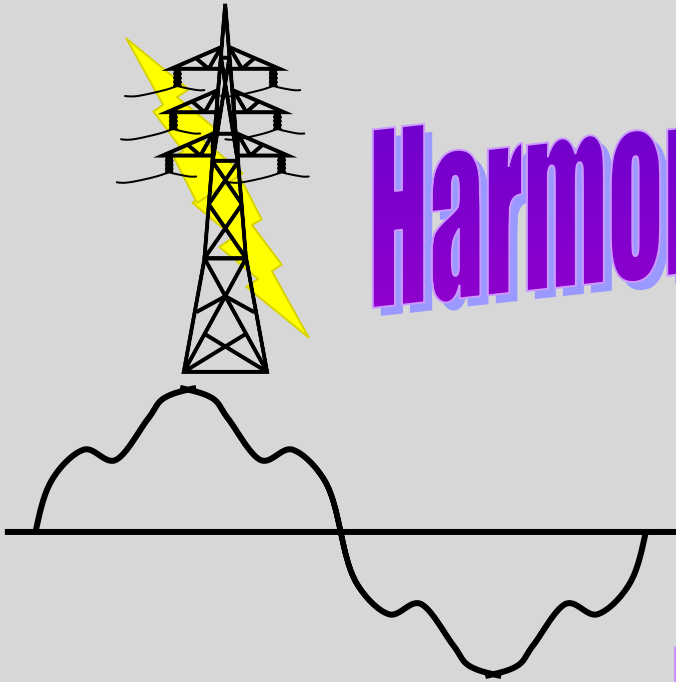
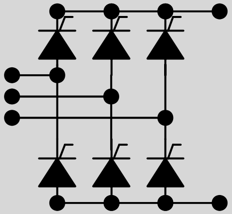
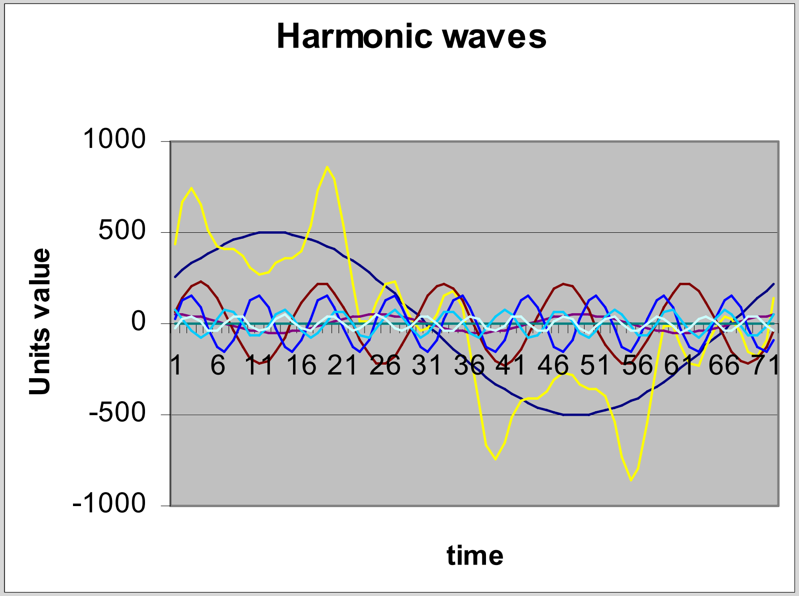
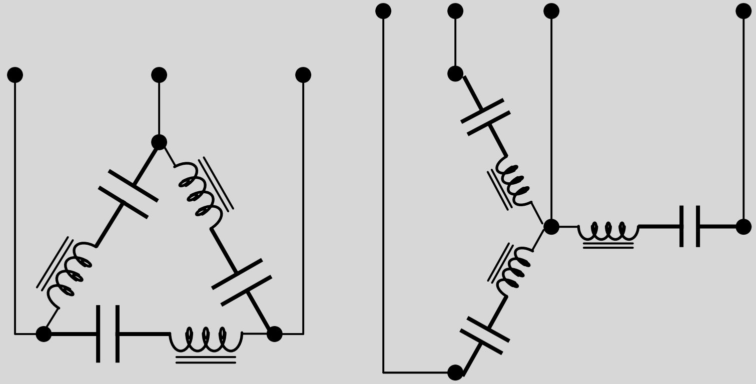
Harmonics on Electrical Supply & Filtering Overview

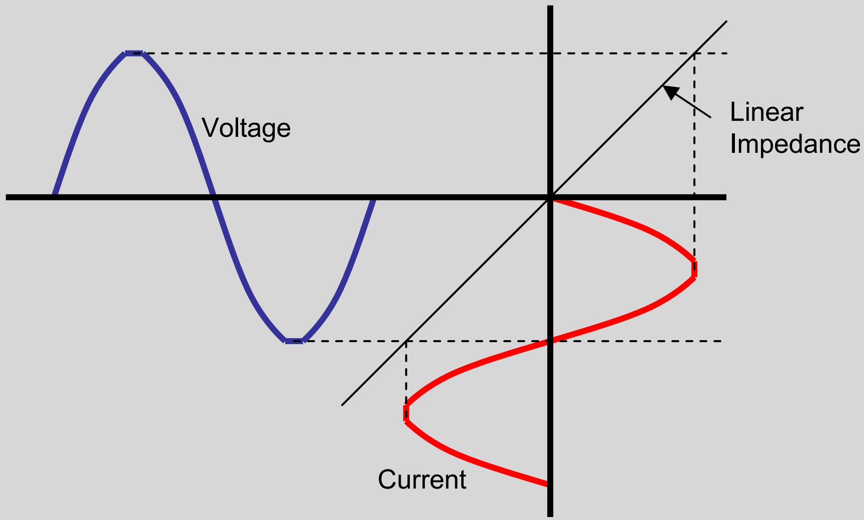






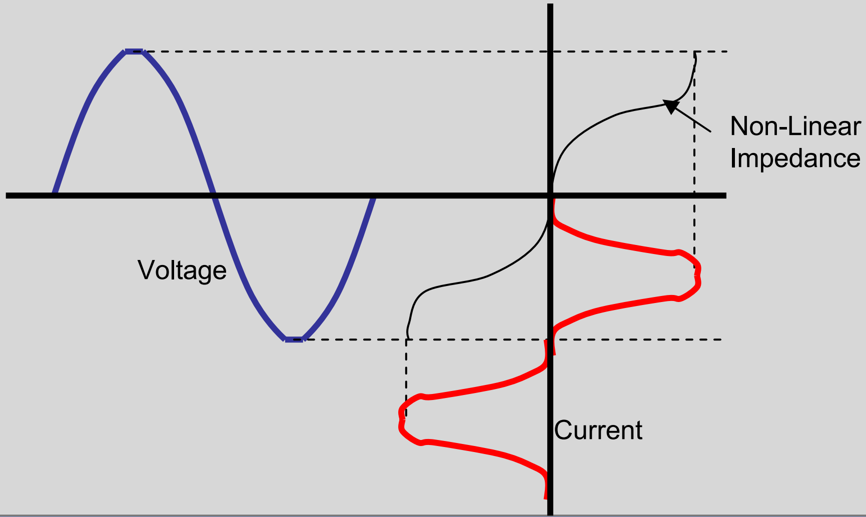


Origin of Harmonics:



Passive Electrical Components are:
• Resistor
• Inductor
• Capacitor.
For an AC supply connected to these components generates sinusoidal currents.
Normally these components depict linear characteristics.

The current output by plotting Voltage against this linear impedance can be seen as sinusoidal waveform of current.
This can be seen here from adjacent diagram.



Electrical Components like fluorescent lamps, Electronic rectifiers, SMPS etc shows non-linear characteristics.
For an AC supply connected to such components generates non-sinusoidal but repetitive currents.
The repetition rate is that of input voltage waveform.

The current output by plotting Voltage against this non-linear impedance can be seen as non-sinusoidal waveform of current.
This can be seen here from adjacent diagram.

Such non-sinusoidal repetitive current waveforms are generated by non-linear loads. Non-linear load is a circuit element, whose current is *not* proportional to voltage.

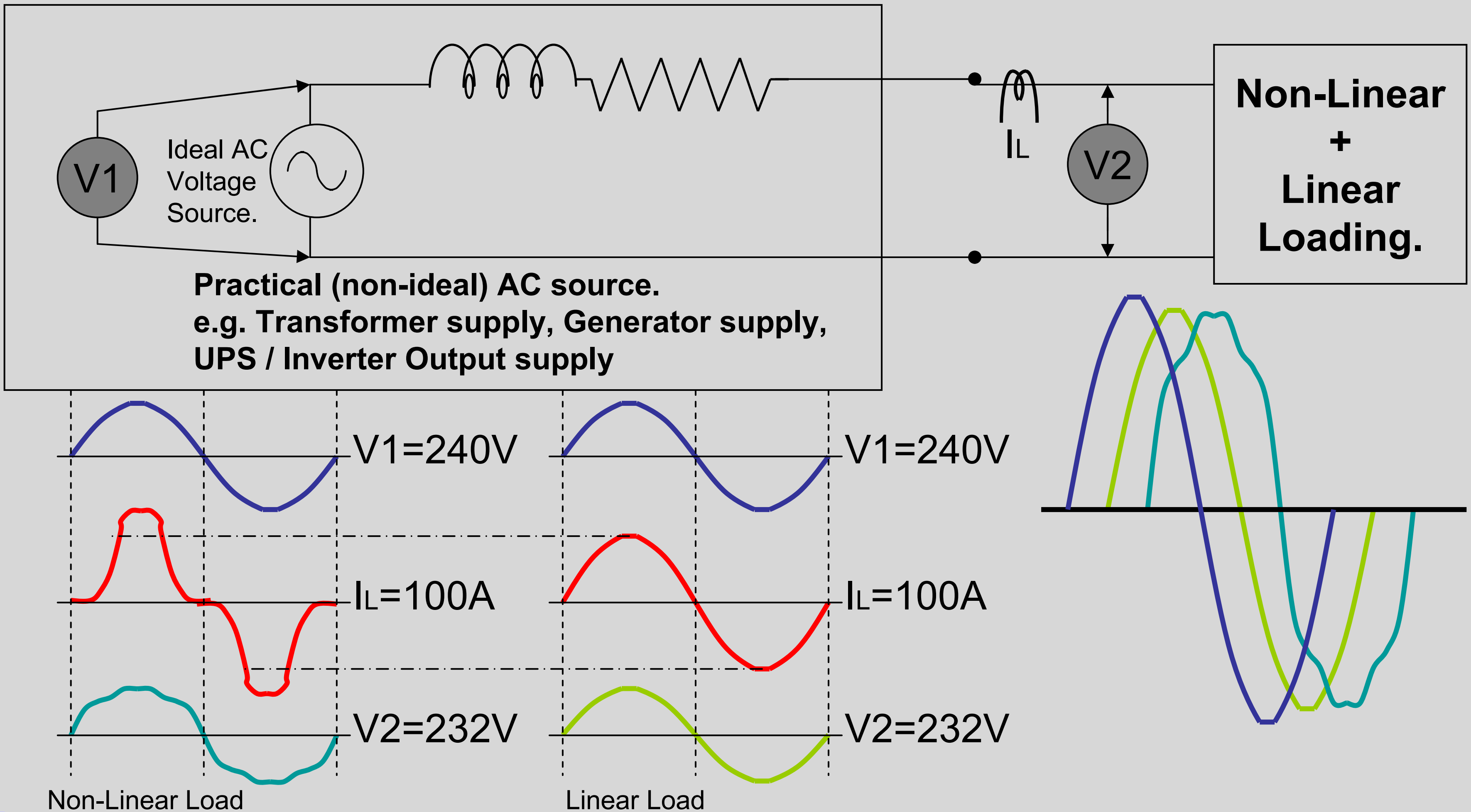
Recently, loads with non-linear components have increased dramatically. (Since year-1990 onwards). Gone up almost 20 times now than that about 20 years ago.

Following are typical examples of Non-Linear Current Loads:

- *Variable Frequency, Voltage speed control drives (VFD) for ind. Motors.*
- *Thyristorised DC motor drives for variable speed applications.*
- *Uninterrupted Power Supplies.(UPS).*
- *Electronic Power Converters/Inverters.*
- *Medium and High frequency Induction Furnaces.*
- *Arc Furnaces.*
- *Electronic ballasts for fluorescent lamps.*
- *Switched Mode Power Supplies used in PLCs, Household equipments etc.*

Practical AC supply systems are not the ideal systems. They have source impedances as well as the Electrical Current carrying cables too have some impedances. Thus, output voltage too is a function of current carried through such supply source and cables.

Due to such Non-Linear currents, disturbances on the voltages are bound to occur and can be a complex function of current non-linearity.



This problem of non-linearity is complex.

Sine wave equation is a known function and can be defined by straight forward formula as $\boldsymbol{f}(\omega t) = e\ \mathbf{sin}\ (\omega t + \text{Ø})$

where "e" is the peak amplitude of sine waveform.

"ω" is the angular velocity of phasor = $2\pi f$ (f – frequency)

"Ø" is initial value phase angle.

"t" is time.

But non-sinusoidal functions are difficult to define.

In practical situation, there are number of loads connected on supply system and some are on, some are off, some are partially loaded etc. In view of the same, non-linearity of the load varies.
This makes the non-linearity function a still more complex topic.

Here to solve this complex problem, we have to take help of the topic in Mathematics:

Fourier Equation and Fourier Coefficients.

Fourier Equation & it's meaning:

As per Fourier Equation: (Definition):

Any **Non-Sinusoidal Repetitive Waveform** can be resolved into the Summation of Sinusoidal waveforms whose frequency is integral multiple of fundamental repetitive waveform and each integral multiple may have different amplitude and phase angle.

This is as per the theory described in the topic of Fourier Transformations.

Mathematical equation, known as "Fourier Equation" can be written as:

$$f(\omega t)_0^{2\pi} = a_0 + e_1 \sin(\omega t + \varnothing_1) + e_2 \sin(2\omega t + \varnothing_2) + e_3 \sin(3\omega t + \varnothing_3) + \ldots + e_n \sin(n\omega t + \varnothing_n).$$

Where
"a_0" is the DC value shift coefficient.
"e_x" is the amplitude,
"ω" = $2\pi f$. , f is the frequency of supply system. (fundamental frequency).
"$\varnothing_x$" is phase angle.
"t" is time.

Fourier Equation & it's meaning:

Now observe the Fourier Equation that we discussed:

$$f(\omega t)_0^{2\pi} = a_0 + e_1 \sin(\omega t + \text{Ø}_1) + e_2 \sin(2\omega t + \text{Ø}_2) + e_3 \sin(3\omega t + \text{Ø}_3) + \ldots + e_n \sin(n\omega t + \text{Ø}_n).$$

Observe every term in the equation.
First term is constant and represents the DC component. It is **DC shift coefficient "a_0"**.
The second term is "$e_1\sin(\omega t+\text{Ø}_1)$" can be seen as a standard sine wave term with amplitude"e_1" and phase angle "Ø_1". It's a sine wave with **fundamental frequency**.

Observe third term "$e_2\sin(2\omega t+\text{Ø}_2)$" can be seen again as standard sine wave term with amplitude"e_2" and phase angle "Ø_2". It's a sine wave with **2 times the fundamental frequency**.

Observe fourth term "$e_3\sin(3\omega t+\text{Ø}_3)$" can be seen again as standard sine wave term with amplitude"e_3" and phase angle "Ø_3". It's a sine wave with **3 times the fundamental frequency**.

This means that as per Fourier Equation,
If we add the sine wave of fundamental frequency + it's integral multiple frequencies in appropriate amplitude and appropriate phase angle + a_0 the DC offset, we can get the desired non-linear waveform.
This means that for every sine wave frequency in the equation,
If we know the amplitude e_x,
& if we know the phase angle Ø_x
We can get the equation for a non-linear waveform desired.

The higher frequency terms in the equation i.e. 2 times, 3 times --- so on (without fundamental frequency term) are known as the **HARMONICS OF THE NON-SINUSOIDAL WAVEFORM.**

Fourier Equation & it's meaning:

i.e.
2^{nd} term indicates the 2^{nd} harmonic.
3^{rd} term indicates the 3^{rd} harmonic.
---- and so on.

Here $\mathbf{e_x}$ is known as the **Combined Fourier coefficient** for corresponding to x^{th} harmonic. It depicts the amplitude of the corresponding harmonic.

The term $\mathbf{Ø_x}$ is known as the **phase angle** corresponding to x^{th} harmonic.

The term $\{(\mathbf{e_x} / \mathbf{e_1}) \text{ X } 100\}\%$ is known as % of x^{th} harmonic on supply system.

The term "a_0" in an AC supply system can exist with the applications like DC half wave rectifier input current. But apart from such smaller applications or some transients like inductance turn on, the DC component $\mathbf{a_0}$ is zero and therefore $\mathbf{a_0} = 0$ (Zero) is presumed by us for further parts of discussions while analysing the harmonics on electrical supply systems.

In fact the component **e sin (ωt + Ø)** can be written down as **a sin (ωt) + b cos (ωt)**
Where $\mathbf{e = \sqrt{(a^2 + b^2)}}$., and $\mathbf{Ø = \tan^{-1}(a/b)}$.

In fact the text book definition of Fourier Equation is

$$f(\omega t) = a_0 + \sum_{n=1}^{N} a_n \sin(\omega t) + \sum_{n=1}^{N} b_n \cos(\omega t)$$

, where $\mathbf{a_0}$, $\mathbf{a_n}$ and $\mathbf{b_n}$ are the **Fourier coefficients**.

This text book definition needless to say is the same equation as we looked before.

Harmonic type analysis and effects

Important points with regards to Electrical supply system harmonics.

If the non-linear part of resistance/impedance are identical for +ve and –ve parts of the AC Voltage waveform, the current non-sinusoidal waveform's +ve and –ve halves are water images of each other.

Note that under such circumstances, the even harmonic terms in the equation are zero.
i.e.
Normally with AC supply system, only odd harmonics are prevalent.
This means that in AC supply, only 3rd, 5th, 7th, 9th, ----- so on harmonics are present.

To summarize,
In normal prevalent electrical supply system,

- **Term for DC component a_0 is absent.**

- **Even harmonic terms (2nd, 4th, 6th, --- so on) are absent.**

But this does not mean that these terms are always going to be absent. All we say is that this is a frequently observed phenomenon. But in some exceptional cases, these terms can be present on electrical supply system Current and therefore the voltage waveforms.

Some exceptions we can see which are against these generalized rules are – Half wave rectifiers, Arc furnaces, Inductor powering up, un-calibrated firing in 3phase full wave thyristorised rectifiers.

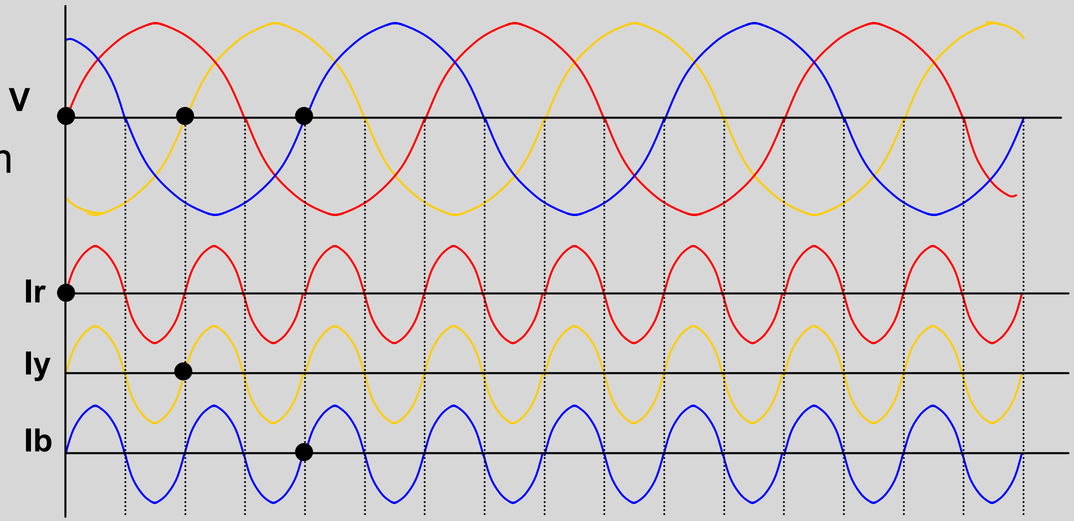
Harmonic type analysis and effects

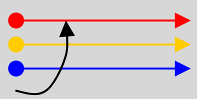
Further, in Electrical system, Harmonics can be analysed based on their sequence analysis:
zero sequence, +ve sequence and -ve sequence components:

Normally for non-linear but balanced loading, which generates current harmonics; the current harmonic contents in every phase are same (identical in terms of amplitude and phase angle).
With this as basic assumption, we can see that some odd current harmonics represent +ve sequence, some show –ve sequence and some are zero sequence components.
As harmonic frequencies are different for different harmonics, it is almost impossible to analyse them by using phasors. In fact it can be convenient to analyse them by waveforms.

Observe this 3rd harmonic waveform

Current harmonics with same
- Amplitude
- Phase angle with regards to V.

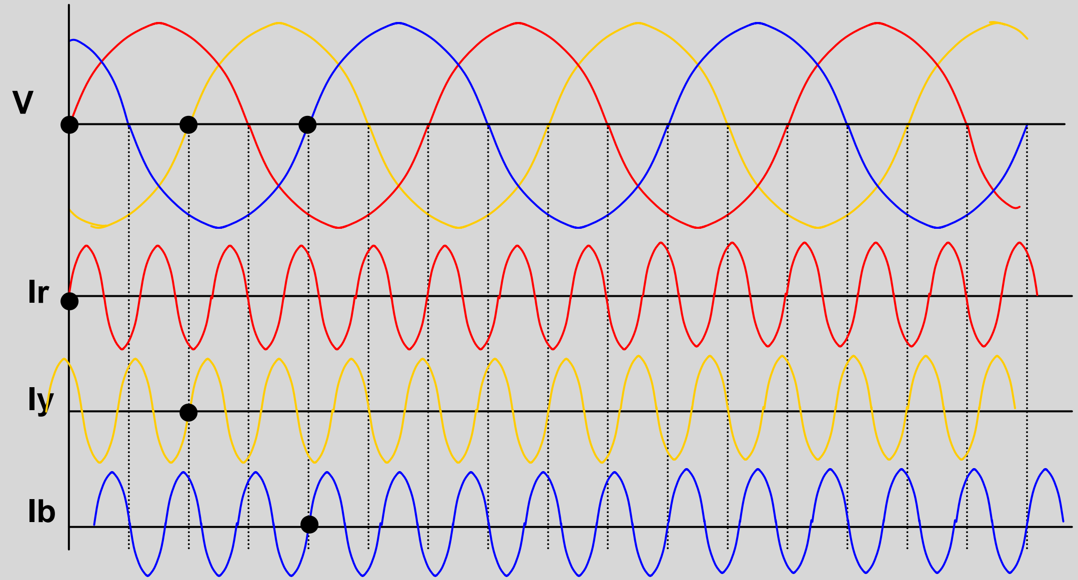


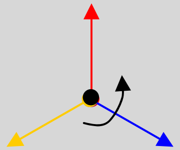


Zero sequence phasors created by 3rd, 9th, 15th 21st - - - so on. Known as triplen harmonics.

Harmonic type analysis and effects

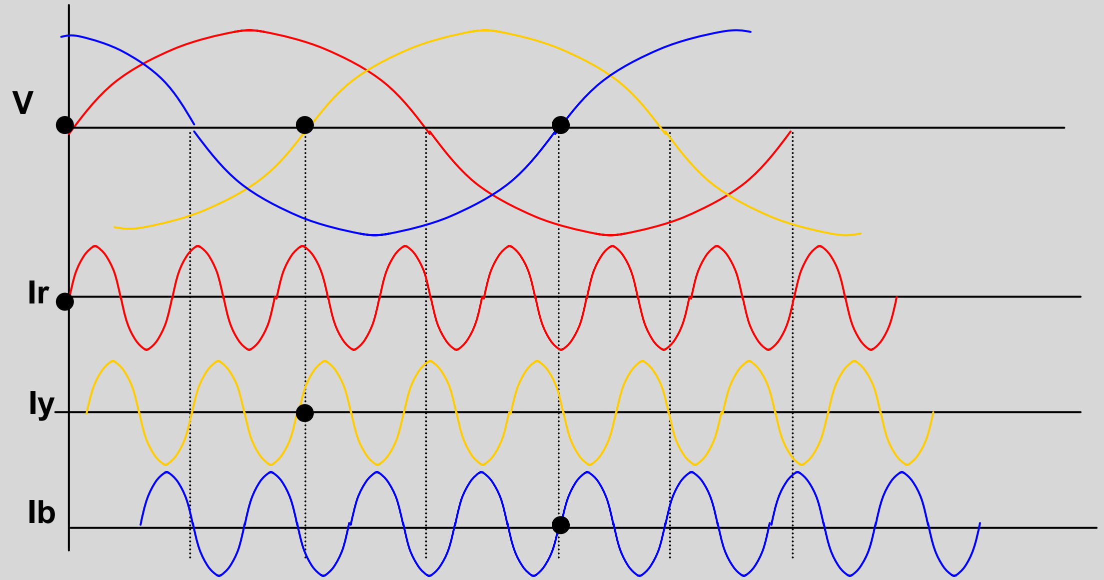
Observe this 5^{th} harmonic waveform

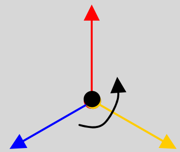




-ve sequence phasors created by 5^{th}, 11^{th}, 17^{th} 23^{rd} - - - so on. Observe reverse Phase sequence.

Observe this 7^{th} harmonic waveform





+ve sequence phasors created by 7^{th}, 13^{th}, 19^{th} 25^{th} - - - so on. Observe reverse Phase sequence.

Harmonic type analysis and effects

Thus, from the previous analytical method, further higher harmonics too can be analysed into 0 sequence, +ve sequence and –ve sequence harmonics.

Sr. No.	Zero Sequence Harmonics (0) (triplen harmonics)	Negative Sequence Harmonics (-)	Positive Sequence Harmonics (+)
1.	3^{rd}	5^{th}	7^{th}
2.	9^{th}	11^{th}	13^{th}
3.	15^{th}	17^{th}	19^{th}
4.	21^{st}	23^{rd}	25^{th}

Effects of each type:

Zero Sequence harmonics: These are also known as "triplen harmonics" (odd multiples of 3). As it can be seen that zero sequence harmonics are phase aligned. Thus, whenever these are present in three phases of loads, they all add up into neutral. Thus, typical problem seen with such harmonics is of overloading of the neutral. E.g. if 3^{rd} harmonic in R-phase is 10Amp, Y-phase is 10Amp and B-phase is 10Amp. Then neutral will see 10+10+10=30Amp 3^{rd} harmonic current flowing through it.

-ve sequence harmonics: These as can be seen shows the reverse sequence. If these harmonics enter the circuit of rotating magnetic field (like 3 phase induction motor or disc type energy meter), they produce the reverse rotating magnetic field. The effect of this on induction motor is to reduce the efficiency and with energy meters running slow.

+ve sequence harmonics: These shows the normal phase sequence. But when present in the circuit produces higher frequency rotating magnetic field in +ve direction. Disc type energy meters thus shows higher readings in presence of these.

Harmonic type analysis and effects

Core Losses in Electromagnetic Equipments:
As we have seen from the Fourier equation that higher harmonics are higher frequency components.

Lot of machines and equipments used with electrical supply system has electro-magnetic components. The electromagnetic equipments normally have “Core Loss” (Iron loss) component. This is mainly due to “Eddy Current losses” and “Hysterisis losses”.

As Eddy current losses are Proportional to square of the frequency and hysterisis losses are proportional to frequency, Normal empirical formula suggests that with such equipments, the core loss factor is normally proportional to frequency to the power of 1.6

i.e. “**Core Losses $\propto$ frequency$^{1.6}$**”.

This means that harmonics on electrical supply system if they enter the electromagnetic equipments, they increase the Core Losses in them. In short reducing the overall efficiency of the electromagnetic equipments.

Transmission Losses in Cables:
Skin effect is the tendency of electrical current to flow on the surface of the conducting material. Skin effect is predominant in the conductors is due to AC currents. More the frequency of AC current flowing through the conductor, more is the skin effect phenomenon is observed.

This means that effective cross-section area of current carrying conductors is less for harmonics. Higher the harmonics, (higher frequency), lower is the effective cross-section area.

Thus, for harmonic currents, the resistivity offered by current carrying conductors is higher. It therefore increases the transmission losses in the electrical supply system.

Harmonic type analysis and effects

Overall PF in electrical billing shows poor effects:

Normally for electrical consumer, the PF is calculated by the Electricity supply company as:

$PF = kWh \,/\, \sqrt{kWh^2 + kVArh^2}$. (where the term $\sqrt{kWh^2 + kVArh^2} = kVAh$)
(Note: There may be some versions of kVArh calculations dependent on different electricity supply companies)

If we look at IEC or IEEE standard definition of kW power or kVAr power, in presence of harmonics, they look as:

$$\mathbf{kW = \sum_{X=1}^{n} Vx \,.\, Ix \,.\, Cos(Øx)} \qquad \textbf{and} \qquad \mathbf{kVAr = \sum_{X=1}^{n} Vx \,.\, Ix \,.\, Sin(Øx)}$$

Where,

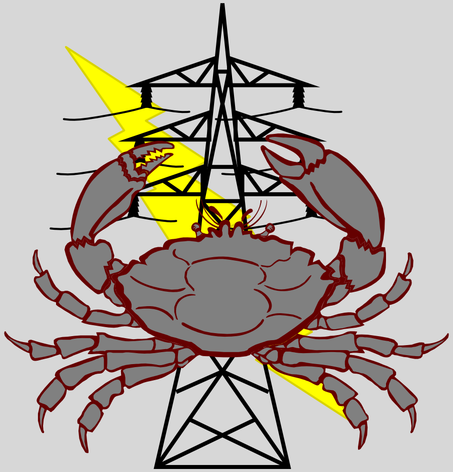
Vx	=	Voltage of “x”th harmonic term. (RMS value)
Ix	=	Current of “x”th harmonic term. (RMS value)
Øx	=	Phase angle difference between Vx and Ix sine waves.

So in presence of harmonics, the term “kVA” gets affected.
Needless to say, the PF in presence of harmonics would be affected and will reflect it in electricity supply metering company bills.

Additionally, the PF improvement capacitors normally placed near the source can give fundamental waveform VAR compensation. Thus cannot improve on poor PF due to harmonic Presence.

What happens if the harmonics are present in the supply system.

Harmonics present on supply system can be considered like a cancer, which goes on deteriorating the electrical equipments and ultimately making the equipments to fail much before their life expectancy.



Without your knowing it, power (kW) consumed on such electrical installations is causing more money burden.

Even the Spurious operations of the protection relays / equipments as well as the energy recording equipments can take place.

Harmonics being higher frequency components, they create more electromagnetic noise which can interfere with communication equipments in near vicinity and can cause these equipments to mal-function.

Spurious blowing of fuses and tripping of circuit breakers without an apparent cause can be due to presence of harmonics.

Higher harmonic distortion levels can cause following problematic Issues.

- Distortion of Voltages on the supply system.

- Harmonics entering Electromagnetic instruments causes higher losses due to increase in core losses component. Therefore reducing the overall efficiency of the electrical system in an industrial environment.

- Some harmonics create a reverse rotating magnetic fields if enters into rotating magnetic field machines or instruments. This can cause the machine efficiencies to reduce and some instruments like disc type energy meters can record low readings.

- Electricity Utility company billing is normally based on PF calculated in presence of harmonics. Harmonic power can hamper this PF and normal PF improvement capacitors cannot improve this PF.

- Skin effect enhancement due to higher frequency components in harmonics. This causes additional Transmission & Distribution losses.

- Higher Electromagnetic noise. The higher frequency components have higher rate of change of flux. Naturally, these have higher ability for electromagnetic induction with magnetic circuits which is normally a noise.

Higher harmonic distortion levels can cause following problems with some equipments.

•Capacitors: The capacitors are subjected to additional power loss, overheating and reduction in life.

•Cables: Neutral overloading and higher transmission losses in the cables. This necessitates the over-sizing of the cables.

•Transformers: The transformers are subjected to additional iron & copper losses, over-stressing of insulation, mechanical vibrations and prohibitive noise level.

•Motors: The induction motor life is reduced due to heat rise in the form of core losses and operating efficiency is reduced due to –ve sequence harmonics.

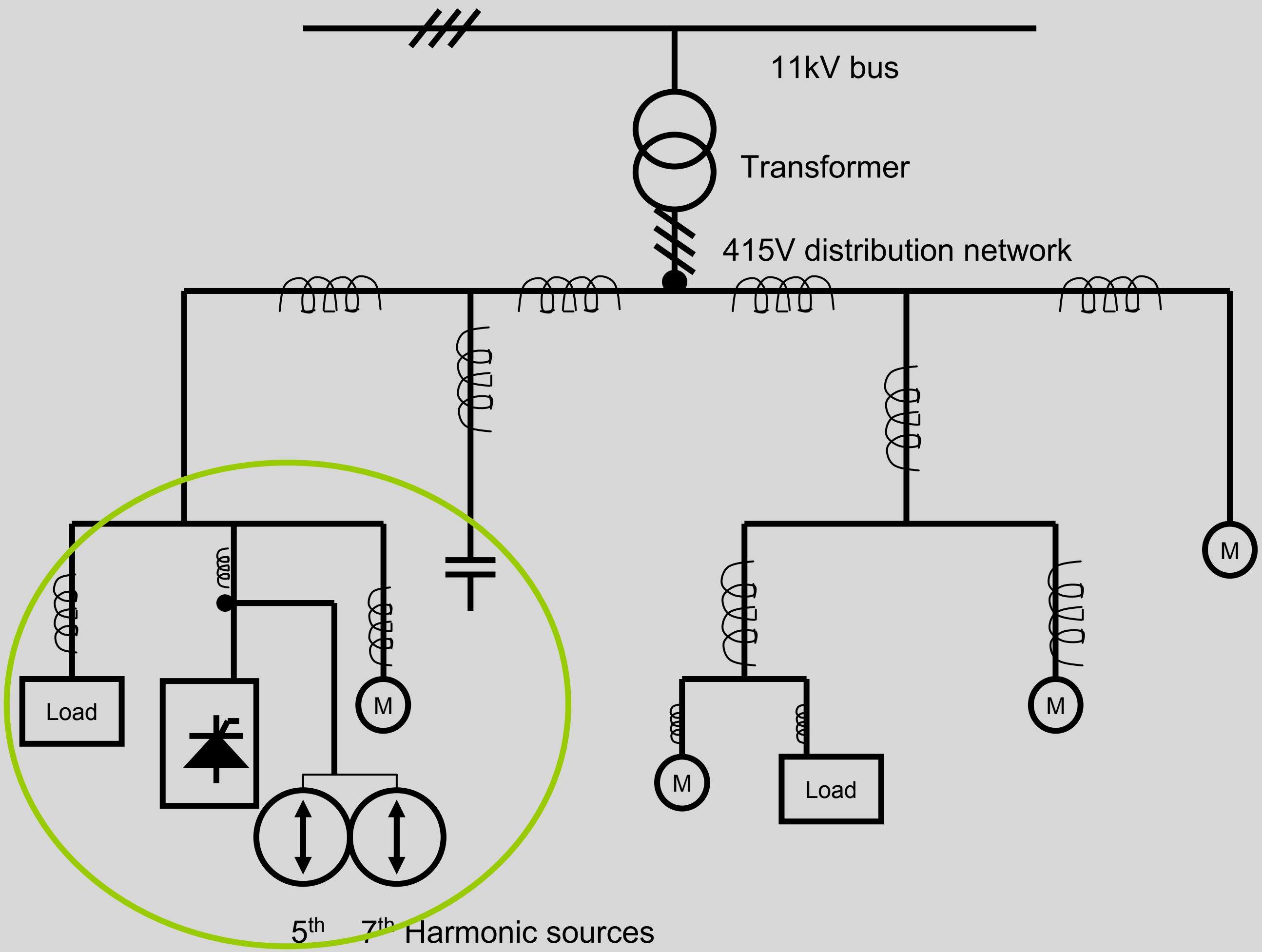
•Communication Equipments: Harmonics interfere with the communication signals causing prohibitive noise level and at times loss of information. The interference with Power Line Carrier System may cause mis-operation while accomplishing remote switching load control and metering.

•Fuses & Breakers: Due to harmonics present, there may be false / spurious operation of the Fuses / Breakers.

•Utility Meters: Utility meters may either over record or under record in the presence of harmonics, causing erroneous results.

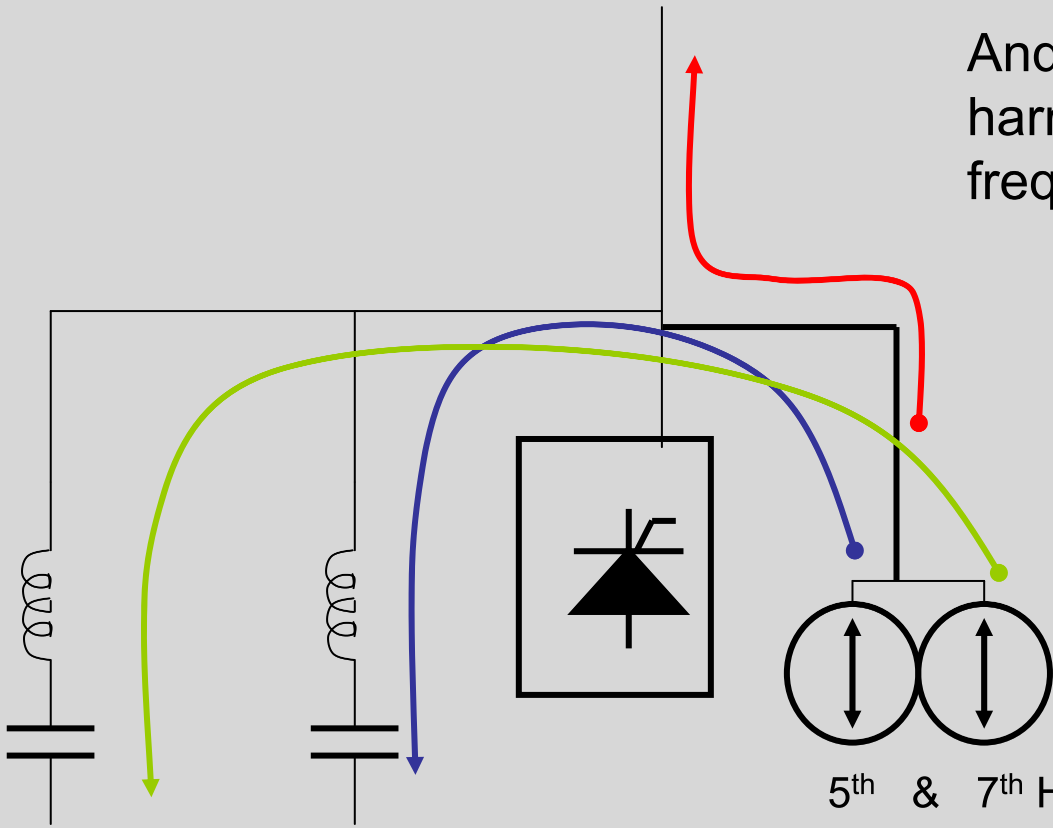
Harmonic distortion Problem Solving Approach:

Consider a typical Electrical supply installation.



Now Lets say a series tuned filter L-C series is put across a load. This filter is say tuned at resonance frequency of 5th harmonic.

And next the 7th harmonic resonance frequency filter L-C.

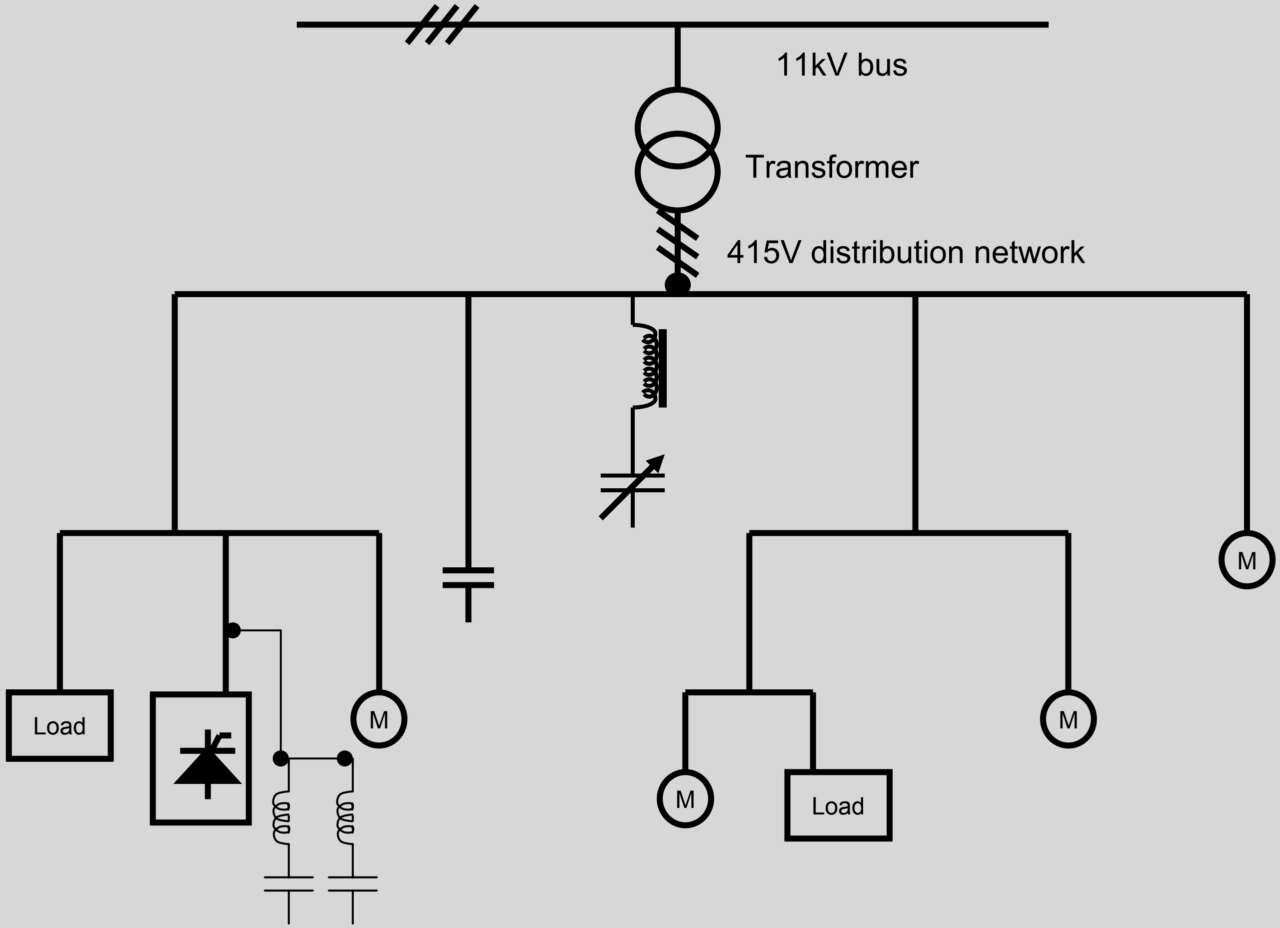


As L-C series filters offer zero impedance at resonance Frequency, all harmonic currents will flow thro' them.

Harmonic distortion Problem Solving Approach:

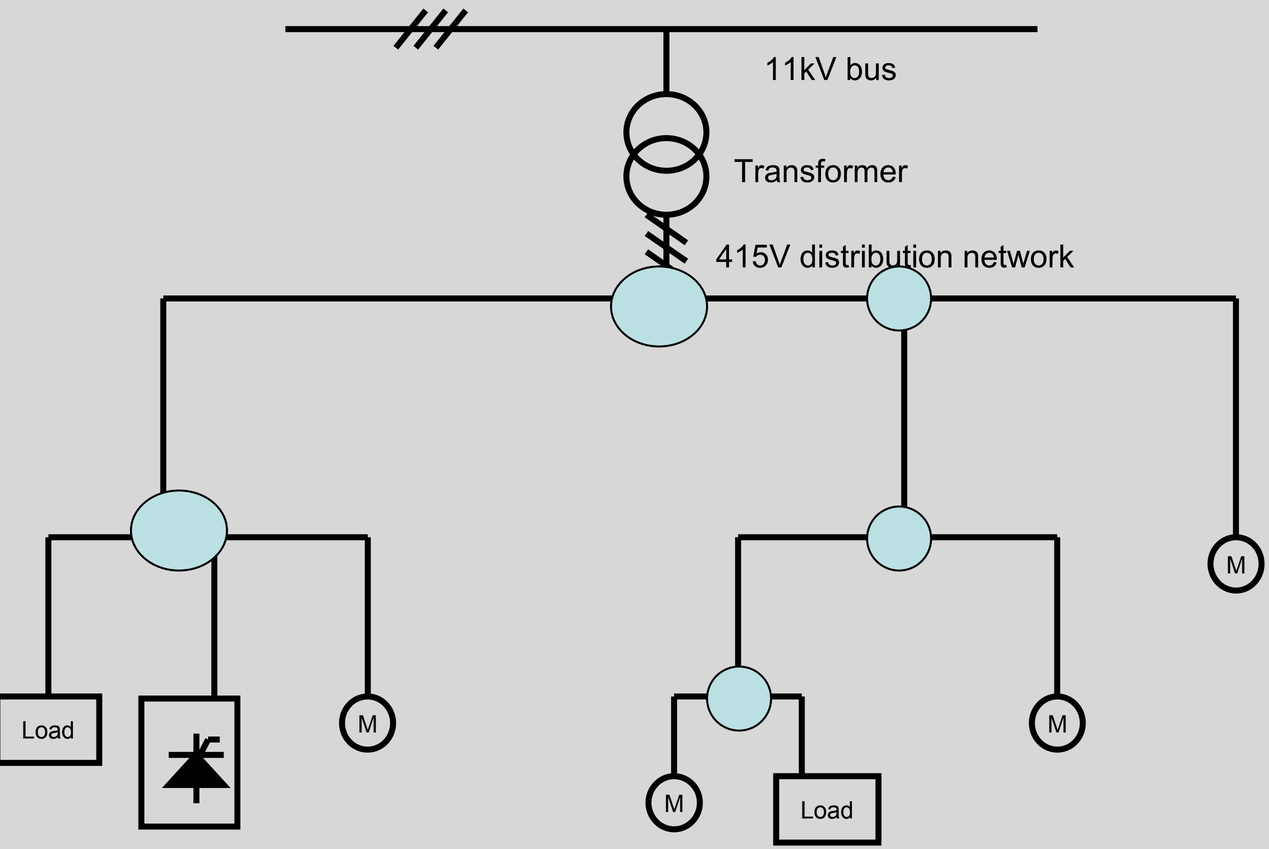
Important Consideration under harmonic presence:

- **Harmonic filters should be electrically as close to source of harmonic.**
- **PF improvement system should be as close to source of supply as possible.**
- **Capacitors used for PF improvement should be properly detuned for harmonic frequencies.**



Harmonic distortion Problem Solving Approach:

Nodal Analysis.



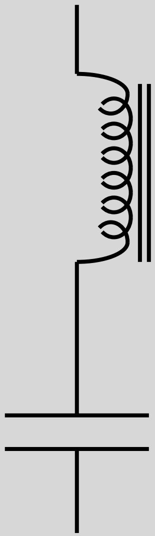
At various nodal points we need to get the various readings of individual harmonic Voltages and Currents.

Once these values are known, the in between path impedance offered for a specific harmonic can be determined.

Based on this impedance calculations, the complete graph of network impedances are drawn.

This is important for calculation of tuned filter offered parallel resonance which under any conditions to be avoided.

Harmonic distortion Problem Solving Approach:



Series L-C filter is the simplest form of harmonic filter.

Impedance offered by inductor and capacitor is a function of frequency.
i.e. it is dependent on the harmonic no.

Inductive impedance $X_L = 2 \pi f L$.
Where, L – is inductor value in Henry. (this is constant of inductor)
f – is the frequency.

Capacitive impedance $Xc = 1 / (2 \pi f C)$
Where, C – is capacitor value in Farad. (this is constant of capacitor)

At resonance frequency of this L-C series combination,

$$X_L = Xc$$

$$\therefore \quad 2 \pi f L = 1 / (2 \pi f C)$$

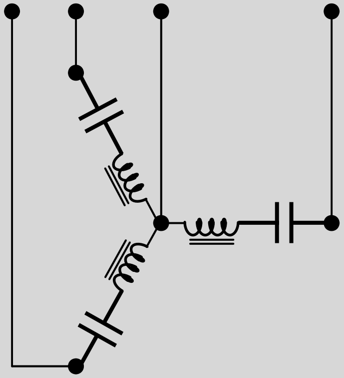
$$\therefore \quad f = 1 / 2 \pi \sqrt{L.C}$$

By such simple formulae, the harmonic filters can be calculated but consideration should be for parallel resonance phenomenon.

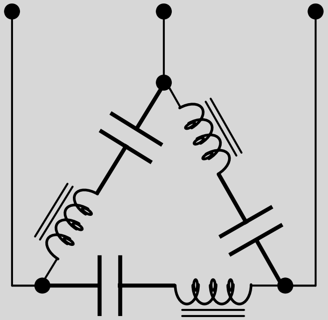
Harmonic distortion Problem Solving Approach:

In three phase supply system:

For triplen harmonic filter, the neutral currents needs to be compensated.
In view of the same, the filters with neutral connection are preferred.



For non-triple filters, the configuration can be delta connected as shown here.



Some other important considerations:

• The reactors used for filters should preferably be air core reactors. These gives linearity though-out the current variation range and does not change Henry (L) values.

• The capacitors used should be capable of withstanding 2 times the normal supply voltage levels on continuous basis and should be stable type. APP capacitors preferred. MPP self healing tend to change their values over time period therefore these are not considered.

We offer Complete Solution to Harmonic Problems:

• Initial Primary Survey for Harmonics and VAR compensation for running plants and electrical installations.

• New Proposed system analysis on basis of Load connected and plant electrical layout.

• Nodal Point Measurements and Analysis.

• Proposing appropriate systems for improving the system performance and Harmonic problem solving. These systems may include:

-- High Speed RTPFC system
-- Tuned Filtering system
-- Active Harmonic Filters or Equi-VAR systems.

• Complete responsibility of equipment commissioning and ensuring performance deliverables of these equipments.

Thank You