Power Quality (PQ) Improvement Systems on LT distribution: Detuned (Anti-Resonant) Reactors for Capacitors in PF improvement system.

Abstract

Majority of Power Factor correction systems are designed by usage of Capacitors to compensate for the load Inductive Reactive Power (VAR).

Since the introduction of Power Electronics based products to the industry and their increasing usage in recent few decades, our Electrical distribution network has started experiencing major Power Quality issue in form of Harmonics on the supply system.

Harmonics on Electrical supply system is the topic concerning deviation of from purely Sinusoidal (Sine & Cosine) waveforms to non-sinusoidal waveforms on AC supply system. These waveform distortions are with regards to Voltage as well as Current waveforms.

The Applied Mathematics topic of “Fourier Series” describes such non-sinusoidal distorted waveforms that are repeating themselves. As per the derivation, these non-sinusoidal repetitive waveforms are made up of vector summation of pure sine wave of fundamental frequency and its integral multiple frequency sinusoidal waveforms. The amplitude and phase angle of such higher integral are the two variable that determine the shape of such non-sinusoidal repetitive waveforms.
In short, the waveforms that are non-sinusoidal are made up of pure sinusoidal waveforms of fundamental frequency and its integral multiple frequencies.

Capacitor impedance is defined by formula
$X_C = 1 / (2.\pi.f.C)$.
Naturally, the harmonics being higher frequency components are going to see smaller values of X_C. Thus, harmonics would be absorbed in Capacitors.

Due to lower impedance path seen, the enhancement in harmonics too can be seen on supply system due to Capacitors.

Even the supply system impedances are inductive, thus if the supply system inductance and PF improvement capacitors values match for any of the harmonics frequency, can cause dangerous resonance conditions on supply system.

Pure capacitors on supply systems if switched ON & OFF on the supply system creates switching ON surge currents that are extreme high amplitude. These can cause Supply system transients Power Quality issue, as well as hampering the switchgear reliability.

Pure capacitors on supply system also have to enhance the adversity during supply system faults. It tends to give very high value of fault currents which is certainly not a desirable phenomenon.

To avoid such inappropriate conditions happening on the supply system, some corrective measures are mandatory. The easiest method that can be seen is to put the reactors in series path with the PF improvement capacitors.

Still one has to understand that putting series reactors with Capacitors has to be done with utmost care. There are various issues with regards to right value selection, right rating and right reliability aspect selection. Inappropriate selection value of such detuned reactors can cause more harm than providing the improvement.

This technical paper tries to throw the light on various aspects of right selection criteria for such series reactors. The reactors that are normally put in series with the Power Factor improvement capacitors are known as “Detuned Reactors” or “Anti-Resonant Reactors” or “Detuned Anti-resonant Reactors”.

Technical Paper covers the following aspects about such Detuned Reactors:

- How, right value of detuned reactor with regards to supply system requirement to be selected.
- What’s the correct selection value?
- How can the right value of Detuned Reactor be calculated.
- Safety aspects, Reliability and Maintenance related considerations.

The stated issues in this Abstract are looked into the main technical paper in details.

It’s assumed that the technical paper is for the reader who has a prior knowledge of Electrical Supply systems and concepts concerning Power Factor improvement (Reactive Power Compensation).

*****

Power Quality (PQ) Improvement Systems on LT distribution: Selection of values for Detuned (Anti-Resonant) Reactors for Capacitors in PF improvement system.

The usage of Capacitors on AC supply system for Reactive Power Compensation (PF improvement) is quite well known method.

Additionally, harmonics on supply system has extreme close relation with the Power Factor improvement capacitors put on the supply system.

First, let's take a short look at the effect of the Power Factor improvement capacitors on supply system with regards to supply system Harmonics, Resonance and Fault conditions

Effect on Electrical supply system with regards to PF improvement Capacitors connected:

Before we start this topic, let's first put down few points that are well known.

- Harmonics (Voltage & Current) are the higher frequency sinusoidal waveform components. Viz. 3^{rd} Harmonic means 3 times frequency and 5^{th} Harmonic means 5 times frequency component…… so on…..
- Capacitor AC impedance is defined as $X_C=1/2\pi fC$. Where f is frequency at which impedance is calculated and C is the Farad value of capacitor which is almost constant. Frequency being inversely proportional to impedance, for higher frequency the capacitors would be offering lower impedance. Additionally, for very fast varying transients, it would offer extreme low impedance path.

Naturally, the effect of putting only the pure capacitors on supply system would cause some undesirable phenomenon such as:

1. Harmonics would see a much lower impedance path through capacitors as Harmonics are higher frequency components. Thus, there would be enhancement in Harmonic levels on the supply system.
2. Capacitors due to higher harmonic currents flowing through them would experience higher current than the RMS rated value. Additionally the dielectric would experience more stress and losses due to higher frequency components it has to experience. These factors can heat up the capacitors and cause it to deteriorate or get damaged.
3. Supply system impedances (specifically source impedance) are inductive. PF improvement capacitors offer capacitive impedance. So during lower Active Power loading condition (Low Watt value of load), the impedances seen are Inductive and Capacitive which can either form series or parallel resonance circuit with a higher Q factor. If the resonance frequency matches with the harmonic frequency present on supply system, the entire system can cause to oscillate at resonance frequency. This is even though a rare phenomenon, but when it happens has a disastrous effects on supply system where voltages seen even 2 times the rated value and extreme high currents causing damage to the supply distribution system equipment and components.
4. During supply system faults, the capacitors connected on supply system show a very low impedance path. Thus, voltages across the capacitors can cause extreme high value of fault currents to flow causing the fault severity to be very high.

This shows that putting the pure capacitors for Power Factor improvement is not a very desirable phenomenon.

To overcome all the specified problematic issues, one simplest method is normally used. That is to use the series combination of Inductive reactors and Capacitors, instead of plain capacitors. Such series Inductive Reactors are known as "Detuned Reactors" or "Anti-Resonant Reactors" or "Detuned Anti-Resonant Reactors".

How to select the right value of a Detuned Reactor?:

Simple one statement answer to this question is to put a value of reactor that eliminates all the 4 issues listed above that create the harmful effects by putting of pure capacitors on supply system.

The first 2 points mandate that the reactor value should be such that impedance offered by series combination of reactor and capacitor should give Capacitive impedance at fundamental supply frequency but should offer much higher impedance to the harmonics. So that there is no harmonic enhancement on supply system and there is no damage to the capacitors connected.

The point number 3 is with regards to resonance. As we know that the supply system impedances are inductive nature. If the L-C combination sees inductive reactance to the prevalent harmonics on supply system then the resonance phenomenon due to any harmonic frequency stimulant would never take place. This even means that to prevent resonance phenomenon occurrence, the L-C circuit resonance frequency, should be lower than the prevalent harmonic frequency on the supply system.
Sometimes the L-C resonance frequency integral multiples too can form supply system resonance as per point no. 3. Thus L-C resonance frequency integral values too should be preferably away from the higher harmonics prevalent on supply system.

With regards to point number 4, one has to ensure that such reactor should be of much higher value than the supply system impedance. This would prevent the fault related short circuit current to have minimum effect due to capacitors present on supply lines.

Before proceeding ahead,
One should know the basic engineering knowhow about how the impedances are calculated.
As, we are dealing with Reactive Power elements like inductor and capacitor, we for arriving at right value would neglect the resistive (or active power component) effect in those because the values are much smaller and would not bring in much error in the calculation.

Inductive impedances are normally due to supply system source impedance, the inductors inserted in capacitor circuit and small impedances in the LT cables used for supply distribution. The value of the impedance is:
$X_L = 2\pi fL$
Where,
X_L is inductive impedance
f is the frequency at which the impedance is calculated.
L is the inductor value in term of Henry.

Thus, as we can see that except for a frequency, 2, π and L are the constant values for a given inductor.
Therefore the value of X_L would rise linearly with the frequency "f". This also means that with higher frequency harmonics, the value of X_L would also rise linearly.

Also, the Capacitors inserted in the supply system has impedance value of:
$X_C = 1 / 2\pi fC$
Where,
X_C is the capacitive impedance
f is the frequency at which the impedance is calculated.
C is the capacitor value in terms of Farad.

Here too, the terms 2, π and C are constants. But frequency f term is in the denominator of the equation. This means that higher frequency harmonics would give lower value of X_C. It also means capacitive impedance is inversely proportional to the frequency.

The frequency plot can be seen therefore as per the diagram as shown hereunder in Fig.1.

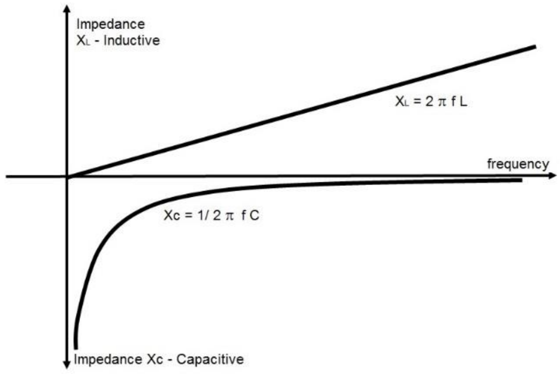


Fig.1.

One should therefore should know that for series circuit of inductor and capacitor, the resonance frequency is at a point when $X_L = X_C$.

Equating the equations for X_L and X_C, one can get L-C combination resonance frequency as:

$f_R = 1 / [2\pi\sqrt{(LC)}]$.

Having defined the criteria and having understood impedance calculation method, let's go further and see how we design the right value of detuned reactor from practical viewpoints.

Designing the right mH value:

From previous description, we can conclude the detuned reactor right value should be such that:

1. Impedance offered by L-C combination in worst case scenario should be at least 4 to 5 times higher than supply system impedance. (i.e. Supply source & network impedances put together).
2. L-C combination resonance frequency should be lower than the prevalent lower most harmonic frequency. This also means that prevalent harmonics should see the L-C combination as inductive impedance but fundamental frequency should see it as capacitive impedance of right value, so that D-PF (Displacement Power Factor) can be improved.
3. The reactive impedance should be high enough so that peak current during system short circuit supplied from Capacitor banks to the fault should be way too lower than the overall system Short Circuit current handling capacity. That means overall PF system inductive impedance should be such that peak current that can be pushed by capacitor in the fault should be less than 10% of overall supply system's Short Circuit current handling capacity.

Once the reactor value is designed for a specific capacitor size bank, it should fulfill the criteria as specified above.

Typical Electrical Supply systems categorized based upon the harmonics are:

- System without triplex (3^{rd} and odd multiple of third like 9^{th}, 15^{th}, 21^{st}…) are with lowest harmonic number as 5^{th} harmonic. With such systems, the lower order resonance frequency selection is at 189Hz or 225Hz for 50Hz and 60Hz supply fundamental frequency respectively.
- System with triplex harmonics are with lowest harmonic number as 3^{rd} harmonic. With such systems, the lower order resonance frequency selection is at 134Hz or 161Hz for 50Hz and 60Hz supply fundamental frequency respectively.

The basis of such resonance frequency value selection is that this selected resonance frequency value and it's integral multiples do not easily match with the higher order harmonics.

So by this method, one of the criteria that prevalent harmonics should see inductive impedance would be surely fulfilled. That is criteria as per point no 2 here above is fulfilled.

But, once the resonance frequency selection is done, one also has to ensure that supply system impedances are much lower than the L-C combination impedances at minimum order prevailent harmonic on supply.
Which also means that supply system without triplet harmonics should have the impedances for 5^{th} harmonic frequency be 4 to 5 times lower (ideally speaking more than 5 times) than the overall PF correction system L-C combination impedance at 5^{th} harmonic.

This can be best explained by some example. Consider following case.

Example:

- *3-ph/50Hz supply with Line-Line Voltage 415Vac.*
- *System without triplen harmonics*
- *Supply source is Generator of 500KVA rating.*
- *Generator output impedance %Z = 15%*
- *Harmonic spectrum as:*
  - ✓ *5^{th} Harmonic – 35%*
  - ✓ *7^{th} Harmonic – 20%*

  All other harmonic numbers negligible.
- *Capacitor used 75KVAR at 525V, 3-ph, 50Hz. (Delta connected balanced capacitor)*

Solution:
Apply criteria first based upon System with non triplen harmonics. So have to go with 189Hz selection criteria first. (even economical cost consideration for this).
Star value equivalent (Phase to Neutral value) can be calculated based upon
$C = KVAR_C \times 1000 / [V_C^2 \times 2 \times \pi \times f_S]$
Where,
$KVAR_C$ = *Capacitor bank 3 ph KVAR value.*
V_C = *Line to Line Capacitor Voltage.*
f_S = *Supply frequency.*
$\therefore C = 50 \times 1000 / [525^2 \times 2 \times \pi \times 50]$
$= 0.000577432$ *Farad*
Resonance frequency = 189Hz
$f_R = 1 / [2 \times \pi \times \sqrt{(L_{189}C)}]$
$\therefore L_{189} = 1 / [C \times (2\pi f_R)^2]$
$= 0.001228$ *Henry*
So impedance offered for 5^{th} Harmonic by such Capacitor & Inductor series circuit
$X_{C\text{-}L250} = X_{L250} - X_{C250}$
$= (2\pi f_{250} L_{189}) - (1 / 2\pi f_{250} C)$
$= 1.92893 - 1.10250 = 0.82643\Omega$
Supply source series impedance which is inductive at fundamental frequency is given as 15% which is primarily inductive.
It's Inductor value
$L_S = 0.15 \times V_S^2 / [KVA_S \times 1000 \times (2\pi f_S)]$
$= 0.15 \times 415^2 / [500 \times 1000 \times (2 \times \pi \times 50)]$
$= 0.0001644$ *Henry*
Thus supply impedance at 5^{th} Harmonic is
$X_{S\text{-}250} = 2 \times \pi \times 250 \times 0.0001644 = 0.25824\Omega$

The ratio $X_{C\text{-}L250}$ / $X_{S\text{-}250}$
= 0.82643 / 0.25824= 3.2002 < 5
This ratio is lower than 5 so in this scenario, the reactor Henry value is to be increased.
(Note that if this ratio value would have been more than 5, one would have to continue with the said calculated value of Detuned reactor).
Thus, next resonance value selected is 134Hz.
Resonance frequency
$f_R = 1 / [2 \times \pi \times \sqrt{(L_{134}C)}]$
$\therefore L_{134} = 1 / [C \times (2\pi f_R)^2]$
$= 0.002443$ *Henry*
$\therefore X_{L250} = 2 \times \pi \times 250 \times 0.002443 = 3.8375$
And $X_{C\text{-}L250} = X_{L250} - X_{C250}$
$= (2\pi f_{250} L_{134}) - (1 / 2\pi f_{250} C)$
$= 3.8375 - 1.10250 = 2.735\Omega$
The ratio $X_{C\text{-}L250}$ / $X_{S\text{-}250}$
= 2.735 / 0.25824= 10.591 > 5
So, in the given example, it is recommended to use the Henry value per phase of detuned reactor as 2.443 mH.

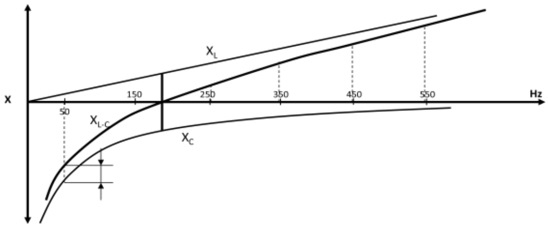
In this example, the major lowest harmonic frequency is of 5th Harmonic (250Hz), in case of triplen harmonics prominence, one would have had to reconfirm impedance ratios at 3rd Harmonic frequency.

The fundamental voltage across the capacitor is going to increase equivalent to the drop across the inductor. Thus, one is even advised to check this rise in voltage is well within the acceptable limits of the capacitor rating.

Next is verification for short circuit value suitability. The impedance offered by such L-C combination and supply source impedance are responsible for short circuit faults. The L-C series combination and the supply source ratio is higher than 5 also ensures that substantial fault currents are governed by supply source impedance. Thus, there is no separate verification needed to be ensured.

End of Example

Typical Impedances seen by L, C and L-C combinations for non-triplen harmonics with 50Hz supply system application of PF correction capacitors can be as shown in frequency v/s impedance graph as here under.



Criteria for Reactor Specifications:

Once the right mH (milli Henry) value per phase is selected, the major calculation work is normally complete.

The other aspects needs to be looked into are

- Linearity of reactor mH value with regards to the current variation through it due to harmonics and voltage variation.
- The losses in the detuned reactors.
- Overload current handling capacity and the protection against this overload handling against winding temperature rise.
- Harmonic overload handling capacity and the protection against iron core temperature rise.
- Maximum Electrical humming audio level with maximum value of harmonics through the same.

The reactors used are of two types.

- Air Core detuned reactors.
- Magnetic Iron Core detuned reactors.

Technically speaking, "Air Core Detuned Reactors" selection is technically superior. Still, in LV application, its usage is almost negligible due to the aspects like "Large size" and "High Costs".

Air core reactors does not have magnetic core, therefore, the effect of magnetic saturation does not arise. Thus, the value of mH in such reactors does not change giving better linearity.
Additionally, there is no question of magnetic core losses and magnetic core temperature rise issues. All that needs attention are the winding losses, right design with regards to insulation and temperature rise against current overloading. Therefore, in MV and HV applications, usage of air core detuned reactors is quite popular.

The iron magnetic core detuned reactors in LV supply system are more popular due to its smaller size and lower costs.
But, specifications with such detuned reactors needs specific attention.

Normally such iron magnetic core reactors specifications consists of:

1. Per phase mH value = ______
2. Winding material Cu / Al.
3. Maximum losses in terms of Wattage at maximum THD current through it at rated voltage value

4. Maximum Continuous fundamental current handling value.
5. Maximum Continuous harmonic spectrum current handling value.
6. Linearity - % mH value reduction with regard to fundamental over-current value.
7. Maximum permissible audio level in term of db (at 1met distance) with worse case harmonics at rated fundamental current flowing through it in all three phase.
8. Maximum temperature rise on surface parts of the reactors.
9. Temperature switches in all the 3 phase windings against over temperature tripping command generation. This is protection against the reactors current overloading in any of the three phases.
10. Temperature switch for trip command against magnetic core overheating due to harmonics current overloading.
11. Terminals for electrical connection. Bus-bars or lugging type.
12. Mechanical mounting arrangement mechanical details.
13. Ability to maintain its mH value against mechanical mounting stresses.
14. Type of insulation and insulating varnish impregnation (Vaccum or dipped impregnation) along with type of varnish.

The reason for writing this technical paper is to create awareness among the Power Factor system designers about the right criteria for selection of the Detuned Reactors.

Many cases it is observed that wrong selection of specifications for the detuned reactor is the reason for major levels of Power Quality problems on supply system as well as failures of the components in the PF correction systems.

- **Tushar Mogre.**
(Graduate Engineer – Mumbai University)
(BEE – EM)
CEO & Director
TAS PowerTek Pvt. Ltd.
Nasik, India.
(Company specialized in PQ audits and providing PQ solution products & systems)

*****

References: Most of the technical paper is written by author by self-experience working in the field.

*****

Readers are advised to read the book by Author on the subject of “Reactive Power Compensation on LV supply system”. Book is available on “amazon.com” as e-book.

*****