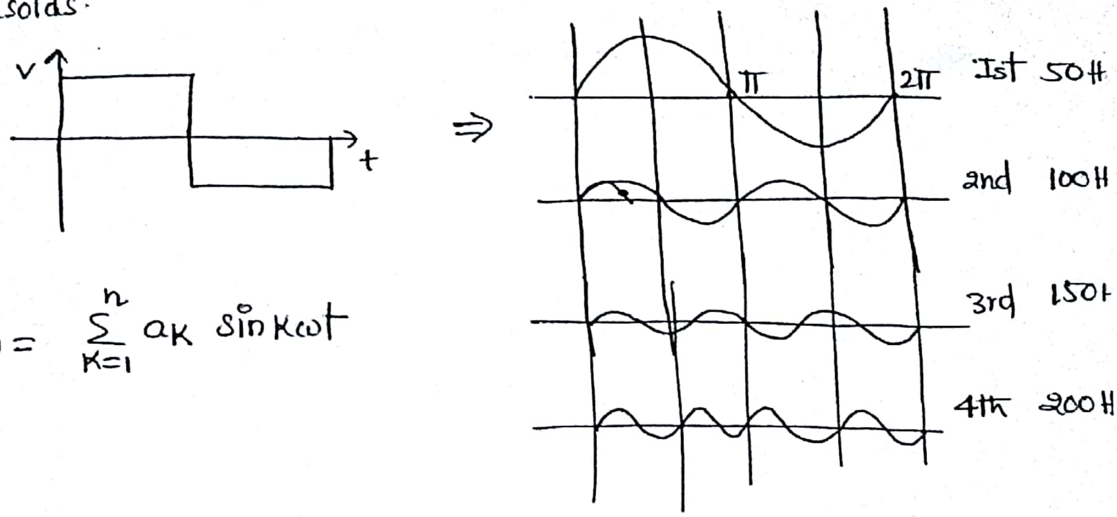
# unit-4

1) Harmonic distortion :-

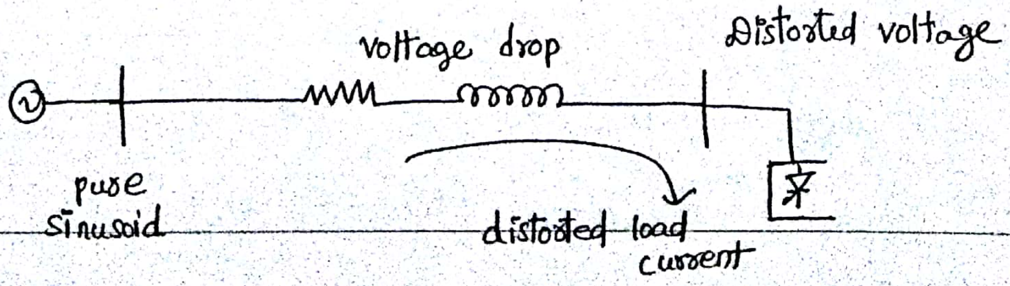
- Harmonic distortion is cause by non-linear devices in the power system
- A non linear device is one in which current is not proportional to the applied voltage.
- A periodic, distorted waveform can be expressed as a sum of sinusoids.




$$v(t) = \sum_{K=1}^{n} a_K \sin K\omega t$$

② voltage versus current distortion:-

- Non linear loads inject harmonic currents into the power system
- so non linear loads called as sources of harmonics
- Due to harmonics, Rms value of load current increases so Transformers must be operated at a lower than rated power
- voltage distortion is the result of distorted current passing through the line inductance.



- The harmonic currents passing through the impedance of the system cause a voltage drop at each harmonic. This results in voltage harmonic appearing at the load bus.
- The amount of voltage distortion depends on the impedance and the current.
- By controlling harmonic current at load can control harmonic voltages.

## (3) Harmonics versus Transients:-

- Transient disturbances contain high frequency components, they may or may not integer multiple of fundamental frequency.
- Transients are result of abrupt change in the power system (Lightning, capacitor switching)
- Transients are aperiodic and usually dissipated in a few cycles.
- Harmonics are associated with continuous of operating load.
- Harmonics are periodic and won't dissipated in few cycles.
- The effect on the equipment is very high for transient than harmonics.

## (4) Power system Quantities under non sinusoidal conditions.

for sinusoidal conditions

$$v(t) = V_{m_1} \sin\omega t$$
$$i(t) = I_{m_1} \sin(\omega t - \theta)$$

apparent power $(S) = V_{rms} \cdot I_{rms} = P + JQ = \frac{V_{m_1}}{\sqrt{2}} \times \frac{I_{m_1}}{\sqrt{2}} = V_1 I_1$

Real power $(P) = V_1 I_1 \cos\theta$

Reactive power $(Q) = V_1 I_1 \sin\theta$

Power factor $P.f = \frac{\text{Real power}}{\text{apparent power}} = \frac{P}{S} = \frac{V_1 I_1 \cos\theta}{V_1 I_1}$

## i) Active, Reactive, apparent power and power factor under non sinusoidal conditions:-

$$V(t) = V_{m1}\sin\omega t + V_{m2}\sin 2\omega t + V_{m3}\sin 3\omega t + \dots$$

$$I(t) = I_{m1}\sin(\omega t - \theta_1) + I_{m2}\sin(2\omega t - \theta_2) + I_{m3}\sin(3\omega t - \theta_3) + I_{m4}\sin(4\omega t - \theta_4) + \dots$$

$$V_{rms} = \sqrt{\left(\frac{V_{m1}}{\sqrt{2}}\right)^2 + \left(\frac{V_{m2}}{\sqrt{2}}\right)^2 + \left(\frac{V_{m3}}{\sqrt{2}}\right)^2 + \dots}$$

$$V_{Rms} = \sqrt{V_1^2 + V_2^2 + V_3^2 + V_4^2 + \dots}$$

$$I_{Rms} = \sqrt{\left(\frac{I_{m1}}{\sqrt{2}}\right)^2 + \left(\frac{I_{m2}}{\sqrt{2}}\right)^2 + \left(\frac{I_{m3}}{\sqrt{2}}\right)^2 + \dots}$$

$$I_{Rms} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \dots}$$

Apparent power $= V_{Rms} \times I_{rms}$

Real power $= P = V_1 I_1 \cos\theta_1 + V_2 I_2 \cos\theta_2 + V_3 I_3 \cos\theta_3 + \dots$

Reactive powe $= Q = V_1 I_1 \sin\theta_1 + V_2 I_2 \sin\theta_2 + V_3 I_3 \sin\theta_3 + \dots$

Powerfactor $=$ $P.F = \frac{P}{S}$

$$P.f = \frac{V_1 I_1 \cos\theta_1 + V_2 I_2 \cos\theta_2 + V_3 I_3 \cos\theta_3 + \dots}{V_{Rms} \cdot I_{Rms}}$$

$$S = \sqrt{P^2 + Q^2 + d^2}$$

$$d = \sqrt{S^2 - P^2 - Q^2}$$

$d \rightarrow$ distortion factor

$$\left[\because I(t) = I_{m1}\sin(\omega t - \theta_1) + I_{m2}\sin(2\omega t - \theta_2) + I_{m3}(3\omega t - \theta_3) + \dots \right]$$

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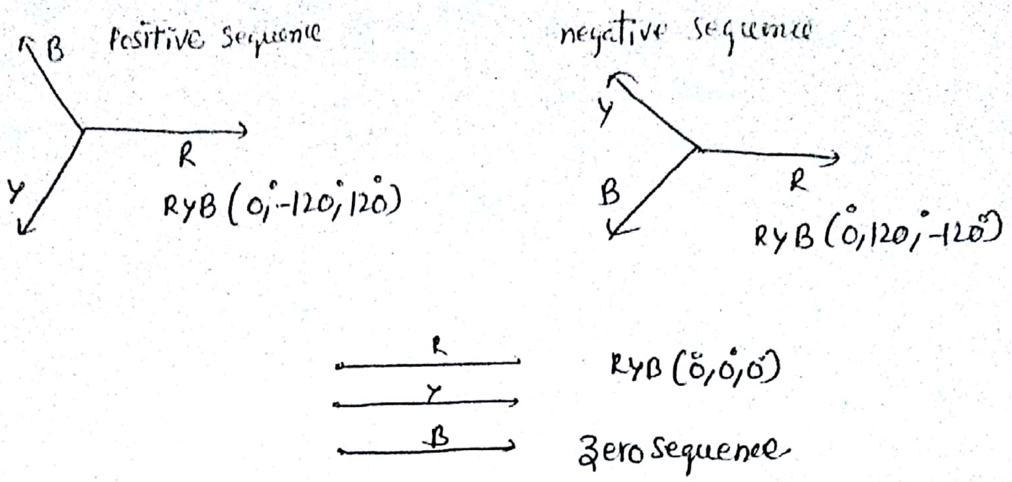
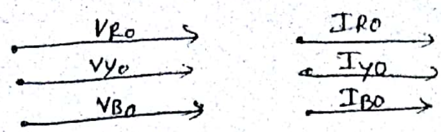
ii) Harmonic phase sequences.




- In a balanced 3 phase system, the harmic phase sequence can be determined by mutiplying the harmonic number h with normal positive sequence phase rotation.
- phase sequence for the Third harmonic is $3 \times (0, -120, 120)$
  $(0, -360, 360)$
  (or)
  $(0, 0, 0)$
- phase sequence for 5 th harmonics is $5 \times (0, -120, 120)$
  $(0, -600, 600)$
  (or)
  $(0, +120, -120)$
- phase sequence for 7 th harmonics is $7 \times (0, -120, 120)$
  $(0, -840, 840)$
  $(0, -120, 120)$
- Harmonics of order h = 1, 7, 13, ..... are generally positive sequence
- Harmonics of order h = 5, 11, 17 are generally negative sequence
- Tripler harmonics h = 3, 9, 15, 21 are generally zero sequence
- In power system most of the waveforms following Half wave symmetry so even harmonics are absent in our power system.

- Triplen harmonics are odd multiples of third harmonic component. ($h = 3, 9, 15, 21, 27, \ldots$)




- Triplens harmonics become an important issue for gronded Y systems with current flowing on the neutral
- Two problems of triplen harmonics are
  - over loading the neutral wire
  - Telephone interference
- Devices will misoperate because the line to neutral voltage is badly distorted by the triplen harmonic voltage drop in the neutral conductors.
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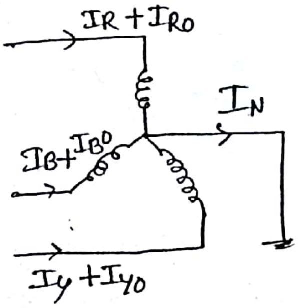



$$I_N = I_R + I_{Ro} + I_y + I_{yo} + I_B + I_{Bo}$$
$$= (I_R + I_y + I_B) + (I_{Ro} + I_{yo} + I_{Bo})$$
$$= 0 + 3(I_{Ro})$$
$$I_N = 3I_{Ro}$$

Sum of all fundamental currents in neutral wire is zero but third harmonic components are in phase so total harmonic current in the neutral wire will become ~~the~~ three times the phase harmonic current.

- In $\lambda - \Delta$ transformer the injected triplen harmonic currents in the primary star connected will flow in $\Delta$ phases but they wont present in $\Delta$ line currents.
- In gronded $Y_1 - Y_1$ winding triplen harmonics will flow from primary to secondary. (They will present in phase and also line in secondary windings)

(5) Harmonic indices:-

1. Total harmonic distortion (THD)
2. Total demand distortion (TDD)

i) Total harmonic distortion:-

- $V(t) = V_{m1}\sin\omega t + V_{m2}\sin 2\omega t + V_{m3}\sin 3\omega t + \cdots$

$$V_{Rms} = \sqrt{\left(\frac{V_{m1}}{\sqrt{2}}\right)^2 + \left(\frac{V_{m2}}{\sqrt{2}}\right)^2 + \cdots}$$

$$V_{Rms} = \sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots}$$

$$V_{Rms}^2 = V_1^2 + V_2^2 + V_3^2 + \cdots$$

$$V_{Rms}^2 - V_1^2 = V_2^2 + V_3^2 + V_4^2 + \cdots$$

$$\sqrt{\frac{V_{Rms}^2}{V_1^2} - 1} = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + \cdots}{V_1^2}}$$

$$THD = \sqrt{\frac{V_{Rms}^2}{V_1^2} - 1} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

- THD can provide good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load.
- It can give an indication of the additional losses caused by the current flowing through a conductor.
- The THD index is most often used to describe voltage harmonic distortion.

ii) Total demand distortion:-

- A small current with a THD value not be a significant threat to the system
- So for small ~~mag~~ magnitude load currents its better to refer "Total demand distortion" value

$$TDD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots}}{I_L}$$

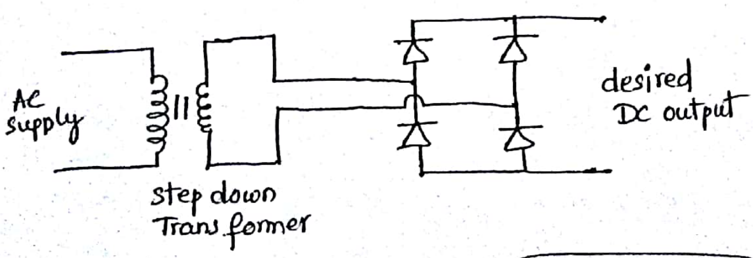
$I_L$ = Peak load current of fundamental component per year

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

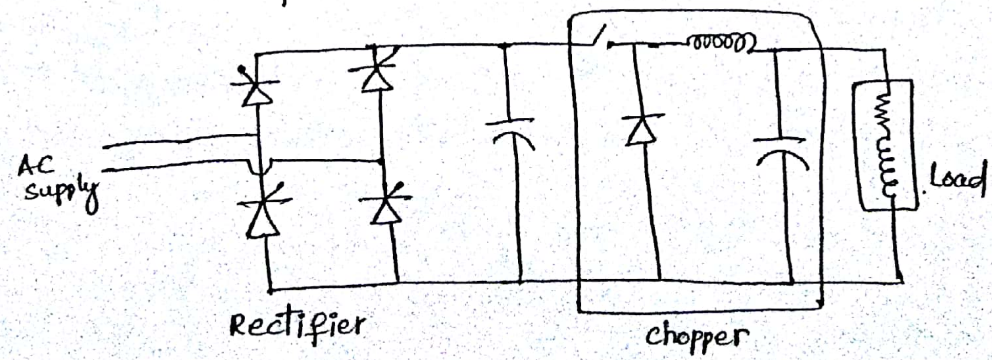
⑥ Harmonic Sources from commecial loads.

- commercial loads are complexes, department stores, hospitals
  - i) single phase power supplies
  - ii) fluorescent lightning
  - iii) Adjustable speed drives for HVAC and elevators

→ <u>single phase power supplies</u>:-

- Electronic power supplies, Battery chargers, Electronic ballasts rectifier and inverters are examples for single phase power supplies
- Electronic equipment will produce too much harmonic current.
- olden days to get desired DC voltage, Transformers and rectifier were used. But now a days rectifiers and DC-DC chopper are using to provide required DC level.
- 


} olden days



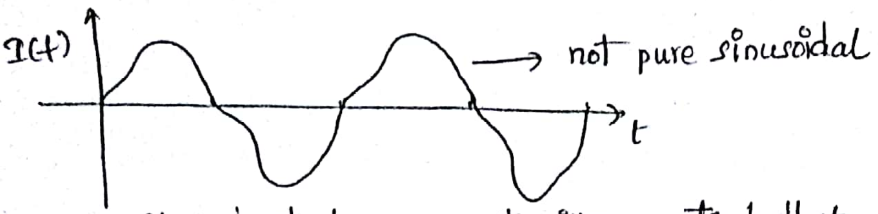

} Now a days

- Personal computers, copiers, pointers is being used every where becaus

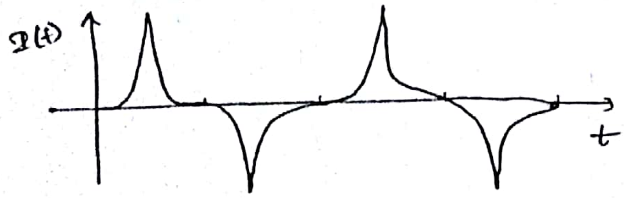
of its light weight, compact in size, efficient operation etc,
lack of need for a transformer. But all are generate harmonics.

## Fluorescent Lighting:-

- Fluorescent light is a non linear load
- Fluorescent lights require a ballast to provide a high initial voltage to initiate the discharge for the electric current flow between two electrodes in the fluorescent tube
- ~~current~~ There are two types of ballasts, magnetic and electronics
- magnetic ballasts are very cost and high weight so now a days all fluorescent lamps are constructed with electronic ballasts
- currents in the fluorescent tube light are shown below




fluorescent lamp current with magnetic ballast




Fluorescent lamp current with electronic ballast.

## Adjustable speed drives for HVAC and elevators:- (ASD)

- Adjustable speed drives are known as elevator motors, pumps, Fans in commercial loads.
- ASDs consists of an electronic power converter that converts AC voltage and frequency into variable voltage and frequency

$$N = \frac{120f}{P}, \quad E = \frac{\phi Z N P}{60A}$$

$$N \propto f, \quad N \propto E$$

↓

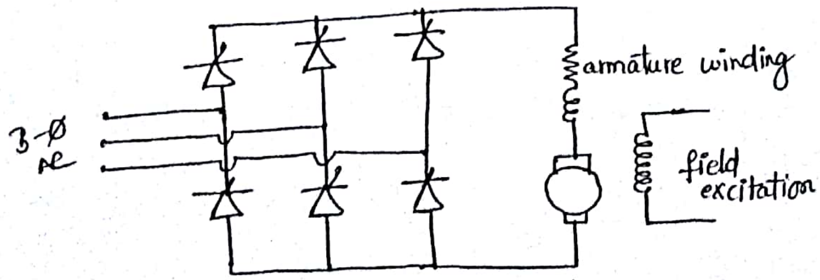
- The variable voltage and frequency allows the ASD to control motor speed to match the application requirements such as slowing a pump or fan.

## (7) Harmonic Sources from industrial loads:-

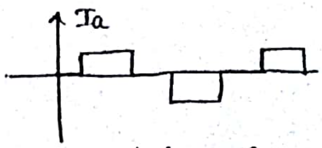
- Three phase power converters
- Arcing devices
- saturable devices

### → Three phase power converters:-

- Three phase power converters are differ from single phase converters mainly because three phase converters do not generate third harmonic components
- DC and AC drives are the main examples of three phase power converters
- DC - Drive offers a ~~higher~~ wider speed range and higher starting torque when compared with AC drives.

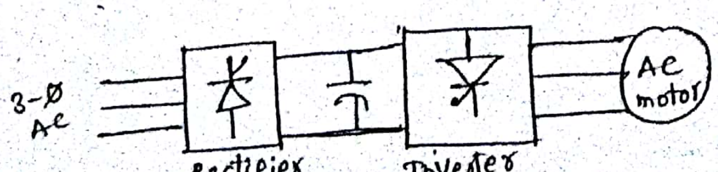


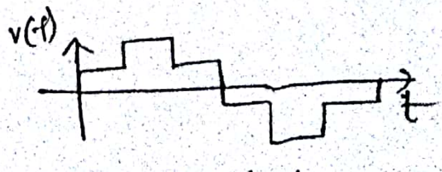

6-pulse thyristor rectifier




current drawn from the source.

- In AC drives AC convert to DC and next DC will convert into Variable frequency and Voltage (Voltage source inverter)

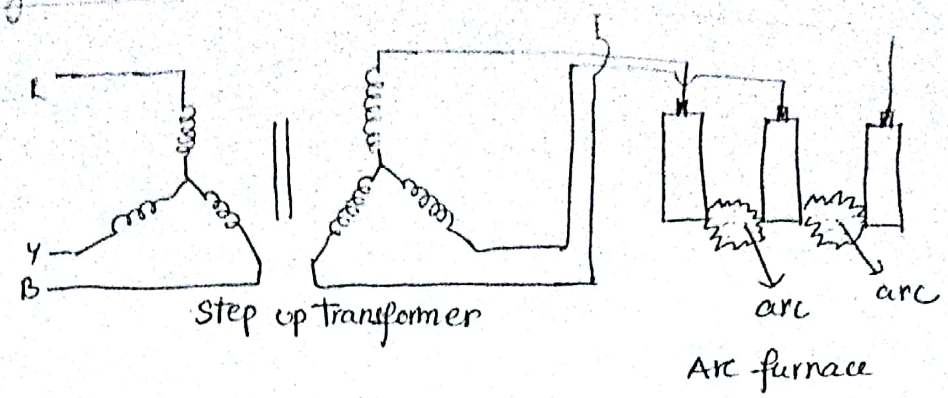



Inverter output

AC → DC → AC, f

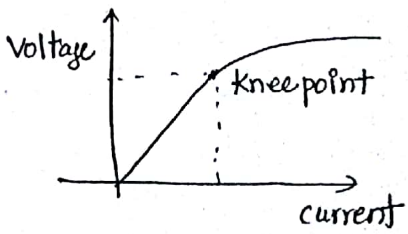
Arcing devices:




- Arc furnaces, Arc welders are examples for arcing devices
- The voltage current characteristics of electric arc are nonlinear
- The arcing load thus appears as harmonics current source.
- And currents in excess of 60,000A are common in arc furnaces
- Arc furnaces mainly used to melt the iron material.

→ <u>Saturable devices:-</u>

- Transformers and other electro magnetic devices with steel core are examples for saturable devices




- Harmonics are generated due to the non linear magnetizing characteristics of the steel core.
- So power transformers are designed to normally operate just below the knee point.
- Harmonic currents are 1% of rated full load current so no need to consider but their effect will be noticeable in distribution systems which have hundreds of transformers.

## 8. System response characteristics:-

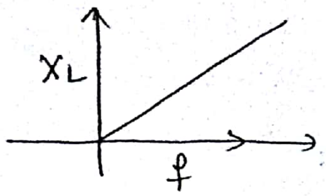
- System impedance
- Capacitor Impedance
- Parallel resonance ( parallel LC )
- Series resonance ( series LC )

### System impedance:-

- $Z_{SC} = R + jX_L$

  $X_L = 2\pi f L$

  $X_L \propto f$




$f\uparrow \longrightarrow X_L \uparrow \longrightarrow$ voltage drop increases

- The inductance of the impedance changes linearly with frequency
- If number of frequency components increase then voltage drop will be there for every harmonic current. So voltage drop increases in the Transmission line.
- The resistance varies approximately by the square root of the frequency once skin effect becomes significant in the conductor at a higher frequency.

### Capacitor impedance:-

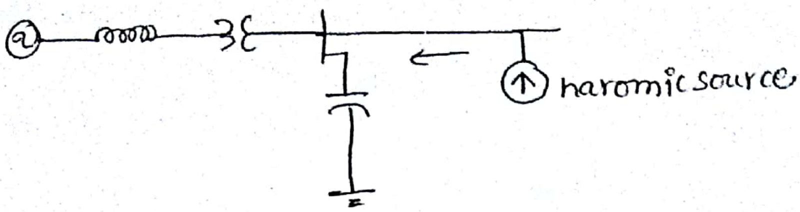
- $X_C = \frac{1}{2\pi f C}$ $\qquad f\uparrow \rightarrow X_C \downarrow$

  $X_C \propto \frac{1}{f}$

- shunt capacitors will be placed either at the customer location for powerfactor correction or on the distribution system for voltage control
- capacitor reactance $X_C$ decreases with increase in frequency causes short CKT at the bus bar.
- capacitors do not create harmonics but severe harmonic distortion can be attributed to their presence.

## Parallel resonance :-

- All CKTs containing both capacitors and inductors
- From the perspective of harmonic sources the shunt capacitor appears in parallel with the equivalent system impedance

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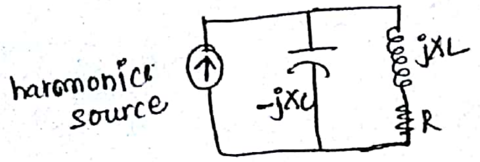



Resont frequency $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$

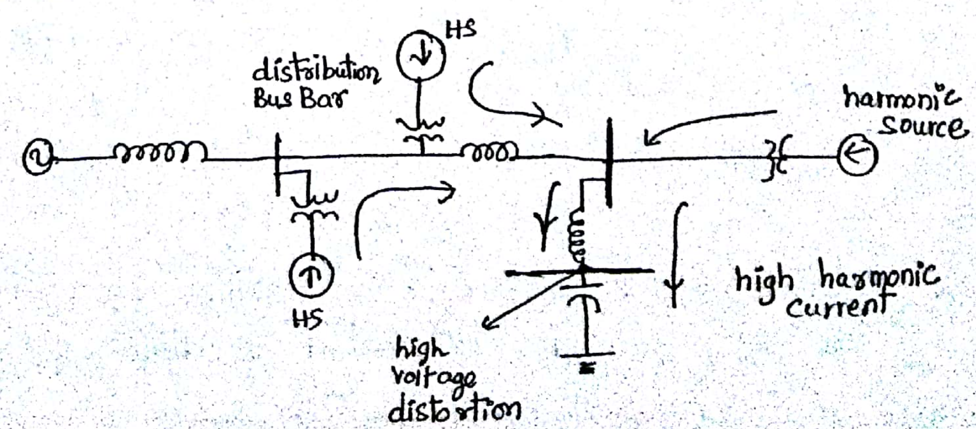
$R \simeq 0$

$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$

- At the resonant frequency, the resultant impedance seen from the harmonic source becomes very large.
- So during parallel resonance, a small harmonic current cause a large voltage drop across impedance. i.e the voltage near the capacitor bank will be magnified and heavily distorted.
- Resonant harmonic $h_r = \sqrt{\frac{X_C}{X_{sc}}} = \sqrt{\frac{MVA_{sc}}{MVA_{cap}}}$

$X_C$ – capacitor reactance $X_{sc}$ – system short CKT impedance
$MVA_{sc}$ – system short CKT MVA
$MVA_{cap}$ – Capacitor rating in MVA

## Series Resonance :-

- 

- A capacitor and inductance of transformer in distribution line may appear as a series LC-CKT to the harmonic currents.
- If the frequency of harmonic current match the resonant frequency of series LC CKT, then LC CKT will draw a large harmonic current that is generated in the distribution systems.
- Results, the voltage is magnified and highly distorted at the busbar where the capacitor is connected.

Resonant frequency of series LC CKT $\omega = \frac{1}{\sqrt{LC}}$

Resonant harmonic $h_r = \sqrt{\frac{X_C}{X_T}}$

$X_T \rightarrow$ (Transformer + Transmission line) impedance

## 9. Effects of harmonic distortion:-

Harmonic currents produced by non-linear loads are interact with a wide range of power system equipment, most notably

i) capacitor
ii) Transformers
iii) motors
iv) Energy and demand meters

### Impact on capacitors:-

- In resonance conditions, the RMS current flowing through the capacitor bank is higher than the capacitor rated RMS current.
- A capacitor bank experiances high voltage distortion during resonance.
- IEEE standards of shunt capacitor are (the maximum allowed Ratings)
  - 110 percent of rated RMS voltage
  - 120 percent of peak voltage
  - 180 percent of rated RMS current

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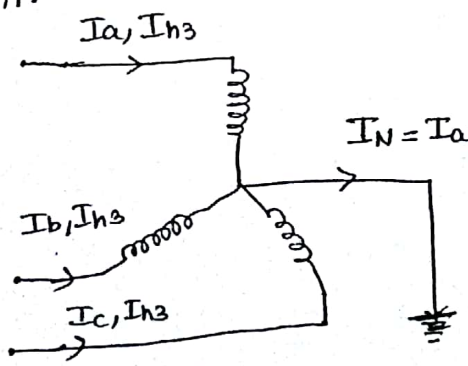
→ Impact on transformers:-

- Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency.
- Harmonic distortion of the current, as well as, harmonic distortion of the voltage will contribute additional heating.
- Harmonic currents of the non-linear load may result in the transformer RMS current being higher than its capacity. The increased total RMS current results in increased conductor losses

$$\text{Copper loss} \propto I_{Rms}^2$$

- Eddy current losses will increases causes additional heating

$$\text{Eddy current loss} \propto f^2$$

- core losses will increase if harmonics are present in applied voltage causes insulation failure.
- In star grounded transformers, 3rd harmonic current in the neutral wire increases 3 times the phase 3rd harmonic current.
- 


$$I_N = I_a + I_{h3} + I_b + I_{h3} + I_c + I_{h3} = 3I_{h3}$$

- Dc harmonic component results in saturation of core, heating losses.

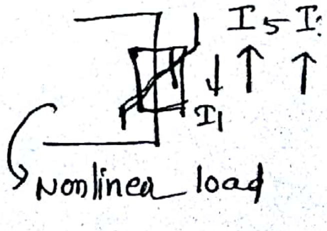
## Impact on motors:-

- Harmonic voltage distortion at the motor terminals is translated into harmonic fluxes within motor.
- Harmonic fluxes do not contribute to motor torque, but rotate at a frequency different than rotor synchronous frequency, inducing high frequency currents in the rotor.
- Harmonics causes additional losses reduction in efficiency, heating, vibration noise in motors.
- For proper operation of motor from IEEE standards
  - Total harmonic distortion (THD) in voltage or current should be less than 5 percent.
  - Any harmonic current magnitude should be less than 3% of rated motor current.

## Impact on energy and demand meters:-

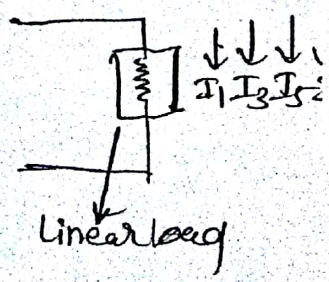
- Harmonic currents from non-linear loads can impact the accuracy of watthour and demand meters adversely.
- conventional magnetic disk watt hour meters have a negative error at harmonic frequencies that is they register low for power at harmonic frequencies.
- Non linear loads tend to inject harmonic power back onto the supply system and linear loads absorb harmonic power due to distortion in the voltage
- for a non linear load, the meter will read

$$P_{measured} = P_1 - a_3 P_3 - a_5 P_5 - a_7 P_7$$




- for a linear load the meter will read

$$P_{measured} = P_1 + a_3 P_3 + a_5 P_5 + a_7 P_7$$

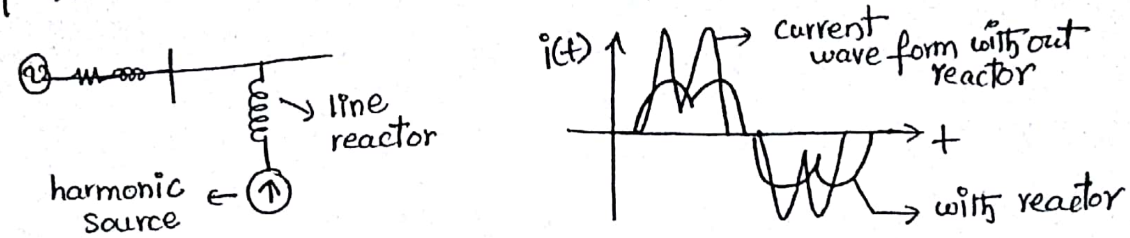


(1c) Devices for controlling harmonic distortion

- In-line reactors or chokes
- Zig-zag transformers
- Passive filters
- Active filters

## In line reactors or chokes:-

- A simple, successful method to control the harmonic distortion is a small reactor insert at the input side of the drive.



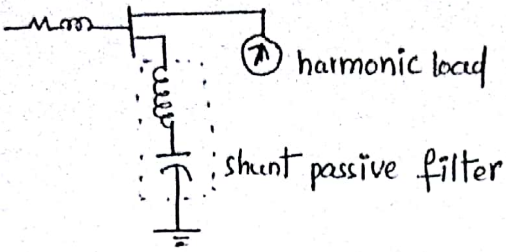

- The inductance doesn't allow sudden change of current so it forces the load to draw constant current.
- A typical 3% input choke can reduce the harmonic current distortion for a harmonic load device from 80% to 40%

## Zig-zag Transformers:-

- A zig-zag Transformers act like a filter to the zero sequence current by offering a low impedance path to neutral. This reduces the amount of current that flows in the neutral wire.
- The two most important harmonic problems are "over loading in neutral conductors" and "Transformer heating". These problems can be solved with proper zig-zag transformer.
- zig-zag Connection will provide on the transformer secondaries.

Passive filters:-

- Passive filters are designed with inductors, capacitors, resisistor elements.
- Shunt passive filters provide zero impedance path to particular harmonic current and then harmonic current will go to ground though filter.

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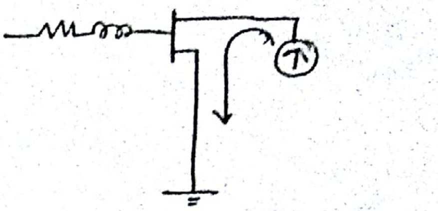
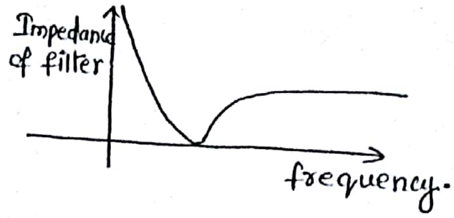
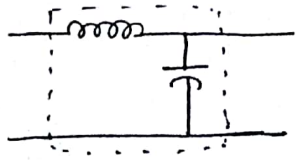


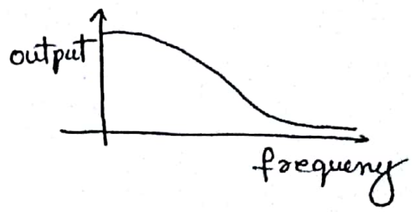
harmonic current will go to earth




- Series passive filters are used to block the multiple or wire spread harmonic frequencies. This low pass filter doesn't allow high frequency currents to flow.



Series passive filters




## Active filters:-

- Active filters are designed with power electronic elements, op-amps (MOSFET, BJT, Thyristors)
- Active filters used in different circumstances where the passive filters causing resonance problems.
- Active filters are used to correct the power factor as well as harmonics
- The basic idea is to replace the portion of sine wave that is missing in the current in a non-linear load.

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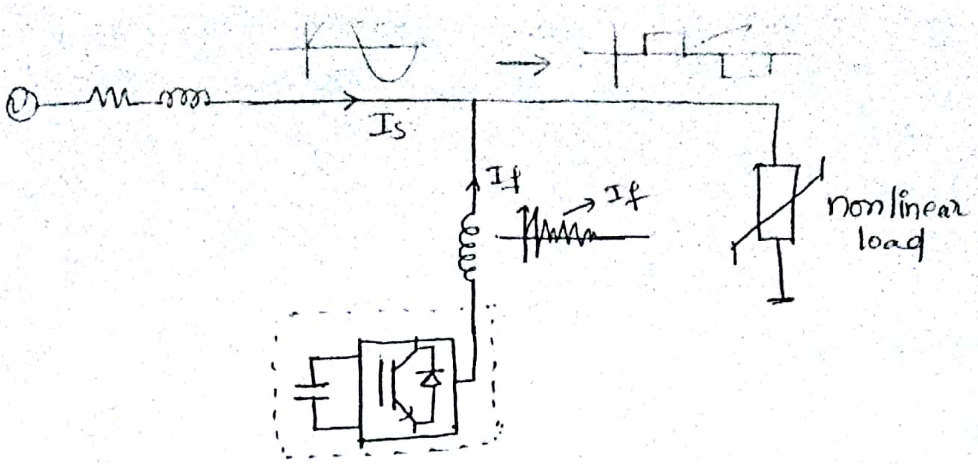
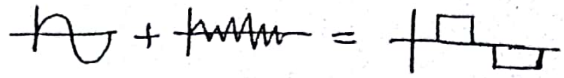



$I_s + I_f = I_L$ ⇒



- Active filter control monitors the line voltage and current and by corresponding switching the power electronic switches, active filters make the supply current sinusoidal.