Detuned Reactors in Capacitor Banks: Mitigating Harmonics and Preventing Resonance

Introduction

Capacitor banks, a common feature in power systems, are employed to optimize power factor and enhance overall system efficiency. However, the integration of capacitors introduces the potential for resonance issues, which can result in elevated voltage stress, excessive currents, and equipment failures. To mitigate these challenges, the use of detuned reactors has become a crucial aspect of power system design.

Detuned reactors are three-phase inductors that play a crucial role in attenuating the amplification of harmonics in networks rich in harmonics. They are also used in series with capacitor banks to prevent harmonic amplification caused by resonance. This paper aims to provide an in-depth understanding of detuned reactors, their role in mitigating harmonics, and how they prevent resonance in capacitor banks.

Harmonics in Power Systems

Harmonics are sinusoidal voltages or currents having frequencies that are integral multiples of the frequency at which the supply system is designed to operate. They are produced by the action of non-linear loads such as rectifiers, discharge lighting, or saturated electric machines. The presence of harmonic distortion due to non-linear loads within the network or due to import of harmonic from grid or power source increases the current flowing through capacitors. This is because the capacitive reactance is inversely proportional to the frequency, consequently subjecting capacitors to overload.

Harmonics in power systems are generated by non-linear loads. VFDs, arcing machines, power converters, fluorescent lights etc. are all non-linear loads. The current waveform distortion can be quite complex, depending on the type of load and its interaction with other components

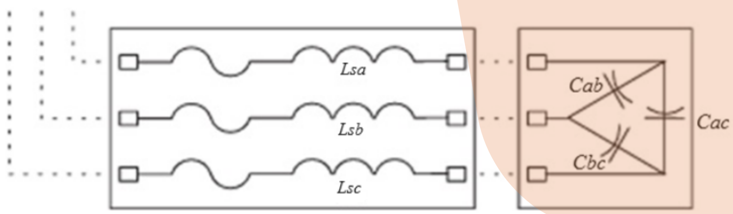
Resonance in Power Systems

Resonance occurs when the inductive reactance equals the capacitive reactance. This can lead to an increase in current or voltage at the resonant frequency, which can cause damage to the equipment or system.

In an electric power system, a harmonic is a voltage or current at a multiple of the fundamental frequency of the system. When waveforms deviate from a sinewave shape, they contain harmonics. The difference between series and parallel resonance in power system is that series resonance creates a low impedance (draw maximum current into the system) whereas parallel resonance creates a large impedance which even in the presence of small current can create large harmonic voltage drop and hence cause voltage stress related damages.

Role of Detuned Reactors

Detuned reactors are used to prevent harmonic amplification caused by resonance and avoid the risk of overloading capacitors. This significantly reduces voltage and current harmonic distortion in the network. All connected equipment, and even remote substations, are subject to voltage fluctuations which may result in equipment malfunction or failure. To avoid this problem, it is common to insert reactors in series with capacitor banks. The diagram is shown in Figure 1.
The inductive reactance (XL) of a reactor is directly proportional to frequency. The magnitude of inductive reactance will increase with high frequency harmonics thus blocking the harmonic current. Hence, the use of detuned reactors in series with capacitors offers higher impedance for harmonics, thus eliminating the risk of overload in capacitors.



Reactor in series with the capacitors .1 Figure

The inductance value of detuned reactors is selected such that the resonance frequency is less than %90 of the dominant harmonic in the spectrum. For example, if the 5th harmonic is dominant in the spectrum, any series LC circuit having a resonance frequency of %90 of 300Hz (for a 60Hz system), i.e., if the natural resonance frequency of LC is less than 270Hz, it is categorized as detuned filters or detuned capacitors.
This resonance can be avoided by putting a detuned reactor in series with the capacitor. The reactor shall be such that the tuning frequency with the capacitor shall be less than the dominant harmonics. This combination of power factor correction capacitor and detuned reactors behaves inductively to frequencies above the tuning frequency.
The reason why reactors are detuned and not tuned to a certain order is to avoid resonance with a particular harmonic order present in the system. If a reactor was tuned to a specific harmonic order, it could potentially amplify that harmonic, leading to increased distortion and potential damage to system components.
Detuned reactors are designed to have a resonant frequency that is different from the harmonic frequencies present in the system. This detuning helps to prevent the amplification of these harmonics and reduces the risk of resonance occurring within the system.
In other words, by detuning the reactors, we can ensure that the series resonance does not coincide with any of the prominent harmonics in the system, thus preventing amplification of these harmonics and potential damage to the system. This is why detuned reactors are a crucial component in power systems, especially those with significant harmonic content

Benefits of Using Detuned Reactors

The typical benefits of a detuned reactor are as follows:
- It eliminates harmonic amplification.
- It enhances the life of capacitors by reducing voltage and thermal stress due to harmonics.
- It prevents the constant nuisance of input fuse blowing or circuit breaker tripping.

• It reduces overheating of the transformer, busbars, cables, switchgear, etc., caused due to harmonic amplification.
• It reduces the harmonic current in the electrical supply system.
• It addresses the harmonic problems created by non-linear loads.
• It improves Power Factor in a harmonic-rich environment.

Formulas and Example

In the detuned frequency, the reactance of the reactor and capacitors are equal. Therefore, according to (1), the detuned order is obtained from the inductance and capacitance.

$$|X_{Ln}| = |X_{Cn}| \rightarrow n\omega_1 L = \frac{1}{n\omega_1 C} \rightarrow n = \frac{1}{\omega_1\sqrt{LC}} \; or \; L = \frac{1}{n^2\omega_1^2 C} \quad (1)$$

For simplicity in the calculations, given the delta configuration of the capacitor cans, the equivalent series capacitance (C_s) is calculated as (2) based on delta capacitance (C).

$$\begin{cases} C_{sa} = \frac{C_{ab}C_{ac}+C_{ab}C_{bc}+C_{bc}C_{ac}}{C_{bc}} \xrightarrow{symmetrical\ legs} C_{sa} = 3C \\ C_{sb} = \frac{C_{ab}C_{ac}+C_{ab}C_{bc}+C_{bc}C_{ac}}{C_{ac}} \xrightarrow{symmetrical\ legs} C_{sb} = 3C \\ C_{sc} = \frac{C_{ab}C_{ac}+C_{ab}C_{bc}+C_{bc}C_{ac}}{C_{ab}} \xrightarrow{symmetrical\ legs} C_{sc} = 3C \end{cases} \quad (2)$$

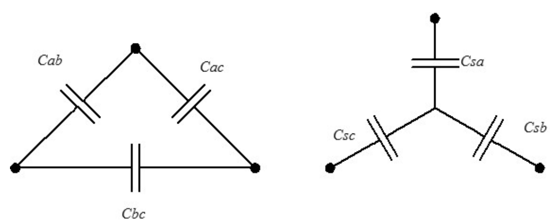


Figure 1. Delta and Wye configuration

$\frac{X_L}{X_C}$ which is known as relative impedance is detailed in (3).

$$\left|\frac{X_L}{X_C}\right| = \frac{\omega_1 L}{\frac{1}{\omega_1 C}} = \omega_1^2 LC \quad (3)$$

Combining equations (1) and (3) yields:

$$\left|\frac{X_L}{X_C}\right| = \frac{1}{n^2} \quad (4)$$

As an illustrative example, consider a capacitor bank in which each step's capacity is 100 kVAR, consisting of four paralleled delta-configured 25 kVAR cans with the capacitance of 61.5 μF per phase. The detuned factor is determined as 4.2 due to the notable presence of the 5th harmonic current. Consequently, the inductance of the reactor can be calculated.
According to (2) The equivalent series capacitance for each leg is:

$$C_s = C_{sa} = C_{sb} = C_{sc} = 3 \times C = 3 \times (4 \times 61.5) = 738\ \mu F$$

Therefore, L for each leg (phase) of the inductor can be calculated:

$$L = \frac{1}{n^2\omega_1^2 C_s} = 540\ \mu H \text{ per leg}$$

Additionally, the relative impedance is calculated based on (4) as:

$$\left|\frac{X_L}{X_C}\right| = \frac{1}{4.2^2} = 5.67\%$$

In summary, to achieve a detuned impedance of the order of 4.2, it is necessary to connect a three-phase reactor with a relative impedance of %5.67 or an inductance of 540 μH for each leg in series with the capacitor cans.

Table 1 presents the prevalent detuned orders along with corresponding data, encompassing relative impedance, targeted harmonic current, and resonance frequency.

Table 1. Detuned Orders

Detuned Order	X_L/X_c	Harmonic Absorption Order Target	Series Resonant Frequency (60 Hz System Frequency)
4.7	4.53%	5^{th}+	282 Hz
4.3	5.41%	5^{th}+	258 Hz
4.2	5.67%	5^{th}+	252 Hz
3.8	7%	5^{th}+	228 Hz
2.7	14%	3^{rd}	162 Hz

It is generally advised to use standard reactor designs, which are tuned to the 4.2nd harmonic, to shield capacitors from harmonic resonance. There is an option to tune to different harmonics. Applications utilizing reactors tuned above the 4.2nd harmonic should assess the harmonic spectrum to guarantee the longest possible equipment life, especially when combined with six-pulse motor drives.

Figure 3 is depicting reactor impedance magnitude versus frequency. As evident, each graph exhibits a resonance frequency, aligning with the detuned order of the main frequency. For instance, by using a %7 reactor in series with the capacitors, the overall impedance will be zero in $f_r = 3.8f_1$. In other words, the resonance frequency is $3.8f_1 = 228\ Hz$.

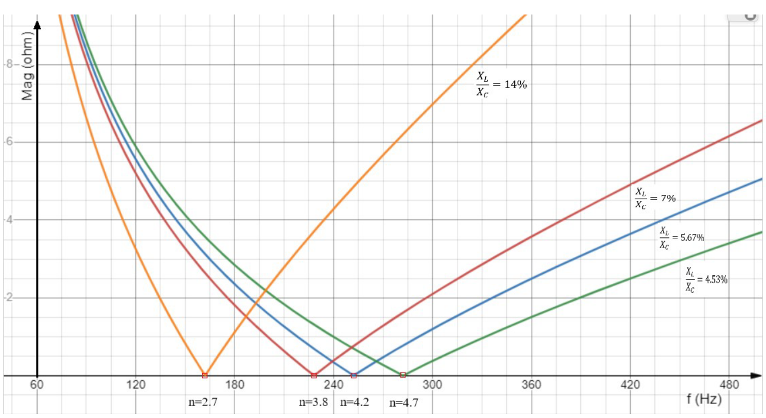


Figure 1. LC circuit impedance magnitude frequency response

Detuned reactors play a vital role in reactive power compensation of facilities by mitigating harmonics and preventing resonance. They protect the different components of the installation and enhance the life of capacitors. By understanding their function and benefits, we can effectively utilize them in our power systems to ensure .efficient and safe operation