{lav}$$

$$i_{fb}^{*} = i_{lb} - i_{sb} = i_{lb} - \frac{V_{sb} - V_0}{\Delta} P_{lav}.$$

$$i_{fc}^{*} = i_{lc} - i_{sc} = i_{lc} - \frac{V_{sc} - V_0}{\Delta} P_{lav}$$

Where $V_0 = \frac{1}{3} \sum_{k=a,b,c} V_{sk}$ and $\Delta = \left[\sum_{k=a,b,c} V_{sk}^2 \right] - 3V_0^2$

Realization and control of DSATCOM:

DSATCOM – Distribution static compensator

The DSATCOM is a shunt device. It should therefore be able to regulate the voltage of a bus to which it is connected. The operating principle of a DSATCOM in this mode has been termed as the DSATCOM in voltage control mode.

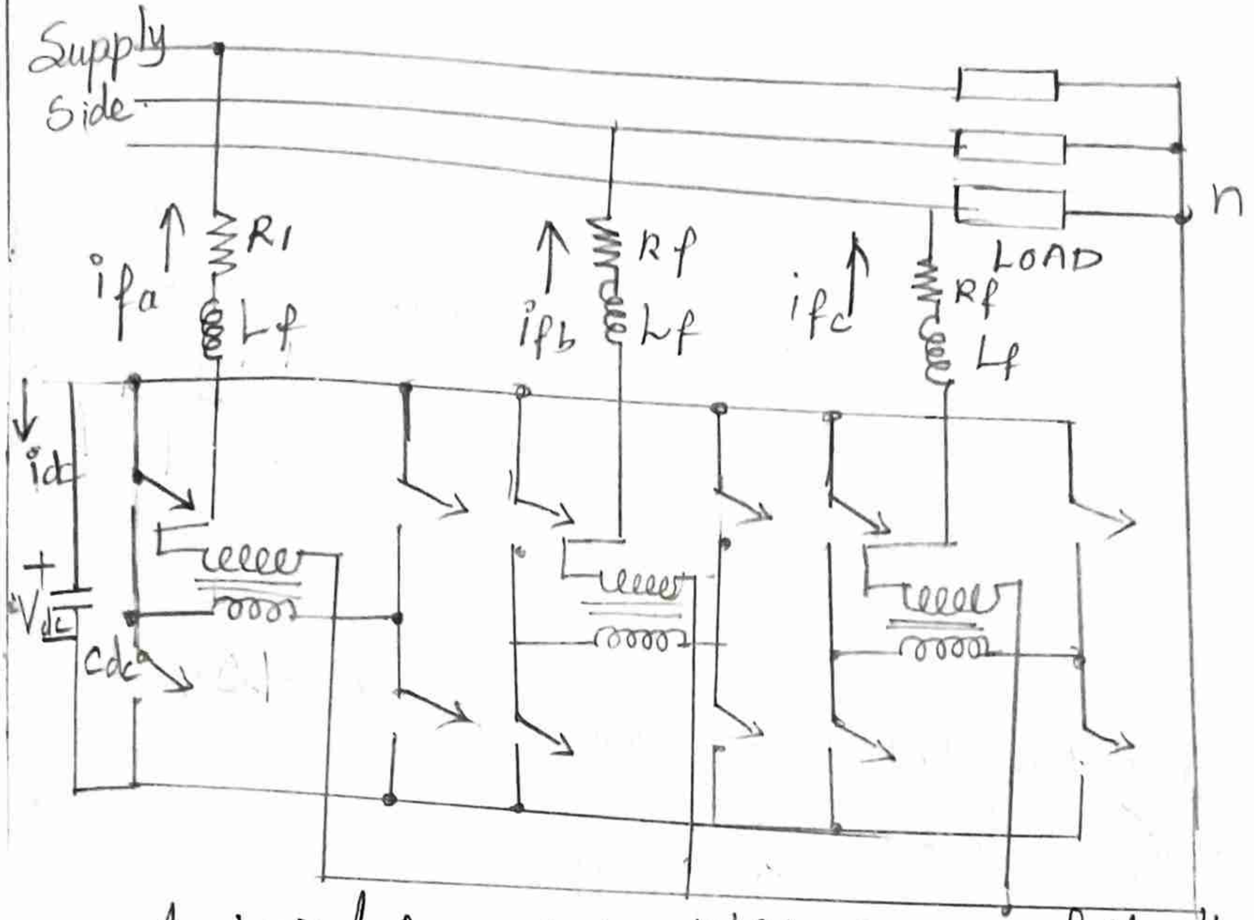
DSATCOM Structure:

It contains three H-bridge VSIs that are connected to 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 through a transformer. Six output terminals of the transformer are connected in star. These six terminals can also be connected in delta to compensate a Δ-connected to load. In this case each transformer is connected to load.

Transformer is connected in parallel with the corresponding load. The purpose of including the transformer is to provide isolation between the inverter legs. This prevents the dc storage capacitor from beigns shorted through switches in different inverters.

The inductance Lf in the figure represents the leakage inductance of each transformer and addition external inductance if any switching losses of an inverter and the copper loss of connecting transformer are neglected. For star connected load the neutral point of the three transformers is connected to the load neutral. The dotted line inductance the 4th wire and is connected to the system neutral N, if available

A three phase full bridge inverter is not suitable for a DSATCOM application. A well known constraint of such inverters is that the sum of current through is three leg must be zero. It will not thus be possible to compensator for the zero-sequence current from flowing into the source from the load. This will result in distortion in the source current.



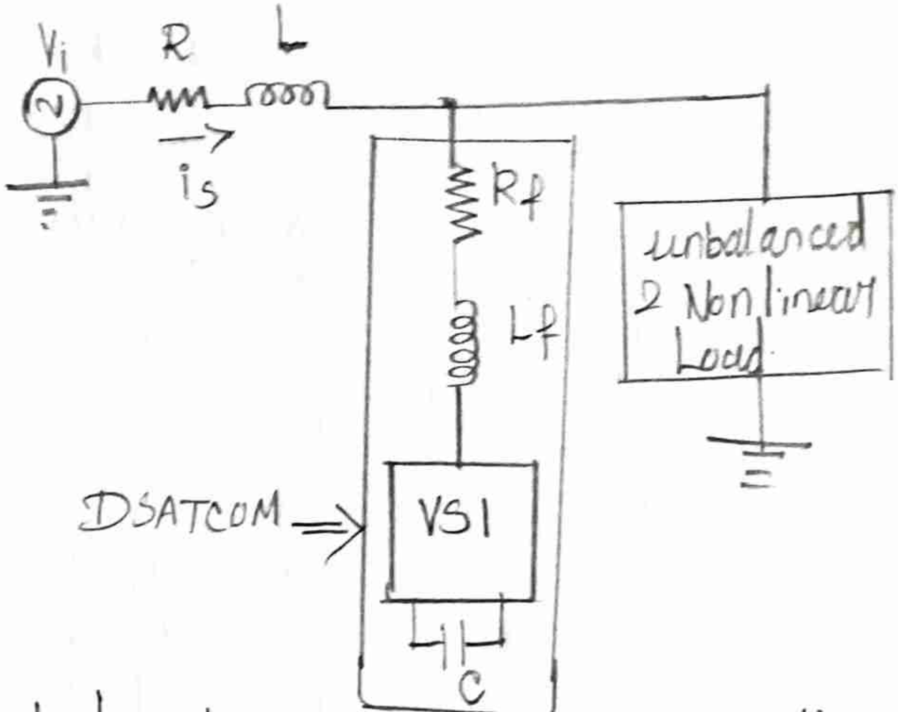
A typical compensator n' structure in which three separate VSIs are supplied from a common dc storage capacitor.

DSATCOM connected to Weak Supply point:

Consider the system shown in figure. In this unbalanced and nonlinear load is supplied by balanced voltage source (Vs) through a feeder.

The feeder has a resistance R and inductance L. Let us denote the PCC voltage as the terminal voltage (v). Then the voltage is applied across the load as well as across the DSATCOM. The load is compensated by a DSATCOM, the reference signal of which is → generated using any of the problem of harmonic → contamination due the VSI of DSATCOM. Let us illustrate this with the following example.

U-4-15



Single line diagram of Shunt Compensation of a Load supplied through a feeder.

* DSATCOM in Voltage Control Mode.

In a distribution System there May be Several compensating device of different kinds. However, in a radial distribution system. The Voltage of a System particular bus can be Distorted System, The Voltage of a System distorted or unbalanced. The customer connected to that bus would be supplied by a set of unbalanced and distorted Voltage. even when their loads are not contributing to the bus Voltage pollution. Therefore a DSATCOM can be used at this bus to reduce harmonic and balance the bus Voltage

STATE Feedback control of DSATCOM in Voltage Control Mode

Feed back control of the DSTATCOM operating as a Voltage regulator. terminal Voltage V_t, injected Current i_f, Current through the filter capacitor i_{cf} and load current i_l. Load current Load dependened that May change any time.

The instantaneous phase - a terminal reference voltage is then given by

$$V_{ta}^{*} = |V_t^{*}| \sin(\omega t + \phi)$$

The reference voltage for the other two phases can be obtained by phase shifting this waveform by 120°. The angle reference signal must be chosen such that the real power drawn by the DSATCOM is zero in the steady state. To facilitate this, we use the following feedback signal.

$$\boxed{\phi(k+1) = \phi_1(k) + c_p P_{fav}}$$

The reference voltage of phase-A is

$|V_t^{*}| \sin(\omega t + \phi_1)$, the reference current for this phase is then given by

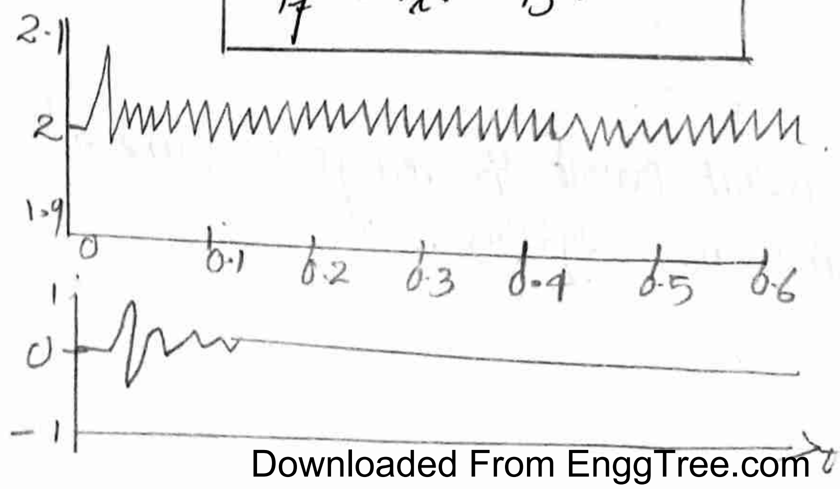
$$|V_t^{*}| \omega C_f \cos(\omega t + \phi_t).$$

$$\boxed{i_l = i_s + i_f}$$

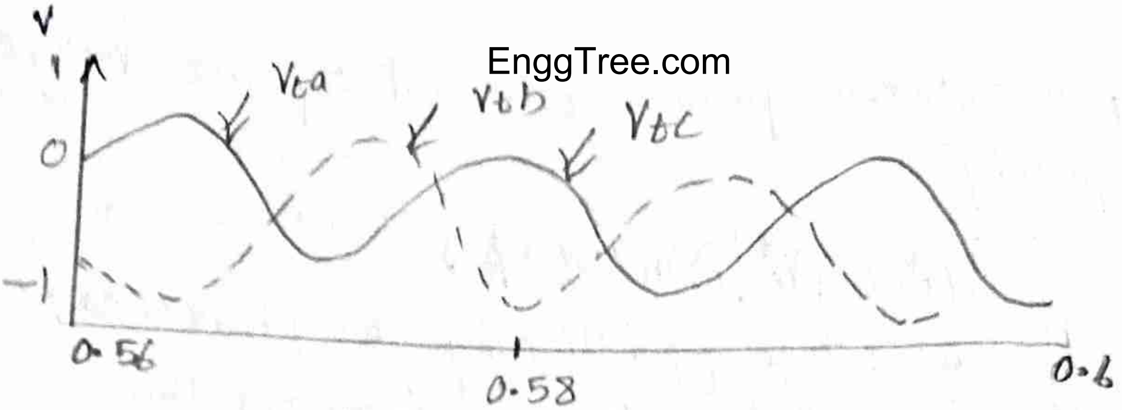
i_f → instantaneous difference between the two currents.

The fundamental value of source current is

$$\boxed{i_f^{*} = i_l - i_{s\,fund}}$$



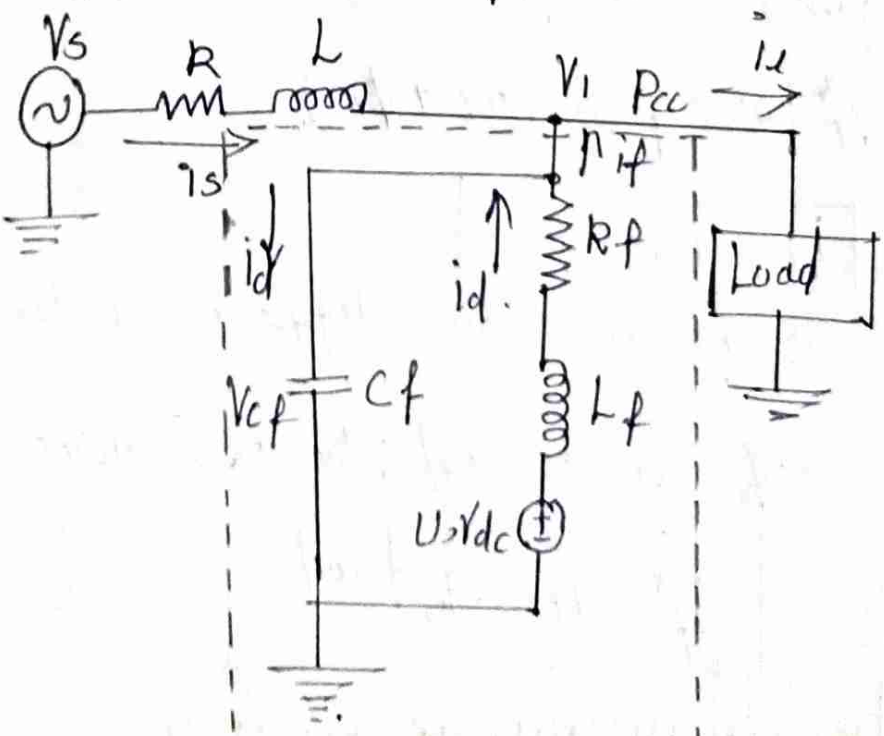
U-4-17



Performance of a voltage controlled DSATCOM with DC capacitor control.

Output Feedback control of DSATCOM in Voltage control Mode

Consider the network shown in figure. In this U is the switching variables that can take on values ±1 corresponding to the s... 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 derive the state space equation for the part system enclosed in the dotted path



Equivalent circuit of voltage compensated Distribution System.

$x^T = [v_t \ \ i_d]$

$z^T = [u_c \ \ i_f]$

The State Space equation of the System is then given by

$$x = \begin{bmatrix} 0 & 1/C_f \\ -1/L_f & -R_f/L_f \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ V_{dc}/L_f & 0 \end{bmatrix} z$$

$$x = Ax + BZ$$

The continuous-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.

$$\phi = e^{A\Delta T} \text{ and } \theta = \int_0^{\Delta T} e^{A\tau} B\, d\tau$$

$$\phi = \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} \text{ and } \theta = \begin{bmatrix} \theta_{11} & \theta_{12} \\ \theta_{21} & \theta_{22} \end{bmatrix}$$

$$V_t(k+1) = \phi_{11} V_t(k) + \phi_{12}\, i_d(k) + \theta_{11} u_c(k) + \theta_{12}\, i_f(k)$$

The reference Voltage of V_t^*, the following cost function is Chosen.

$$J = \{ V_t(k+1) - V_t^*(k+1) \}^2$$

The minimization of this function results in the following control input

$$u_s(k) = \frac{V_t^*(k+1) - \phi_{11} V_t(k) - \phi_{12} i_d(k) - \theta_{12} i_f(k)}{\theta_{11}}$$

u is obtained from hysteresis control band.

UNIT-V : SERIES COMPENSATION OF POWER DISTRIBUTION SYSTEM :

Rectifier Supported DVR :

DVR – Dynamic Voltage Restorer :

A power electronic converter based Series Compensator that can protect Critical load from all Supply side disturbances other than outage is called a dynamic Voltage restorer.

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.

The DVR is capable of generating or absorbing independently controllable real and reactive power.

The DVR is made of Solid-Switch (Solid State Switch) dc to ac Switching power converter that injects a set of three phase ac output Voltage in Series and Synchronism with the Distribution feeder Voltages.

It is assumed that the System is compensated by an ideal Series compensator.

The following Components of the distributed System

* ideal Series compensator represented by the instantaneous Voltage Sources V_{fa}, V_{fb}, V_{fc}

* Supply Voltage represented by the instantaneous Voltage Source V_{sa}, V_{sb} and V_{sc}

* Load Voltage : represented by the instantaneous Voltages V_{la}, V_{lb} and V_{lc}

Load Currents: represented by i_{sa}, i_{sb} and i_{sc}. Note that these currents will also flow through the load and therefore we right also call them currents.

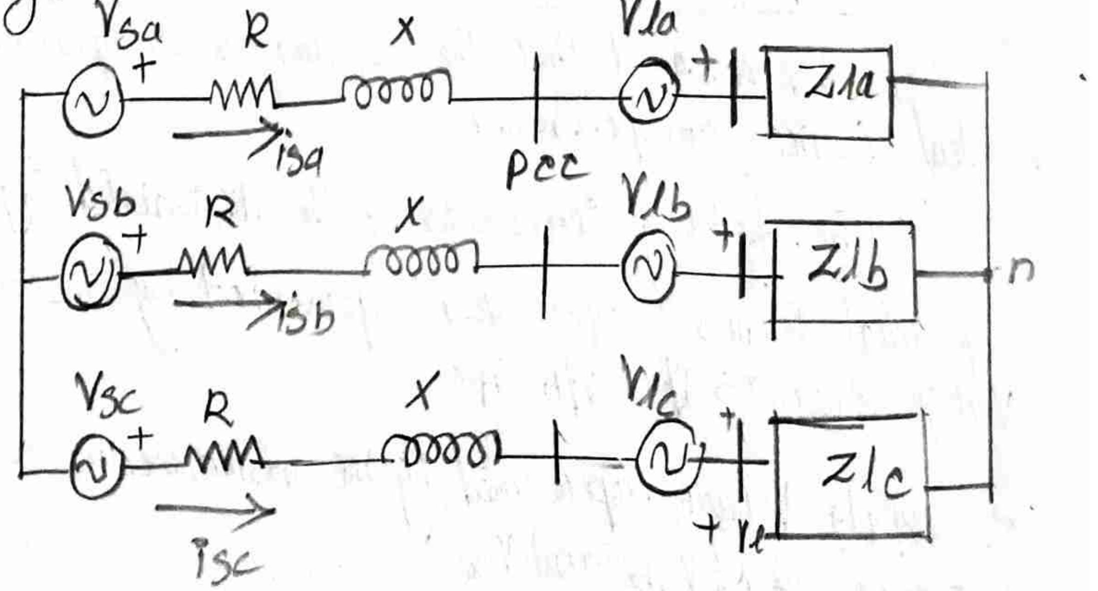
Sensitive Loads: represented by the impedance Z_{la}, Z_{lb} and Z_{lc}, it is assumed that these loads are balanced. i.e

$$Z_{la} = Z_{lb} = Z_{lc}$$

The Series Compensator is connected b/w a terminal bus on the left and Load bus on right. The instantaneous Voltage 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 $R+jX$.

$$Z_{la} = Z_{lb} = Z_{lc} = R_l + jX_l$$

$\phi \rightarrow$ phase angle b/w terminal Voltage V_l and the line current is depends on the load impedance and is independent of the line impedance or the Series Compensator Voltage.



Schematic Diagram of a Series Compensator Connected power System

$V_L = V_t + V_f$

It is desired that the DVR regulates the load voltage. The reference voltage of the DVR (V_f) is then given by

$$\boxed{V_f^* = V_L^* - V_t}$$

$V_L^* \rightarrow$ Desired load voltage.

DC capacitor supported DVR:

DVR structure 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 illustrate these by example of the simplified distribution system shown in figure.

Fundamental Frequency Series Compensator Characteristic

First we shall present the sinusoidal steady state analysis of a series compensator connected power system.

The magnitude of 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:

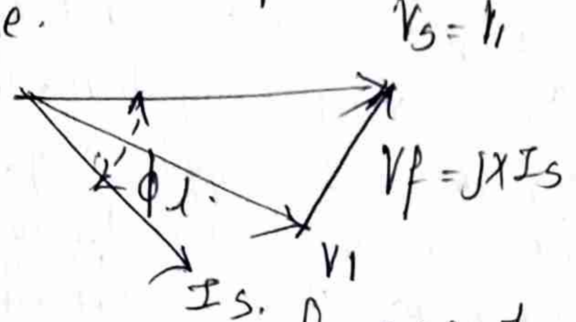
The series compensator need not supply any real power in the steady state. This implies that the phase angle difference between series compensator voltage

Phasor and line Current phasor must be π/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.

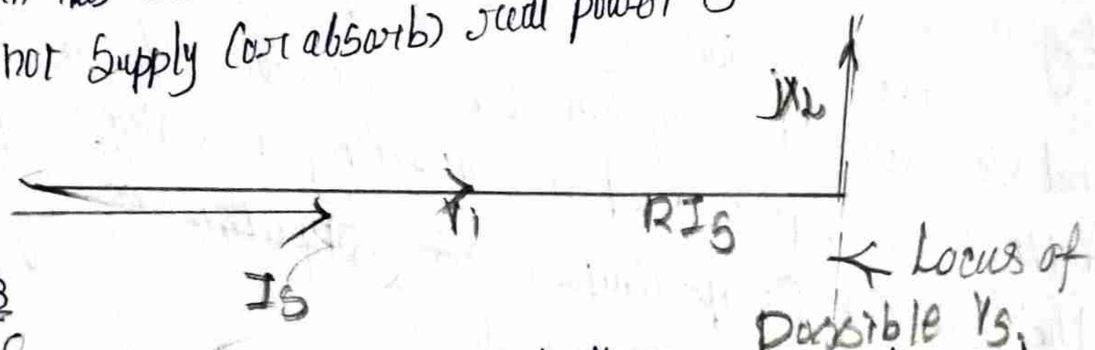
These are discussed below:

Case 1: When the Line Resistance is Negligible, R=0; The phasor diagram for this case is shown in figure. The only way the load and Source Voltage Magnitude can be equal is when the Series Compensator completely Compensator for the reactive drop in the feeder. This will force the Source and load Voltage to be in phase.



Phasor Diagram for case-1.

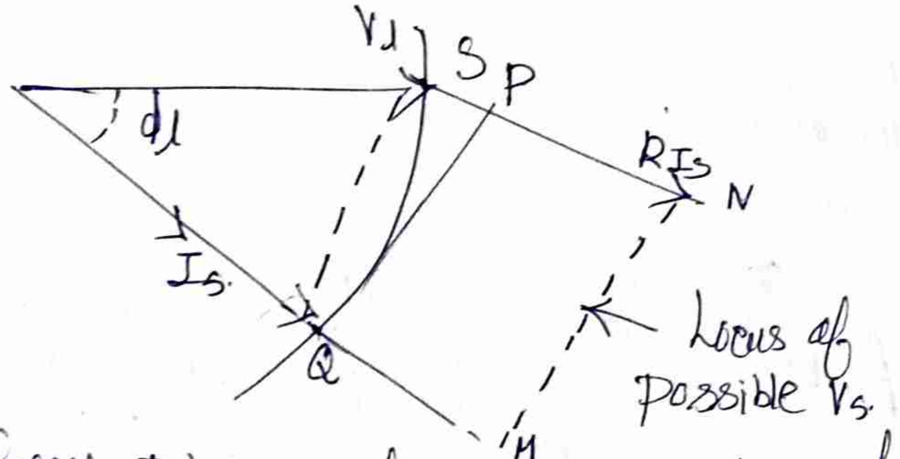
Case 2: When the load is resistive, i.e., $X_L = 0$; The phasor Diagram for this case is shown in figure. It can be Seen that the magnitude of the Source and load Voltage will never be equal in this case unless the Condition that the Series Compensator must not Supply (or absorb) real power is relaxed.



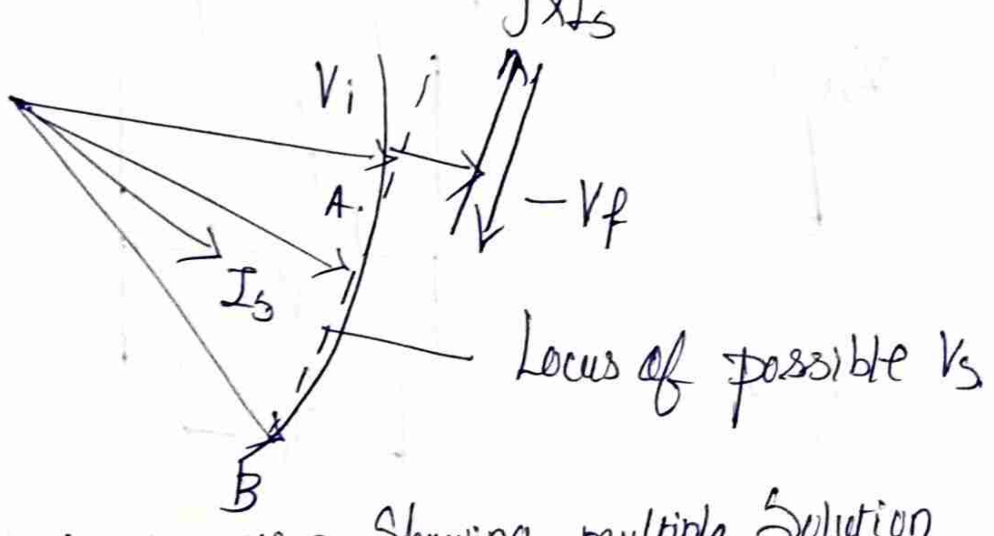
Case-3

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 become V per unit. It can be Seen from the following figure.

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 be along OA, while in the other case it will be along OB. it needless to say that the best choice is the A intersection requiring much smaller voltage injection from the series compensator.



Phasor Diagram of the limiting condition for the case - 3.



phasor Diagram showing multiple solution case - 3.

To obtain a valid solution we require that

$$RI_1 \leq 1 - V\cos\phi_1 \Rightarrow I_s \leq \frac{1 - V\cos\phi_l}{R}$$

Alternatively, we can also regulate the load voltage to a value that is other than 1.0 per unit. The below figure shows that the system load current characteristics for different value of V. The regulated voltage decreases, the maximum current drawing capacity of the load increases.

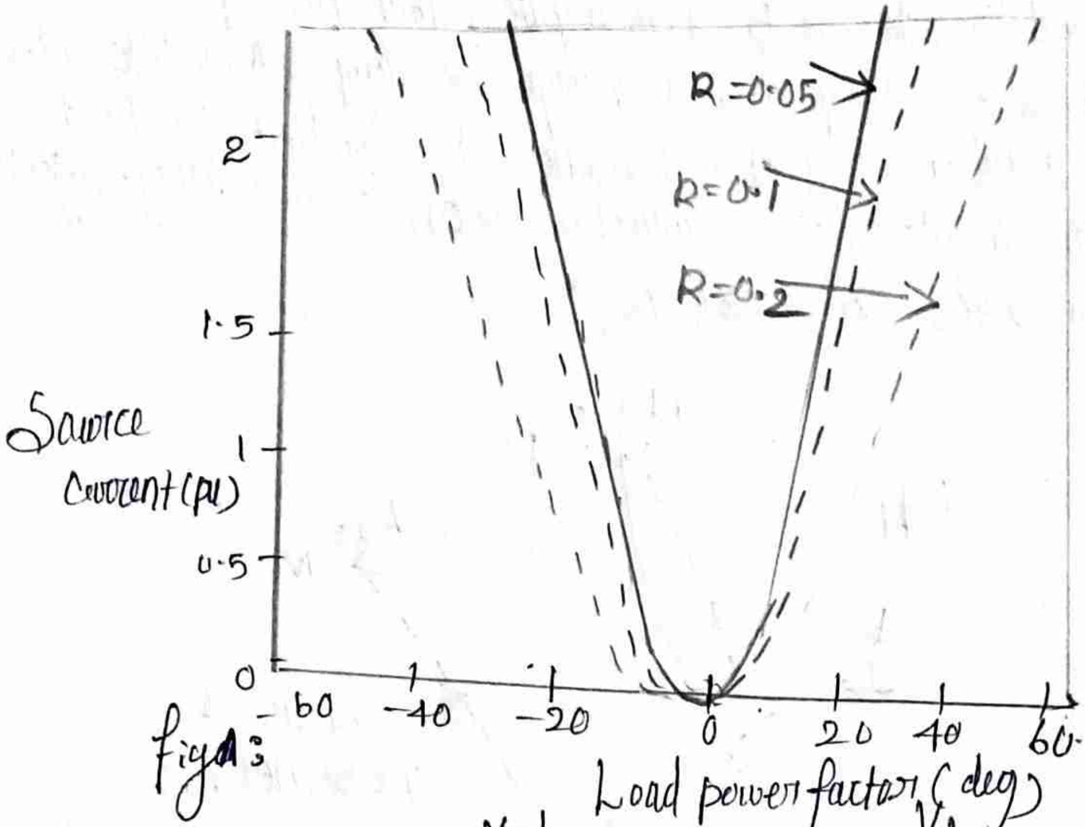


Fig a:

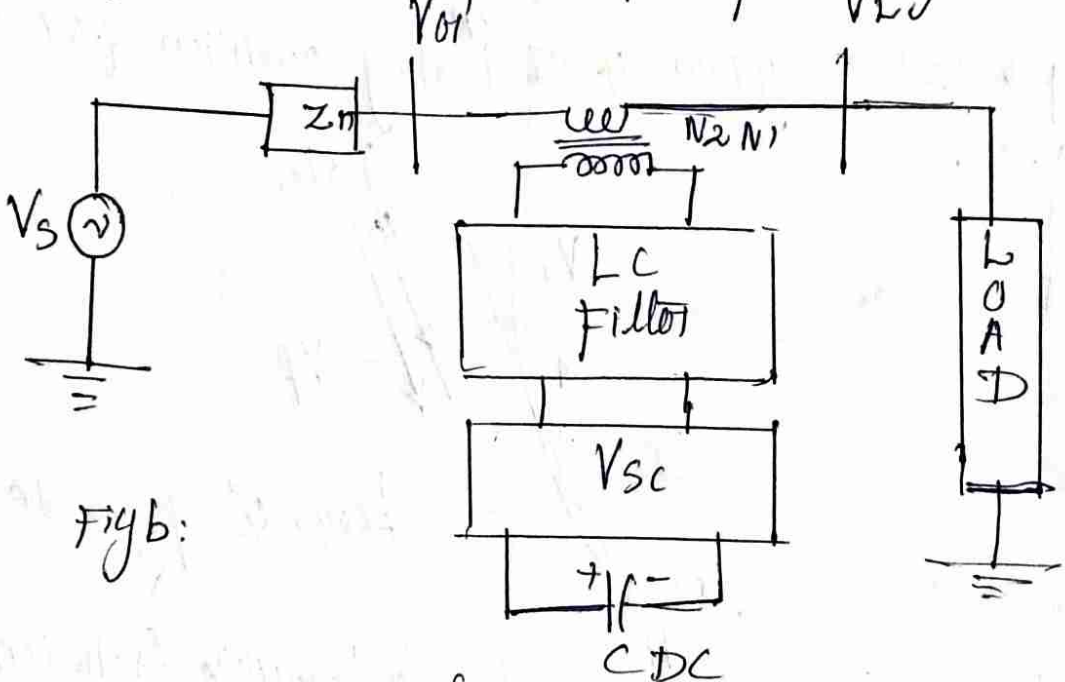


Fig b:

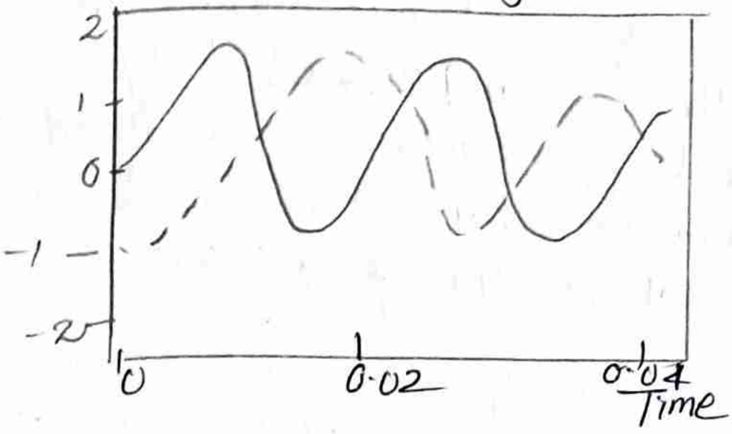
Fig a. Compensatable Source current, Versus power factor Source and load voltages equal: a range of feeder resistance.

Fig(b): Dc compensated DVR.

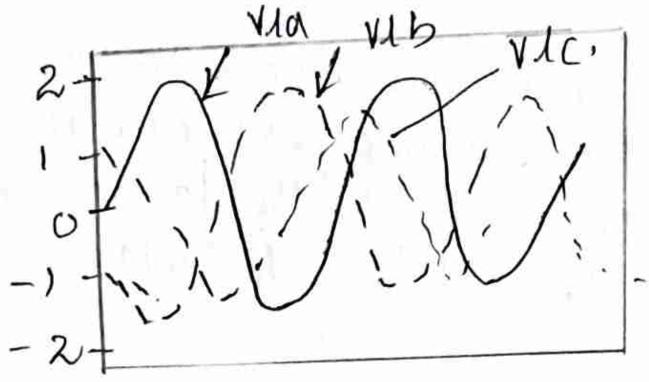
from the line current. Assuming that $V_l = |V_l| \angle 0$

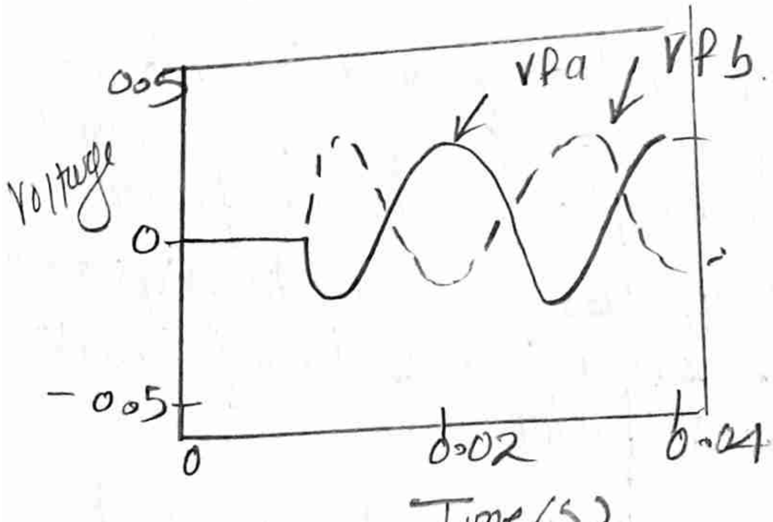
$$|V_f|^2 - 2a|V_l||V_f| + |V_l|^2 - |V_t|^2 = 0$$

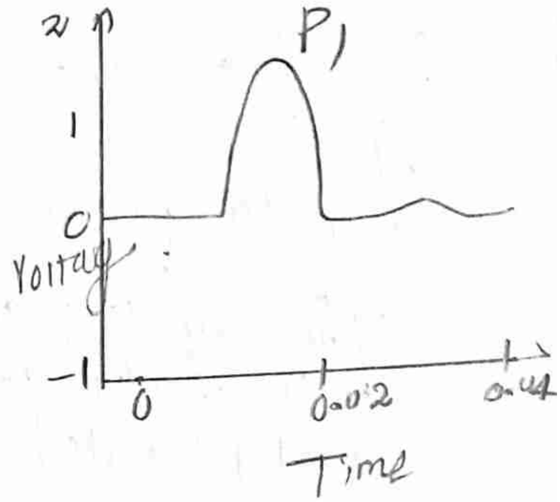
Terminal Voltage.



(b) Load Voltage







This algorithm will be reffered to as Type-2 control. It requires the Measurement of the local Quantities only. To implement this algorithm we need the fundamental of the series compensator terminal Voltage (V_t) along with line current.

DVR Structure

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 DSATCOM Structure of Figure.

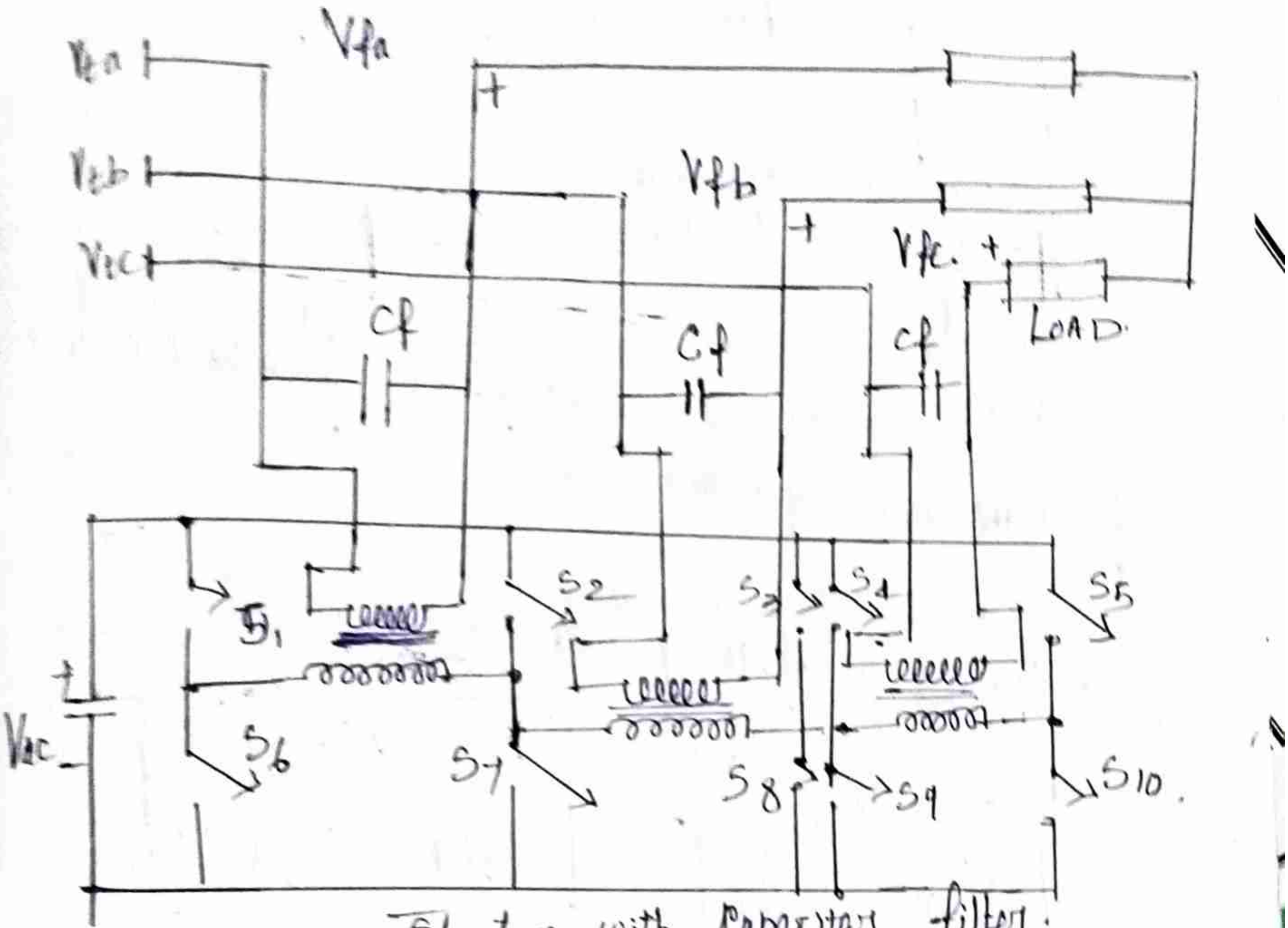
In each Switch represents a power semiconductor device and an anti-parallel diode combination. Each VSI is connected to the network through a T/f and capacitor filter (Cf)

The Transformer is 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 Switching in different inverters.

The high frequency flux Variation causes Significant increase in transformer iron losses. A switch frequency LC filter (Lf – Cf) is placed in the transformer primary as Shown in figure.

The Secondary of the transformer is directly connected to the feeder. The Secondary of the transformer is directly connected to the feeder.

Either of the DVR realization can be controlled through output feedback.



DVR Structure with capacitor filter.

Output Feedback control of DVR:

In this type of control, the square of the error b/w reference DVR voltage and actual DVR voltage is minimized to obtain a deadbeat control action. The single

The single-phase equivalent circuit of the DVR with capacitor filter is shown in figure. Here u.Vdc denotes the switched voltage generated 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 connecting transformer are modeled by a resistance R_T.

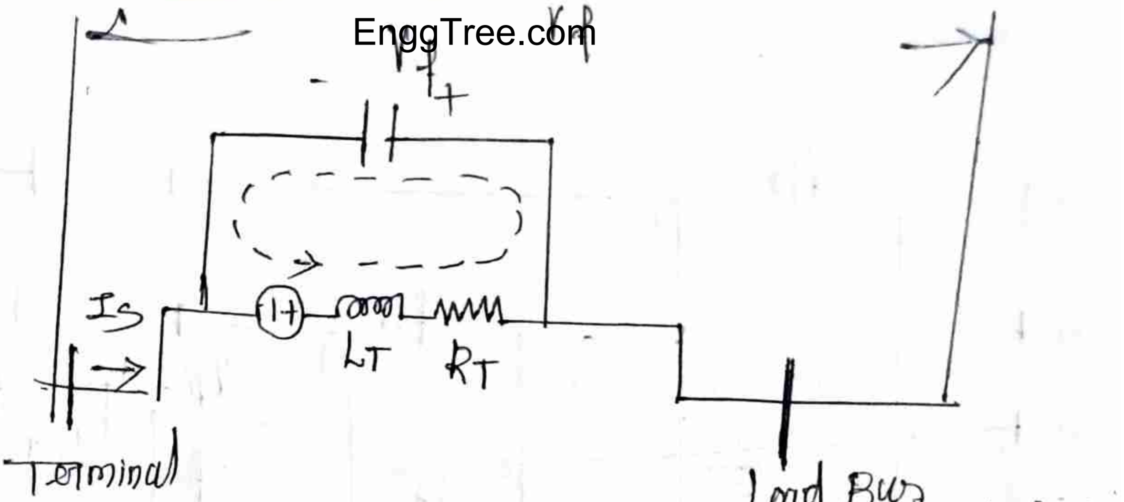


Figure 9.24 Single phase equivalent circuit of DVR with capacitor filter.

Let us define a state vector as $x^T = [V_f \ \ i_{sc}]$. We then get the following state space model from figure.

$$\dot{x} = \begin{bmatrix} 0 & 1/C_f \\ -1/L_T & -R_T/L_T \end{bmatrix} x + \begin{bmatrix} 0 & -1/C_f \\ V_{dc}/L_T & 0 \end{bmatrix} \begin{bmatrix} u_c \\ i_x \end{bmatrix}$$

The Significant:

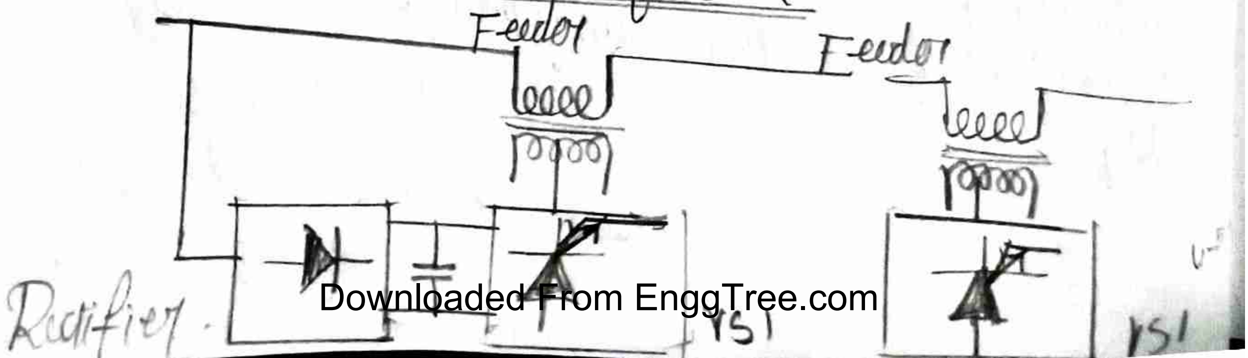
The DVR voltage is given by

$$V_f = V_{cf} - L_T \frac{di_s}{dt}$$

The above equation results in the following quadratic

$$|V_{cf1}|^2 - 2|V_{cf1}|(X_T|I_S| + a_1|V_1|) + |V_1{}^2| - |V_{t1}|^2 + X_T{}^2|I_S|^2 + 2a_1X_T|V_1||I_S| = 0.$$

Two possible Structure of DVR.



A hybrid Structure of series active and Shunt passive filter has been proposed by for harmonic neutralization of non-linear loads.

Voltage Restoration:

The 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 Shown that the Series compensator, which is Supplied from a dc Storage capacitor, ordinary 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 alternate form in which it comes on online only when There is a Voltage sag. otherwise it Says inactive. The Steady State operation of the circuit when the Series Compensator acts as a Voltage restore 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 Voltage by an angle δ_{new}.

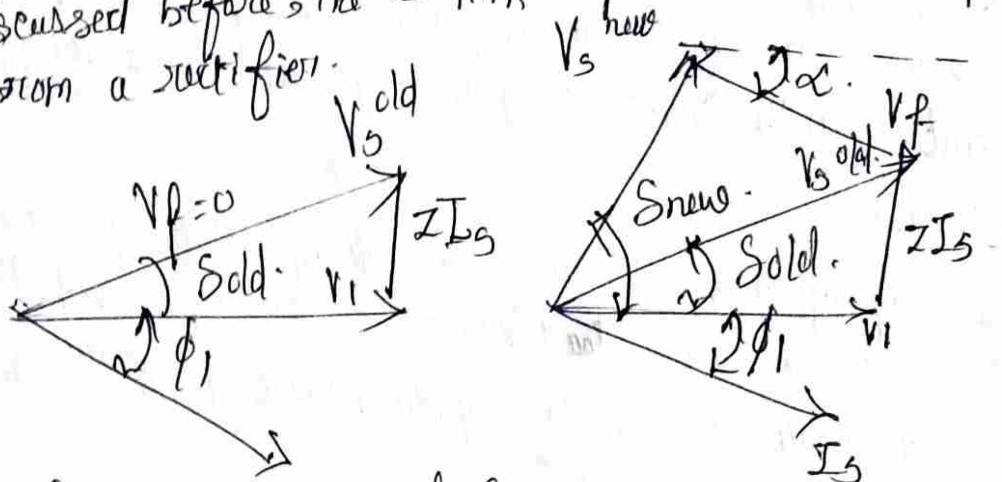
The Series Compensator Then must inject a Voltage Such that the Vector Sum of load voltage and line drop remains unchanged and equal to V_s^{old}

The phasor Diagram shown in figure. The Restoration behaviour for transient control of sudden voltage dip. Since since only we can measure the local measurement. 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.

$$V_f = V_l^{pf} - V_t$$

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.

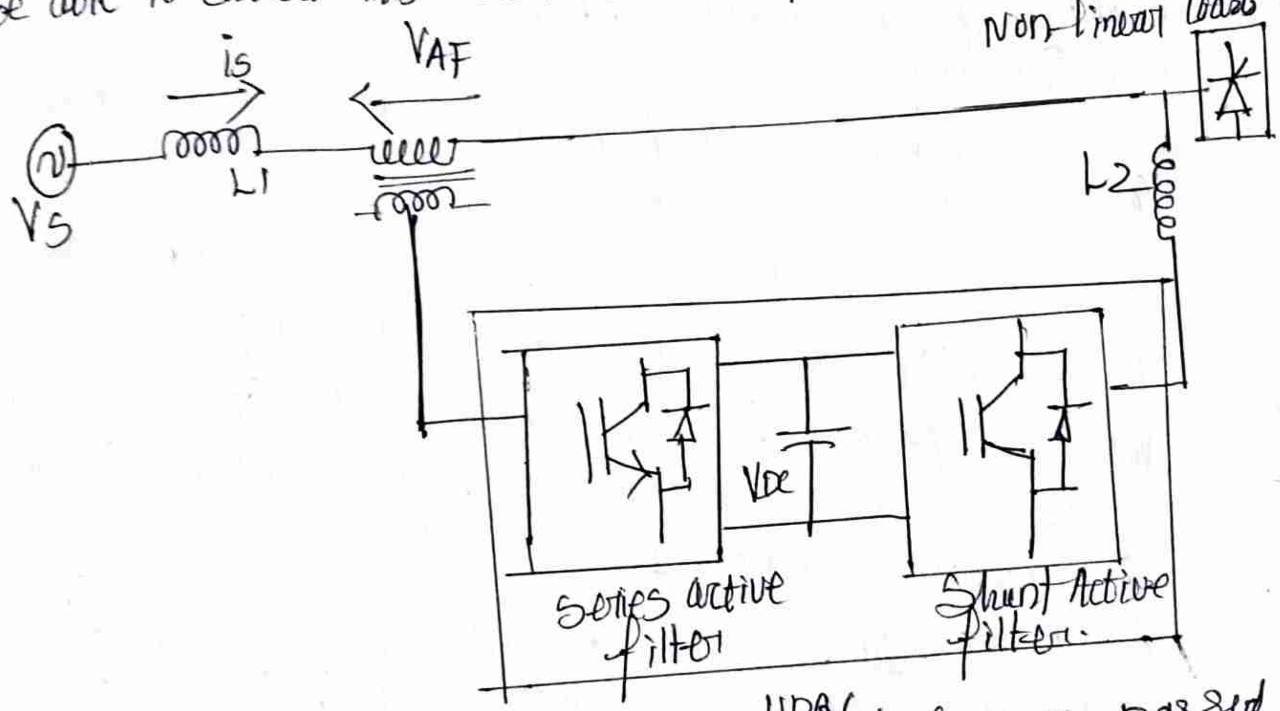


phasor Diagram of series operation (a) steady state operation and (b) transient voltage restoration.

Series Active Filter:

A Series Compensator, which injects a voltage in Series can also act as a Series active filter to isolate the Source from harmonic generated by loads.

Consider the distribution System Shown in figure. if the load is unbalanced, then by injecting a voltage in Series We shall are able to correct this unbalance at the PCC (terminal bus)



Series Active filter, Supplied voltage Source passed Via of inductance and Transformers.

Then this supply voltage passing through Via of Series active filter and Shunt Active filter.

Then this supply voltage filtered out unwanted harmonic distortion. Then pure Sinusoidal supply voltage get to the Consumer side.

This type of conditioner, connected in Series on the distribution network, Compensates both the harmonic current generated by the load and the voltage distortion already present on the AC System.

It is Connected in Series with the distribution line through matching transformer. VSI is used as the Controlled Source thus the principle configuration of Series APF is Similar to Shunt APF, except that the interfacing inductor of Shunt APF is replaced with the interfacing Transformer.

The operation principle of Series APF is based on isolation of the harmonics inbetween the non linear load and Source.

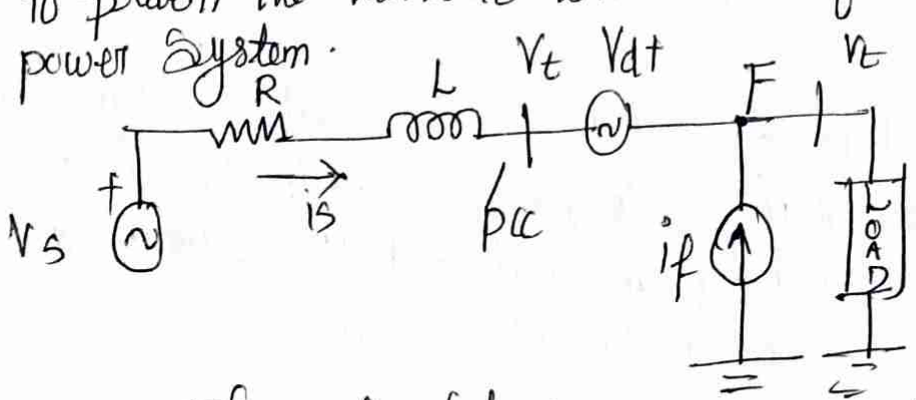
This is obtained by the injection of harmonic Voltages across the Transformer.

The injected harmonic Voltages are added/Subtracted to/from the Source Voltage to maintain a pure Sinusoidal Voltage impedance for the fundamental Component, but appears as a resistor with high impedance harmonic frequencies Component.

That is, no current harmonic can flow from non-linear load to Source, and Vice-Versa.

Unified power Qualified conditioner:

UPQC is a multifunction power Conditioner that can be used to compensate Various Voltage disturbances of the power Supply to Correct Voltage function fluctuation, and to prevent the harmonic load Current from entering the power System.



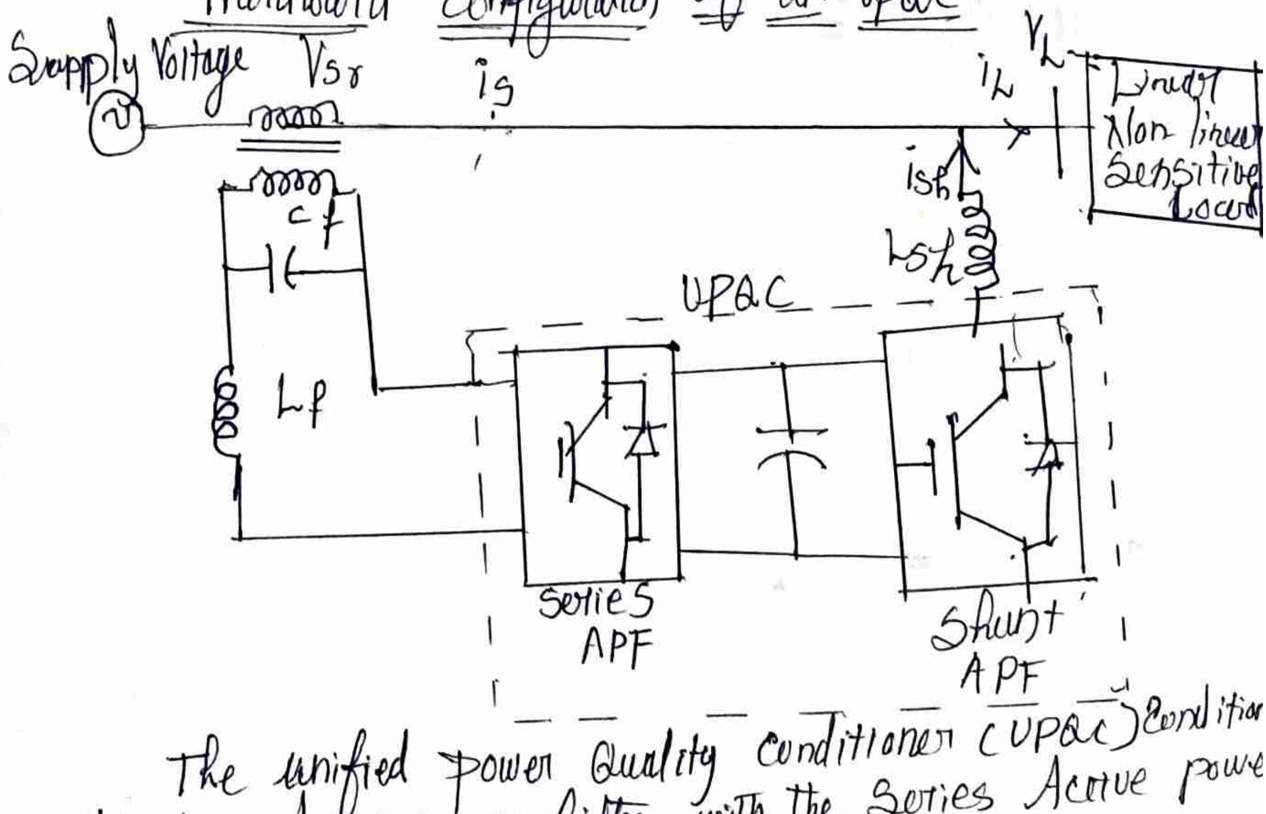
The right-Shunt UPQC compensation configuration

Let us assume that both the Source Voltages and load Currents are unbalanced and distorted. We stipulate that the UPQC shall perform the following function.

* Convert the feeder (Source) current (i_s) to balanced Sinusoids Through the Shunt Compensator and also regulate it to a desired Value.

* Convert the feeder (Source) Current (i), to balanced Sinusoids The shunt compensator
* Convert the load Voltage (V_L) to balanced Sinusoids Through the Series Compensator and also regulate it to a desired Value.

Hardware Configuration of an UPQC



The unified power Quality conditioner (UPQC) Condition the Shunt Active power filter with the Series Active power filter, Sharing the Same DC Link, in order to compensat-ion both Voltages and Currents, so that the load Voltages become Sinusoidal and at nominal Value and The Source Currents become Sinusoidal and in phase with Source Voltages

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Advantages:

UPQC can compensate both voltage related problem such as voltage sags/swells, voltage flicker as well as current related problem like reactive power compensation, power factor correction, current harmonic and load unbalance compensation.

* There is significant increase in interest for using UPQC in distributed generation associated with smart grids because of availability of high frequency switching devices and advanced fast computer device (Microcontroller, DSP, FPGA) at lower cost.