CAP TALK

Detuned capacitor banks, tuned capacitor banks or harmonic filters - Components Ratings

INTRODUCTION

Fifteen year ago, power factor correction was done just by adding capacitors to the distribution system and harmonic resonance was rarely a concern as non-linear loads were not common. Nowadays, variable speed drives and other non-linear loads are so common that many consulting engineers will only specify power factor correction equipment with series reactor to avoid having resonance problems in the distribution system. These systems are commonly called detuned banks, tuned banks or harmonic filters. All of them are second order filters and though they are all made of a series connected capacitor – reactor combination, they have different functions and will be constructed and rated differently depending on the application. Construction and application will not be reviewed in this paper, but the basic electrical characteristics of the LC circuit and its components will be reviewed and discussed.

THE LC CIRCUIT

The series combination of an inductor and a capacitor has frequency dependant impedance. At DC voltage, the inductor is a short circuit while the capacitor is an open circuit, so that the LC-circuit then results in an open circuit. As the frequency increases, the impedance of the capacitor decreases and the impedance of the reactor increases. These two impedances are opposite in terms of polarity and cancel each other with respect to their amplitude.

The impedance of an inductor is given by:

$$Z_L = j\omega L = jX_L$$

and

$$X_L = \omega L$$

with

$$\omega = 2\pi f$$

Where: X_L is the inductive reactance, ω the angular frequency, f the frequency in Hz, L the inductance in Henrys and j the imaginary unit

The impedance of a capacitor is given by:

$$Z_C = -j / \omega C = -jX_C$$

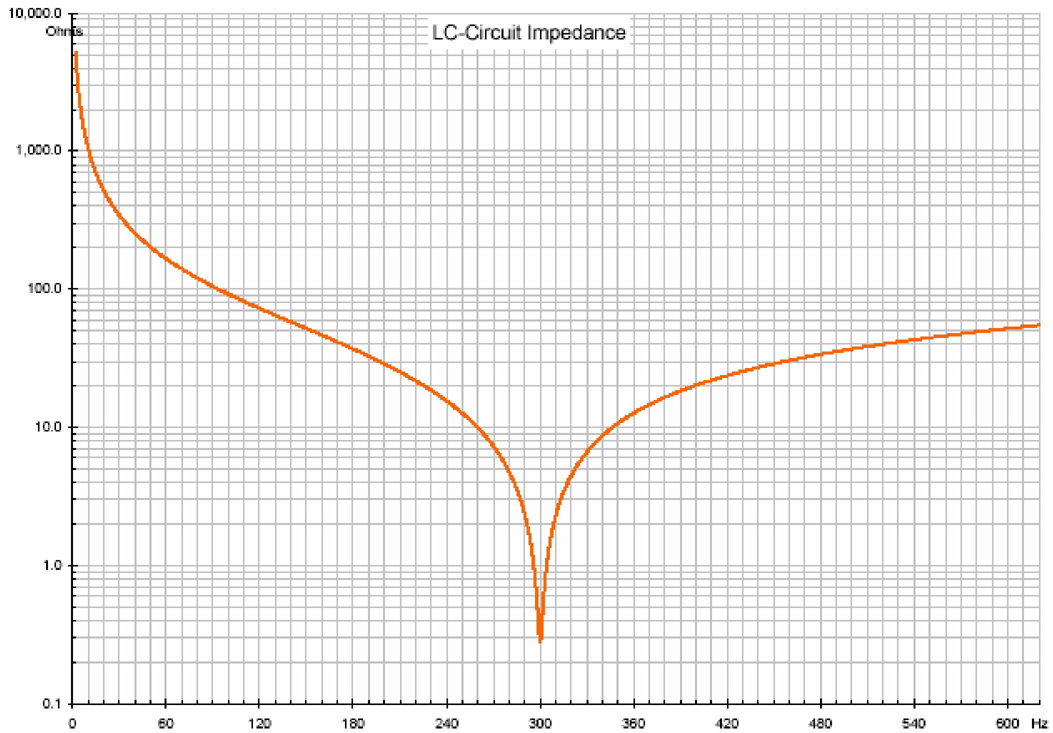
and

$$X_C = 1/\omega C$$

Where: X_C is the capacitive reactance, ω the angular frequency, f the frequency in Hz, C the capacity in Farad and j the imaginary unit

When the reactance and capacitance impedances are equal in amplitude they cancel each other because of their opposite polarities and the resulting circuit impedance is minimum as only the resistive portion of both impedances are still present, this is called the tuning point of the LC circuit.

The impedance curve of the LC circuit has the following shape when scanning the frequency axis:



This LC circuit is called a filter, a tuned capacitor or a detuned capacitor. But from a purely technical stand point, this is a simple RLC band pass filter, the resistive portions of the inductor and the capacitor will determine the quality factor of the filter. Filter design can be made into more complex configurations such as high-pass filter, C-type filter and other types, which are beyond the scope of the present paper and are discussed in the paper *Filter Topology: Single tuned, High Pass, C-Type and Others*.

The practical application of an LC filter is to:

- Provide capacitive kVAR to cancel the inductive KVAR of the load and thus and thus correct power factor.
- Control the system impedance to avoid having resonance condition that can amplify harmonic current.
- Reduce harmonic currents by providing a low impedance path to selected harmonic current frequencies.

The terminology about an LC filter has not yet been standardized and is used differently by different people. In general the following description should apply:

- **Harmonic Filter**: an LC circuit that is tuned close (usually below) the frequency of a specific harmonic current, with the goal of providing a low impedance path to that frequency and to reduce the amount of that harmonic current being injected into the distribution network.

- **Tuned Filter**: an LC circuit that is tuned to provide both harmonic current attenuation while avoiding a resonance condition and also providing some capacitive compensation to improve the power factor of the system it is connected to.

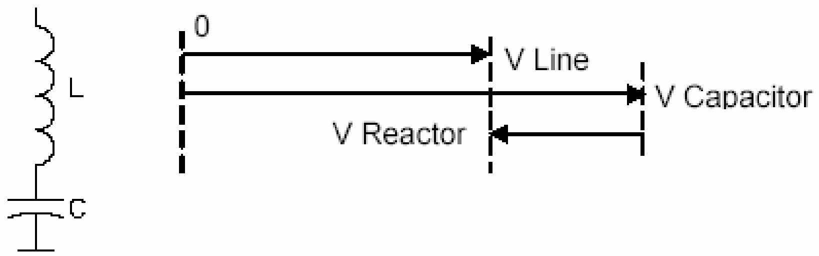
- **Detuned Filter**: an LC circuit that is tuned to first avoid a resonance condition while providing capacitive kVAR to compensate the power factor, but with some or little reduction of harmonic current distortion.

CAPACITOR RATINGS

Capacitors construction is covered under the UL standard 810 and the CSA C22.2 No 190 for the North American market and the IEC standard 60 831 in Europe. These standards have similar requirements but only cover the capacitor construction and do not well cover the application requirements especially for filter / tuned or detuned applications, let's look at these applications and their impact on the capacitor.

CAPACITOR VOLTAGE RATINGS

Standards do require capacitors to be able to sustain a continuous 10% over voltage to cope with capacitor tolerance, system voltage regulation and harmonic current distortion. So what is the capacitor voltage rating that should be used for a filter application? The voltage phasors across the reactance and the capacitor of a typical filter are opposite in polarity, which means that they do not add up but subtract. Practically speaking a 5th harmonic filter applied on a 480V network will see the capacitor bearing about 505V, while the series reactor will see about -24V across its winding.



These voltages will be influenced by the tuning point of the filter, i.e. the lower the tuning point, the voltage across both, reactor and capacitor, will increase. For a detuned bank, the optimum tuning point from a manufacturing stand point is the 3.78th harmonic, where the voltage rise on the capacitor is still reasonable while the 5th harmonic current (the predominant harmonic current distortion on most industrial distribution systems) absorption is limited. This has been confirmed in several studies by European manufacturers.

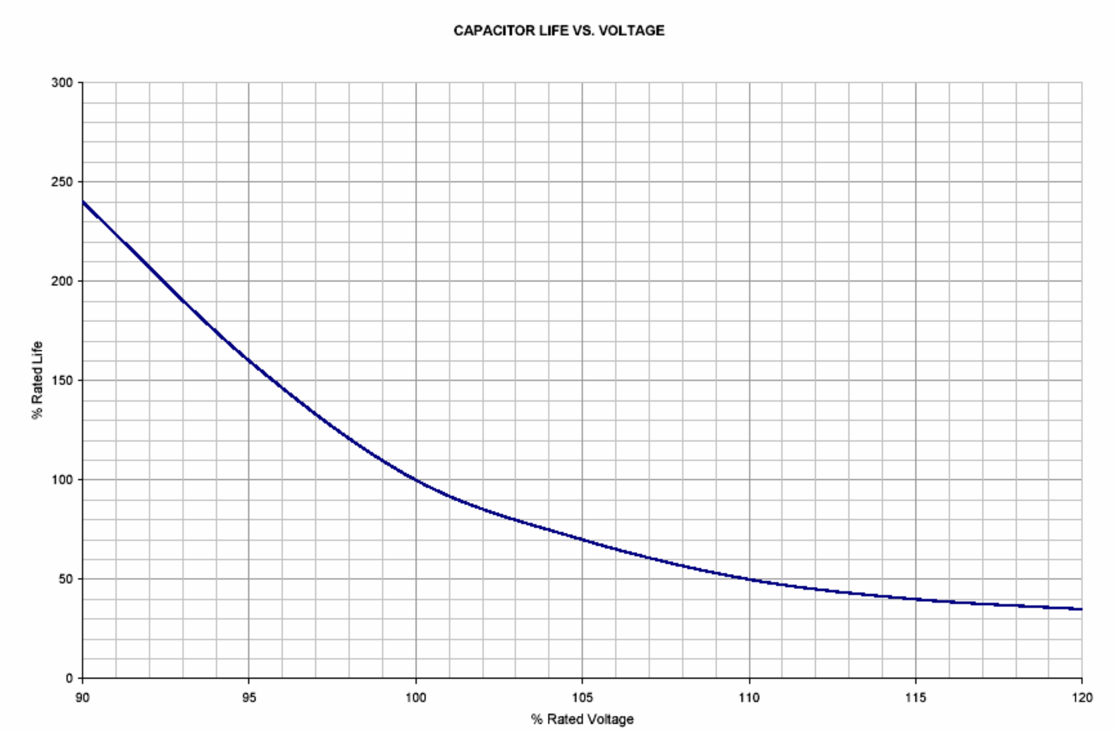
The voltage rise on the capacitor can be calculated with the following formula:

$$\text{Vrise } (\%) = (f_n / f_t)^2 \times 100$$

Where f_n = frequency of the network in Hz
f_t = tuning frequency of the LC circuit in Hz

Manufacturers have established their own standard tuning point over the years, as for example most North American manufacturers were using the 4.7th harmonic tuning over the past decade. Though this tuning was adequate in relatively low harmonic distortion environments, it showed some weakness in heavy harmonic environments, where this tuning provides for a fairly good 5th harmonic absorption of the filter, but subsequent large losses in the reactor, resulting in overheating and reduced performance of the overall capacitor system. Nowadays, most manufacturers propose a detuned bank with tuning ranging from 4.3rd to 3.78th. It is to be understood that the closer you get to the 5th harmonic tuning the more 5th harmonic current will be absorbed by the filter and the more losses will be dissipated into the tuning reactor and the more 5th harmonic voltage will develop across the capacitor adding to the insulation stress on the capacitor.

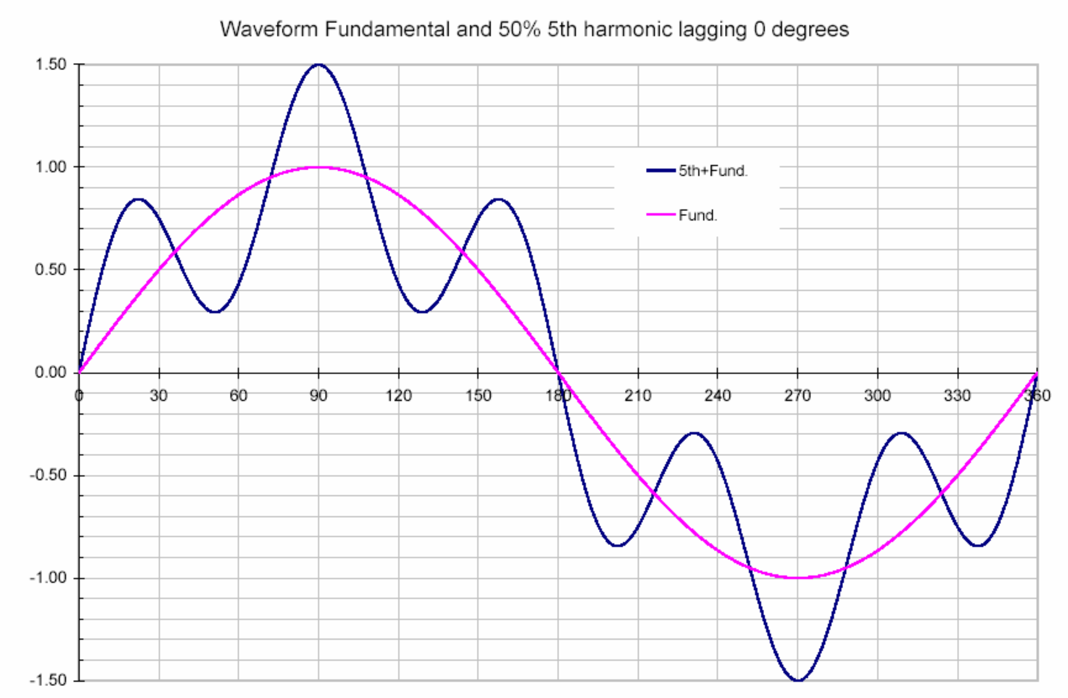
But never mind the tuning point and let's look at the rating of the capacitors used in a filter configuration: If tuning to the 5th harmonic or close to it, the voltage rise on the capacitor due to the series reactor will be of about 4%. If tuning lower, like at the 3.78th harmonic, the voltage rise will be of about 7%. But in any case, the series reactor will never create a very large fundamental voltage rise on the capacitor and a 10% margin on capacitor voltage rating would be sufficient to cope with reactor voltage rise, but the increased voltage will reduce the capacitor life expectancy as per the following graph.

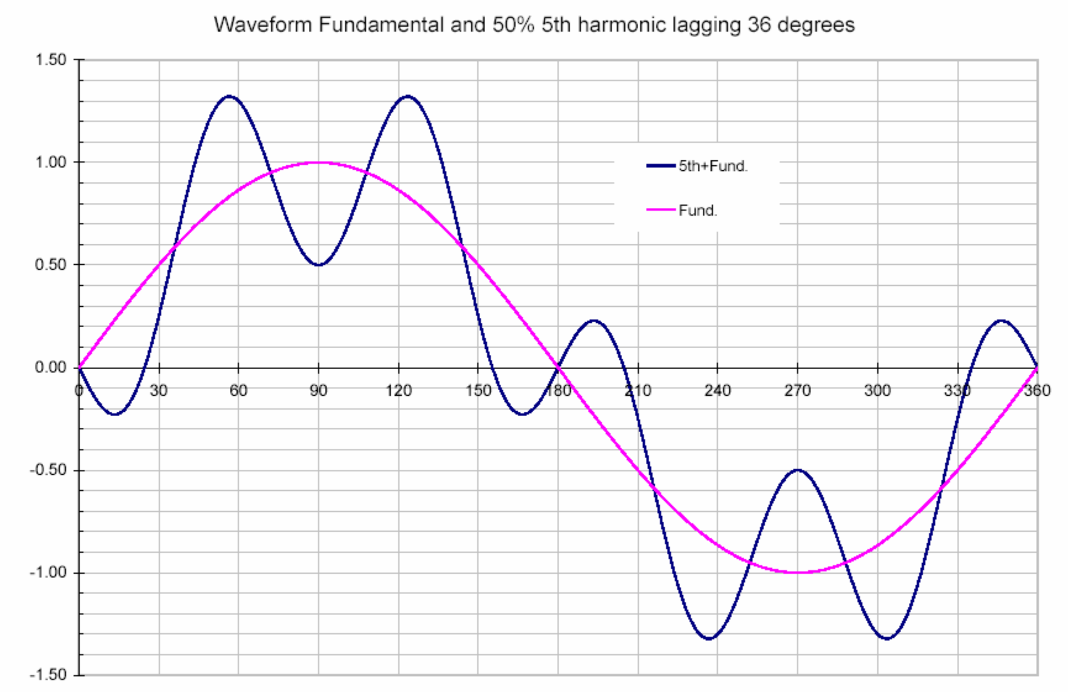


For a 480V system, it is current to use 600V rated capacitors, which is the next commercially available standard rating for capacitors. For 600V rated systems, it is current to use 700V, which is a European standard voltage class. Voltage rating of the capacitors is not only a function of the tuning point; it is also a matter of how much harmonic current will be absorbed by the filter circuit. If tuning close to the 5th, let say the 4.7th, the voltage rise due to the reactor will be minimal at about 4.5%, but the 5th harmonic current absorption will be important and the capacitor will see a relatively important 5th harmonic voltage drop across its terminals. Though it is hard to predict the phase angle of such 5th harmonic voltage drop, in the worse case this 5th harmonic voltage drop will be in phase

with the fundamental voltage and will add up to increase the crest voltage and create additional peak voltage on the capacitor.
Since most capacitor failures are related to insulation failure, it is not desirable to increase peak voltage beyond the rated peak RMS voltage of the capacitor ($\sqrt{2}$ x V nominal).

When designing harmonic filters, it is common practice to rate the capacitor for a voltage calculated as the arithmetic sum of all the voltages generated by the fundamental current and all the harmonic currents going through the capacitor. Although this approach assumes that all harmonic voltages across the capacitor terminals are all in phase, it represents a safe design approach. IEEE standard 1531, Guide for application and specification of harmonic filters, recommends this approach.
The reason behind this concept can be explained in a simplified way, taking the next two graphs for example. These two graphs show a fundamental voltage with 50% fifth harmonic. In the first graph, the fundamental and the 5th harmonic voltages are perfectly in phase (0 degrees lag). In the second graph, the 5th harmonic is lagging the fundamental voltage by 36 degrees. At 0 degrees lag, the resulting peak voltage is exactly the addition of the two individual peak voltages, at factor 1.5 At 36 degrees lag, the resulting peak voltage is at its absolute minimum, at factor of 1.3216.
It makes sense to take always the arithmetic addition of the fundamental plus all harmonic voltages for calculating the capacitor rated voltage, as the harmonic voltage drop across the capacitor will always increase the peak voltage on the capacitor


Waveform Fundamental and 50% 5th harmonic lagging 0 degrees
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0
30
60
90
120
150
180
210
240
270
300
330
360
5th+Fund.
Fund.


Waveform Fundamental and 50% 5th harmonic lagging 36 degrees
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0
30
60
90
120
150
180
210
240
270
300
330
360
5th+Fund.
Fund.

So, there is a compromise to be done with capacitor insulation level and tuning point of the filter, that is:

- The closer you tune to the 5th harmonic the less fundamental voltage rise is induced on the capacitor, but the more 5th harmonic current is seen by the capacitor, thus increasing the peak voltage due to the 5th harmonic voltage drop across the capacitor with resulting insulation stress.
- The lower you tune (let's say the 3.78th) the more you increase the fundamental voltage rise on the capacitor (about 7%) but the less 5th harmonic current is being absorbed and thus the less peak voltage increase is seen from 5th harmonic voltage drop across the capacitor.

REACTOR RATINGS

Reactors are a key component of an LC filter but their ratings are often overlooked. Reactor losses are typically of 5W per kVAR for a detuned capacitor bank compared to about 0.5W per kVAR for the capacitor itself. These losses consist of core losses, coil losses and gap losses. We will discuss those losses in a different paper as this matter is fairly complex. But it is important to say that these losses are very dependant on the harmonic currents that the reactor is subjected to, and such currents are dependent on the harmonic current distortion produced by the non-linear loads and the tuning point of the LC filter.

Reactor ratings are important and should be adjusted to the application to minimize losses and to ensure that the temperature inside the capacitor bank enclosure is maintained within standards requirements (maximum 46°C) to insure proper capacitor operation.

Reactor ratings will be discussed in a different paper.

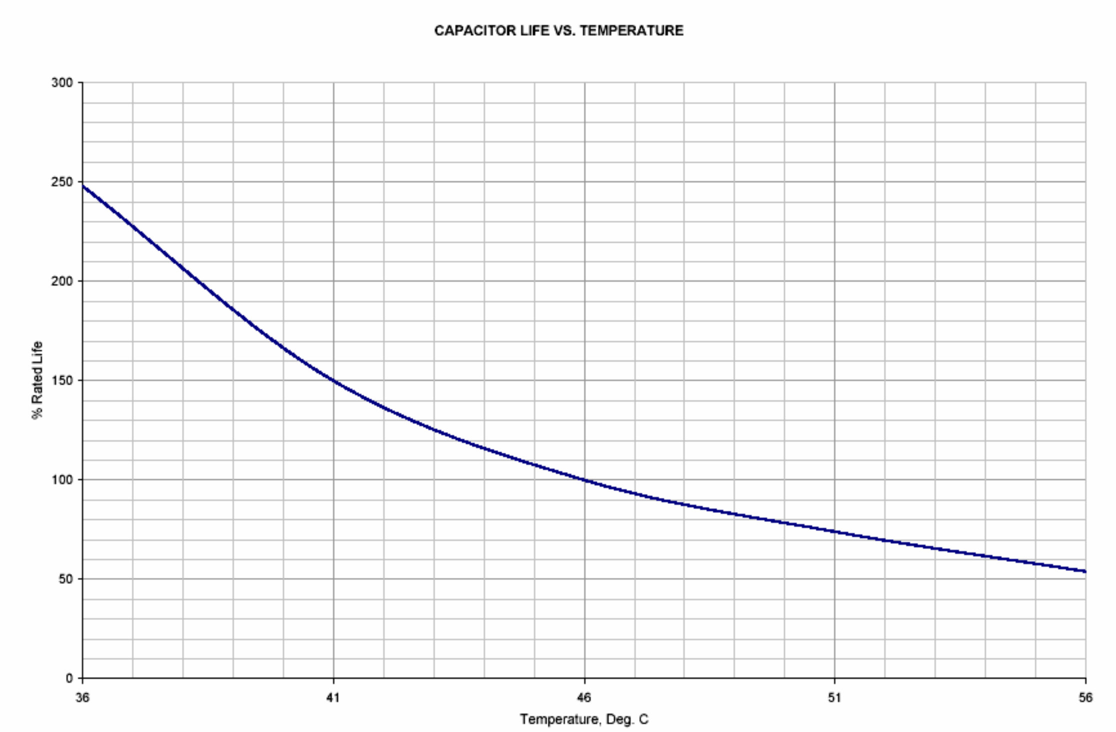
CAPACITOR RATINGS

In today's applications, most of the cases where LV power factor correction is required and that harmonic producing equipment is present, only detuned capacitors are required. There is most of the time little or no restriction applied for harmonic rejection so that the main goal sought by the specifying engineer is to correct power factor while avoiding harmful resonance condition.

In such cases the specification should call for:

- Detuned capacitor banks with tuning range of 3.78th to 4.3rd harmonic
- Capacitor voltage of 600V for 480V rated systems
- Capacitor voltage of 700V or more for 600V rated systems

In the case where reactors are poorly designed or the tuning point is too high, the losses can climb significantly with costly losses and also, and most importantly, a capacitor bank excessive operating temperature which in turn shortens the capacitors life expectancy. Maximum operating temperature of capacitors is 46°C as per the standards and typical capacitor life versus temperature is as per the following graph.



CONCLUSION

The key element for a good performance of a detuned bank is the selection of its two major components, i.e. the capacitor and the reactor and obviously the control of the operating temperature of the unit.
But the reactor is definitely the key element that will insure the performance of the equipment. A good capacitor with a poorly designed reactor will not last, but a good reactor design will make a good capacitor work properly for many years.