

General Overview of Harmonics in Power Networks with PFC Capacitors

It is commonly accepted that utilities generate a near perfect sine wave voltage. In most areas, the voltage found on transmission systems has very low distortion. However, as we move closer to the load, the distortion increases.

The utility which is represented at the customer end by the power distribution transformer is the most common power source in industry. The type of this power source is voltage source and its main objective is to maintain stable voltage across its secondary windings. The load's impedance should be much higher than its internal windings' impedance. Ideally, the internal windings' impedance should be zero. In practice it is commonly 5%-7% of the full load impedance, due to windings' reactance and parasitic resistance.

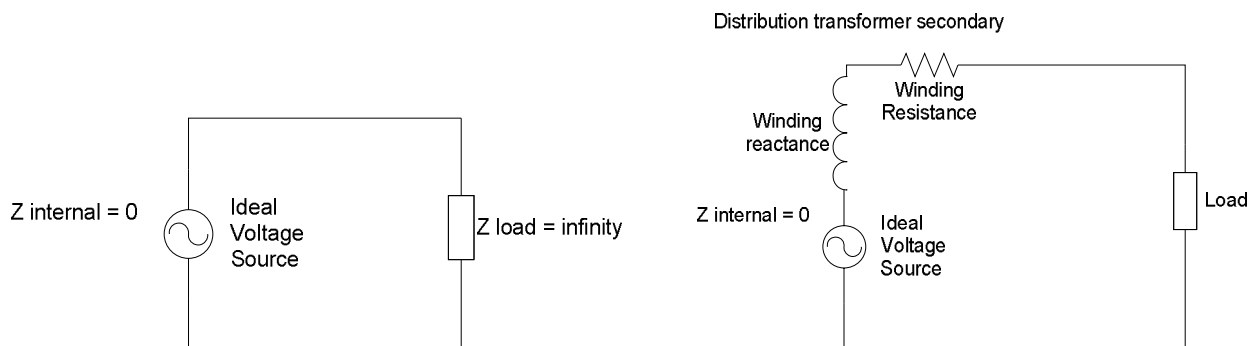
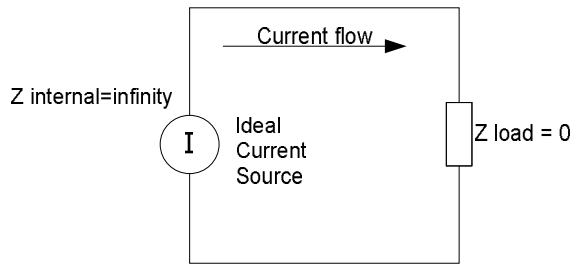


figure 1 – Ideal voltage source Vs. a practical voltage source

The quality of the voltage sine wave on an unloaded distribution transformer depends on the quality of power generation and interferences from other distribution branches.

Let's analyze a theoretical case, where the power is generated exclusively for one distribution transformer and the voltage is a pure sine wave. In this case, any load connected to the transformer's secondary will "see" a pure sine wave voltage and will draw current, according to the load's impedance. When the load's impedance is linear (does not change within a network period), the current waveform will follow very accurately the voltage's wave shape. If the load's impedance is changing periodically, due to chopping, or any other nonlinear operation, the current waveform may differ considerably from the voltage sine wave. The distorted, non-sinusoidal current wave can be expressed as a sum of pure sine waves, in which the first component is the fundamental frequency and the others are integer multiples of that basic frequency. Each multiple is called *a harmonic of the fundamental*. All the components (including the fundamental frequency) are simply referred to as *harmonics*.

Harmonics are current waves created by nonlinear loads. Their frequencies (harmonic order) and magnitudes are determined by the nature of the load's operation. For example, most DC drives have 6-pulse rectifiers, which generate harmonics, mostly 5th and 7th orders. The 5th harmonic has a frequency 5 times faster than the basic, or fundamental, frequency and the 7th is 7 times faster. Each harmonic is actually a power source at a higher frequency. Since the harmonics are created in current, the type of that source is current source.



Unlike voltage source, an ideal current source has infinity internal impedance and prefers zero load impedance, to maintain stable current.

figure 2 – Ideal current source

The nonlinear load can be expressed as a linear load part and a high frequency current source(s) part. For simplicity, let’s consider a situation, where only one of the connected loads is nonlinear, and generates only 5th order harmonic current.

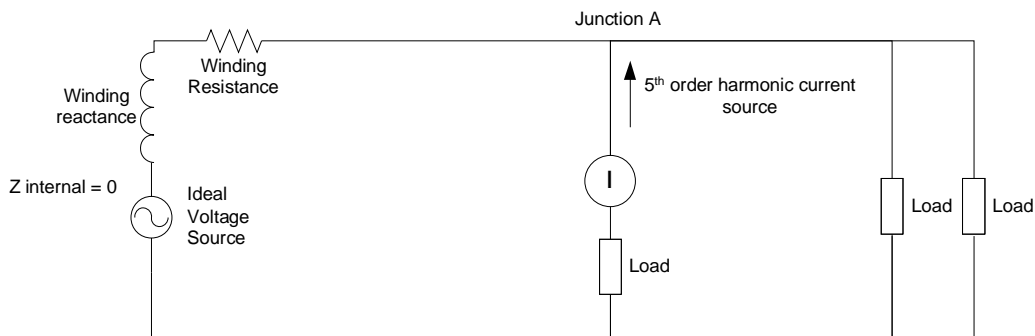


figure 3 – A network diagram of a plant which one of it’s loads generate 5th harmonic

The 5th harmonic current is represented by a current source, which is a part of the load’s operation elements. This harmonic current is being pushed to the network through junction A. At junction A, the current will choose the lowest impedance path to flow. The impedance to the left is composed of the internal impedance of the distribution transformer and the line impedance. The total impedance on the left side is much lower than the impedance of the loads on the right side. Thus, most of the harmonic current will flow towards the power transformer.

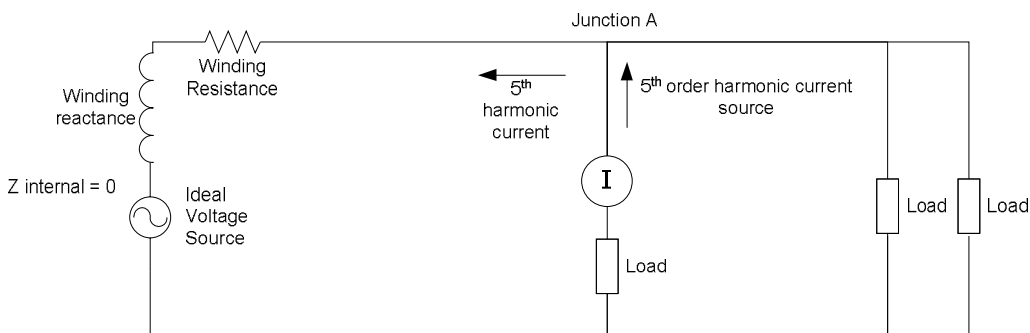


figure 4 – the 5th harmonic current path

This current, flowing through the line and transformer’s impedances, generates fluctuations, within the same frequency order over the voltage sine wave. These are the voltage harmonics. Additionally, this current, flowing through the transformer’s secondary, will induce harmonics over to its primary side, towards the utility. Still, these fluctuations are relatively small.

Now, let’s assume that our plant requires power factor correction due to low power factor at the fundamental frequency. A power factor correction capacitor has been added to correct this situation.

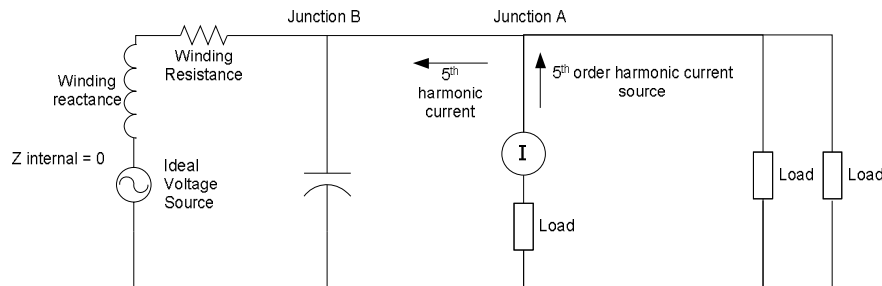


figure 5 – adding a PFC capacitor

The harmonic current coming to junction B finds a capacitor and a branch that includes a resistance and a reactance, parallel to it. The resistance part is negligible in most cases, so basically the above can be expressed as a parallel resonance circuit, on the path of the 5th harmonic current. In a case where X_L will equal X_C , parallel resonance will take place.

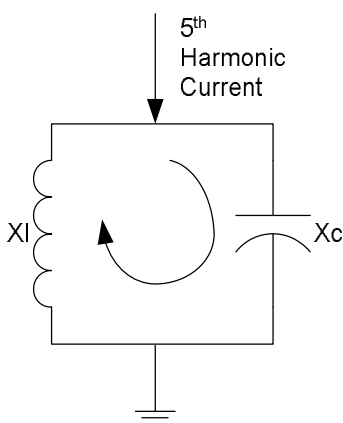


figure 6 – parallel resonance

The parallel resonance raises the circuit’s impedance dramatically, to infinity values. The current is circulating between the capacitor and the inductance, without being passed to the grounded terminal.

At parallel resonance, or even near resonance condition, the path of the PFC capacitor and the distribution transformer introduces very high impedance at the harmonic current frequency. That path is no longer the lowest impedance path, for the harmonic current, starting at junction A. At parallel resonance condition, the harmonic current is forced to go to the load part of the plant.

Since the path’s impedance is increased dramatically, the harmonic voltage is increased dramatically too. The parallel resonance between the PFC capacitor and the distribution transformer’s windings is an extremely dangerous situation for the entire electrical system. This situation may cause very significant damage to the electrical infrastructure. Normally, the weakest part, which is the PFC capacitors, will be the first to fail. The PFC capacitors will most likely not be able to withstand the high harmonic current, circulating between the capacitors and the distribution transformer. In few cases, where the capacitors withstand the

high harmonic current, more costly consequences may happen. In this situation, the power distribution transformer or some of the loads may be badly damaged.

The PFC capacitor itself has linear impedance. It does not generate harmonics. However, it always changes the network's frequency response. Regardless to parallel resonance it can either increase or filter harmonics in the network, generated by nonlinear load(s).

Resonance condition is determined by the overall capacity (and overall X_c), influenced by the number of capacitors connected, and the network's inductive impedance. It is enough for a little harmonic source to generate noticeable voltage distortion and potentially cause damage to the electrical network.

In order to prevent parallel resonance, Elspec and some other PFC systems manufacturers strongly recommend using "Detuned" system configuration, as a standard for any PFC application.

We will now demonstrate this solution on a power network of a plant, with the following characteristics:

1. Transformer- 1000kVA with 7% impedance.
2. Capacitor system- 6 steps of 100kVAr at 400V, 50Hz.
3. The utility generates power exclusively for the plant's transformer.

In case where no capacitors are connected, the network impedance behavior matches the pure inductance frequency response.

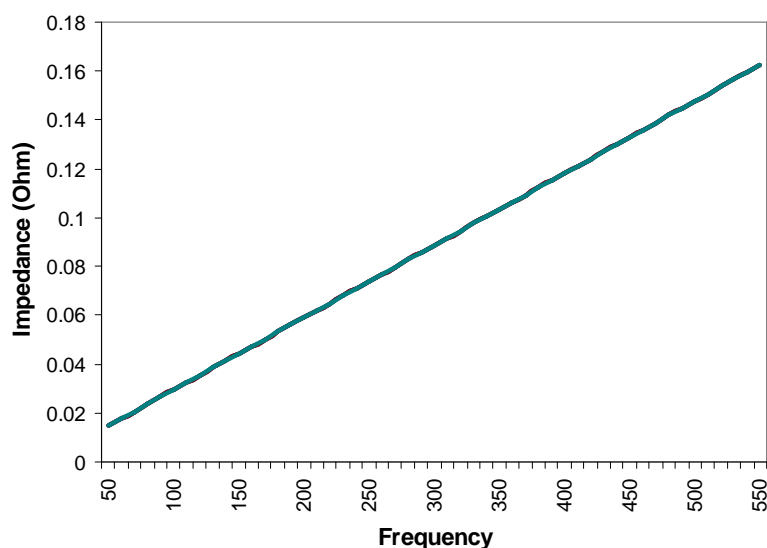


figure 7 – pure inductive impedance of a network without capacitors

The network impedance, from the harmonic source point of view, is linear. It starts somewhere at 0.02Ω for 50Hz and goes up linearly to 0.16Ω at 550Hz (H11).

Please note: the values are valid for this specific case only.

Now, we will connect the capacitors:

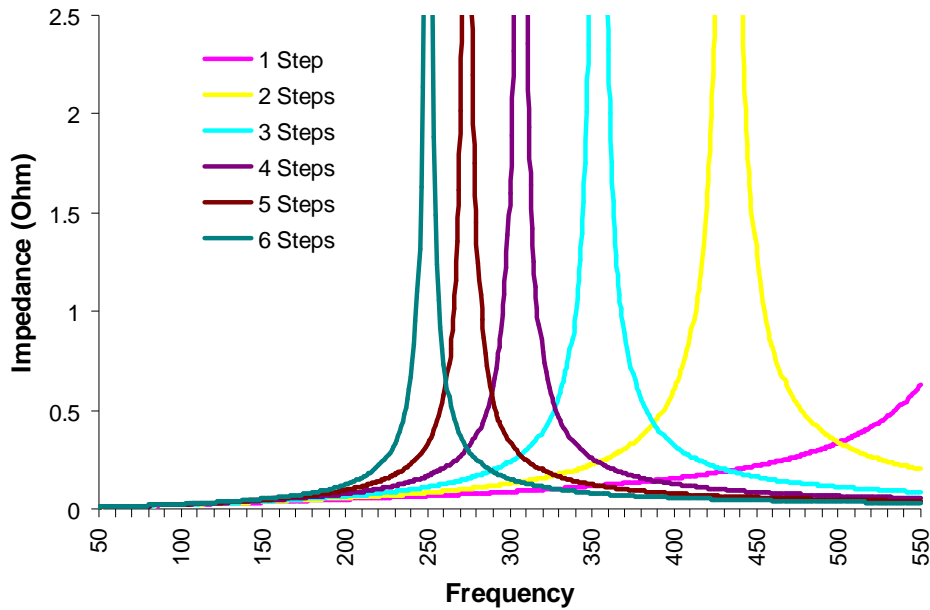


figure 8 – impedance of a network with capacitors

The network impedance has been changed dramatically. A few pure parallel resonance points are observed, depending on the number of capacitor groups engaged.

For example, there is a pure resonance condition at 250Hz (H5), when all 6 groups of 100kVAR are connected. The skirts of the resonance graph are not very steep, so even at points out of the pure resonance area; the network impedance is significantly increased. When only 5 capacitor groups are engaged at that frequency (H5), major disturbance to the network will occur as well, since the network impedance is increased from 0.06Ω to 0.4Ω (almost 7 times higher)!

In order to create major disturbance, it is enough to have a parallel resonance condition somewhere in the area of harmonic source frequency.

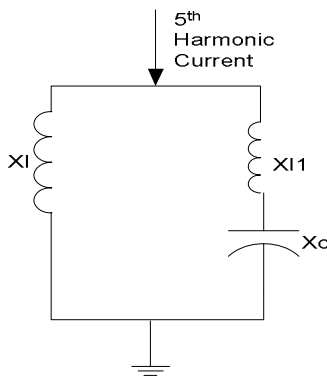


figure 9 – adding a Detune inductor

Whenever capacitors are used for PF correction, there is a frequency where the network will resonate (parallel resonance). The only way to prevent parallel resonance from occurring is to insure that the resonance frequency is located in an area (frequency) where there are no harmonic injection sources. It can be accomplished by adding inductors in series to the PFC capacitors. This is the main idea behind the “Detuned” system configuration.

The tuning frequency is the frequency of the serial resonance between the “Detune” inductor (X_{L1}) and the capacitor (X_C). That frequency is always higher than the parallel resonance frequency. The most popular “Detune” solution is the 7% inductors in series with the capacitors. 7% means that the inductor’s impedance at fundamental frequency (50Hz in our case) is 7% of the capacitor’s impedance at the same frequency. The 7% inductors will meet serial resonance condition at 189Hz, which means zero impedance in the inductor-capacitor branch, at that frequency. From this frequency and up, the inductor becomes more dominant and the branch’s impedance increases, following the shape of the inductor frequency response.

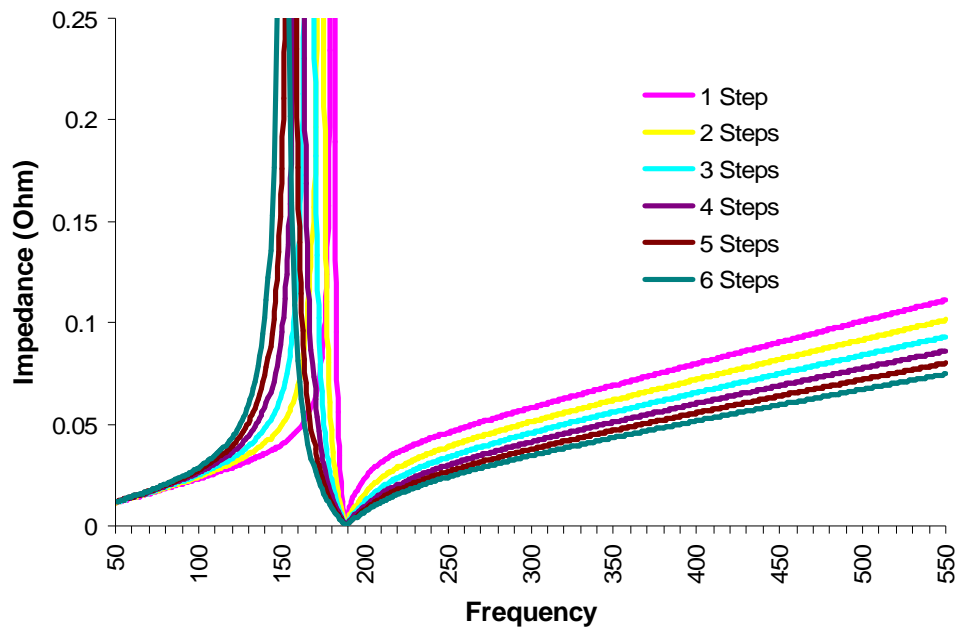
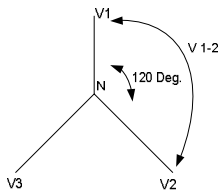


figure 10 – impedance of a network with capacitors and 7% inductors

The parallel resonance condition cannot be avoided. It is just moved downstream along the frequency. The frequency of the parallel resonance still depends on the number of engaged capacitor groups, but now it must be lower than the serial resonance point (189Hz). The tuning frequency is normally chosen to be lower than any dangerous harmonic source frequency. The only potential harmonic sources below 189Hz are H2 and H3. H2 (100Hz) normally doesn’t exist, since it has an even harmonic order. Even harmonics are created by non symmetrical sources only. Most of the electric power applications are symmetrical, so H2, as much as H4, H6 ... are usually not present in industry.

H3, which falls directly in the parallel resonance frequency, in our case, is special too. The frequency of H3 is three times faster than the fundamental frequency (50Hz). When H3 exist on phase to neutral voltage and current, the phase-phase representation will be as follows:



$$V_{1(H3)} = A_1 \times \sin(3 \times \omega \times t + 3 \times 0)$$

$$V_{2(H3)} = A_2 \times \sin(3 \times \omega \times t + 3 \times 120)$$

$$V_{1-2(H3)} = A_1 \times \sin(3 \times \omega \times t + 3 \times 0) - A_2 \sin(3 \times \omega \times t + 3 \times 120)$$

Since the $3 \times 120 = 360$ degrees which equals 0 degrees, in cases where $A_1 = A_2$:

$$V_{1-2} = 0 \text{ !!!!}$$

The meaning is that when H3 is balanced (similar magnitudes: $A_1 = A_2 = A_3$) and the capacitors are connected in Delta, H3 is canceled by itself across the load's terminals. The same behavior applies to all triple order harmonics H3, H6, H9 ...

In most cases H3 is balanced and capacitors' configuration is Delta, so H3 is invisible to the capacitors and cannot create parallel resonance condition.

6%-7% detuning inductors are the most popular "of the shelf" solution for Delta connected capacitors. For single phase capacitor systems and for cases where H3 is not balanced out, the tuning frequency should be set below 150Hz.

Setting the capacitor-inductor serial resonance frequency can be used for harmonic filtering. The low impedance path at the harmonic current can absorb most of the harmonic distortion. This is actually the basic idea of the passive harmonic filtering in "Tuned" systems. It is categorically not recommended to tune exactly to the harmonic source frequency, since the capacitors can be easily overloaded. Tuning to 220-240Hz is normally adequate for making an efficient H5 filter.

The filter application demands a deep study of the network and load conditions, prior to the installation, in order to avoid overloading.

Another popular solution is tuning to 210Hz frequency (5.67% inductors), which is not close enough to serve as a filter, but can help reduce the overall network impedance at H5 frequency and absorb some significant part of H5 current. This type of system is still considered as "Detuned" system.

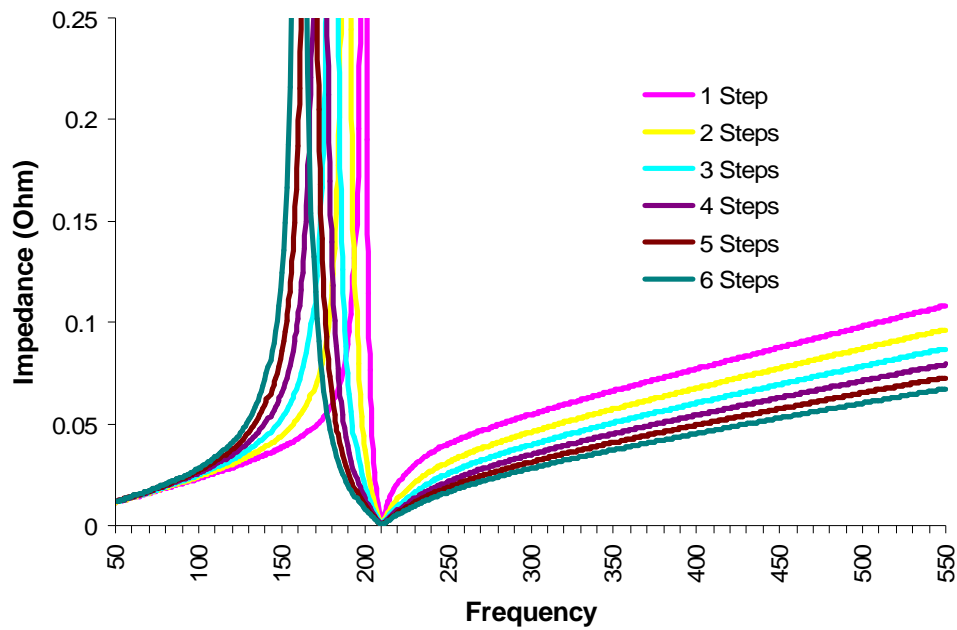


figure 10 – impedance of a network with capacitors and 5.67% inductors, tuned to 210Hz.

Summary:

Power factor correction capacitors always change the network impedance for all harmonic sources. The final impedance depends directly on the number of activate capacitor groups (steps) and the inductors' tuning point. Setting the right impedance curve is the key to avoid harmonic problems, mainly, parallel resonance.