Is Your Power Factor Correction (PFC) System a Ticking Time Bomb?

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Overview:

I worked for major OEM's Power Quality business for 15 years, including running it in North America for 7 years. This group was responsible for sales, design and manufacture of LV and MV capacitor banks and harmonic filters. I could write a novel about the modes of failure of capacitor banks. While product quality can certainly be a problem, most of the root causes are due to poor product application or design choices and due to customers adding non-linear loads (variable speed drives most often) to the system AFTER the capacitor bank was installed changing the harmonic profile. Applying capacitors without fully considering the harmonic interaction possibilities, now and in future, can be disastrous. Failure of a PFC system can be catastrophic and cause substantial secondary damage to adjacent equipment. Fortunately, most of these failure modes are detectable with a properly designed Condition Based Maintenance (CBM) program.

Application Note

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Power Factor Correction (PFC) equipment is installed to offset the demand charges that utilities levy as part of the monthly electricity bill for industrial and commercial customers. There are two broad categories of traditional automatic PFC equipment – standard and detuned (or filtered). Note that "automatic" implies that the system has a controller that switches the stages of the capacitor bank on/off based on trying to achieve a target Power Factor for the total system as the load fluctuates. The switches themselves can be electromechanical contactors or static switches like thyristor-diodes pairs. Static switches have the advantage of generating significantly lower switching transients as switching can be done at the zero-crossing of the voltage waveform and, with a special controller, they can be switched much more rapidly provide voltage regulation due to highly fluctuating loads.

Standard PFC systems have a controller and each switched stage has fuses (or breaker) for short circuit protection, switching device and capacitor. Stage power ratings of 50 or 100KVAR are most common. As the controller switches on stages of the PFC system, a variable LC tank circuit between the upstream transformer and the capacitor bank is created that has the potential to magnify any harmonic current present on the system due to non-linear loads like variable speed drives, rectifiers, etc. The approximate point of this parallel resonance is in accordance with the equation:

$$H(0) = \left(\frac{\left(KVA \div \% \, Impedance \right)}{KVAR} \right)^{0.5}$$

where
H(0) = Harmonic resonant Order (multiply by 60 to get frequency in Hz)
KVA = Transformer KVA rating
% Impedance = Impedance of the transformer
KVAR = Power rating of the Capacitor Bank energized

What this means is that as you increase the size of the capacitor by switching on more stages, you drive down the resonant frequency and risk hitting on a dominant harmonic like the 5th, 7th or 11th order where significant harmonic currents are already circulating in the distribution system. The LC tank circuit can than act to magnify those harmonic currents significantly which will then circulate in both the capacitor bank and the transformer (and all current carrying components in between) causing more heat and voltage waveform distortion as well. For example, on a 1500KVA transformer with 5.5% impedance and a 600KVAR capacitor bank installed with 50KVAR steps, the resonant points will be:

KVAR	50	100	150	200	250	300	350	400	450	500	550	600
H (0)	23.4	16.5	13.5	11.7	10.4	9.5	8.8	8.3	7.8	7.4	7.0	6.7
Fr (Hz)	1401.3	990.9	809.0	700.6	626.7	572.1	529.6	495.4	467.1	443.1	422.5	404.5

Table 1: Parallel Resonance Points of a 600KVAR Standard PFC System on a 1500KVA Transformer

In this example, sharp resunance at the 11th harmonic may occour with 200-250 KVAR energized and at the 7th harmonic with 500-550 KVAR energized.

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A rule of thumb is that Standard capacitor banks are not recommended unless non-linear harmonic producing loads comprise less than 10% of the total connected load on a given transformer. In this way, you can be fairly certain that harmonic interaction will be minimal. However, if the loads change in the future problems can ensue. The only fallback is that if the capacitors degrade due to hitting a resonance and magnifying the harmonics, the capacitor degradation causes a loss of KVAR and can eventually shift the resonance point slightly higher stopping the sharp resonance and avoiding further rapid degradation. Of course, the controller may see this as a failure to provide adequate PF correction and add another stage restarting the resonance problem.

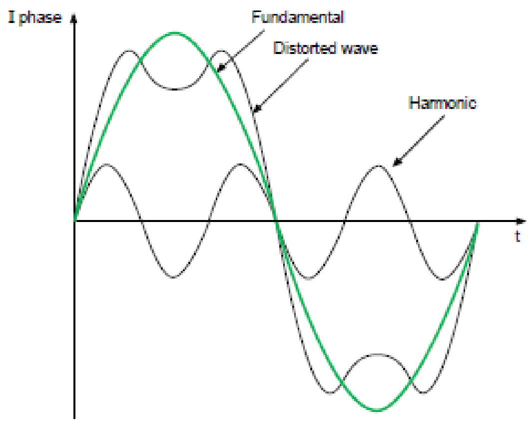

Figure 1: Harmonics are a Mathematical Representation of Distorted Waveforms breaking them down into Component Parts

Detuned or Filtered capacitor banks have a controller and each switched stage has fuses (or breaker) for short circuit protection, switching device, tuning reactor and capacitor. The tuning reactor in each switched stage essentially breaks the dependence on resonance between the capacitor and upstream transformer and intentionally sets a locked resonance point below the first possible dominant harmonic. Theoretically, this tuning frequency does not change regardless of how many switched stages of the PFC system are energized at any given time. As the dominant harmonic from most non-linear loads is the 5th, tuning points of 3.8 - 4.3 x 60Hertz are most common in detuned capacitor banks. A detuned capacitor bank will typically remove (filter) up to 50% of the 5th harmonic current from a system reducing the amount "seen" by the upstream transformer by that level. A reduction of 10-15% of the 7th harmonic is also typical with this type of system. However, the primary goal of a detuned bank is power factor correction but while avoiding potential for harmonic magnification via resonance. Detuned capacitor banks are typically deployed on networks where up to 50% of the total connected load is non-linear.

On systems where more than 50% of the connected load is non-linear, Active Harmonic Filters (AHF) should be considered instead of traditional PFC. AHF systems work much like noise-cancelling headphones, monitoring the harmonic "noise" and injecting anti-harmonics out of phase to cancel out the load harmonics. With an appropriately sized AHF, upstream of the point of connection of the AHF, the harmonics are almost completely eliminated. AHF systems can also inject reactive power (VARs) to waveshape the fundamental frequency and correct power factor. From an economic perspective, AHF solutions tend to be more expensive to deploy than Detuned PFC systems and, as such, are usually only used when analysis has determined the risk of using tradition technology for power factor correction is too high.

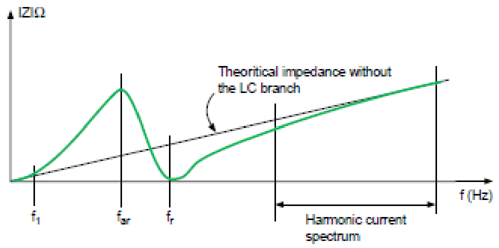

Figure 2: Tuning Point of the Detuned PFC System Branches is fr – Below the Harmonics Generated by the Non-linear Loads on the System

With Detuned PFC systems, tuning higher than 4.3rd harmonic is rarely recommended as it increases the potential for harmonically overloading the stages. Furthermore, great care must be taken as to how the switched stages are controlled as one stage energized will try to absorb the same amount of harmonics from the network as 5 or even 10 energized stages would. A single stage can be significantly overloaded with harmonics as the load ramps up and while it waits for the controller (under time delay) to activate more stages. This overload manifests in many ways including overcurrent damage to the capacitors but audible "grunting" from the reactors is always a dead giveaway that the stage is being asked to absorb more harmonics than it was ever designed for. Standing in front of a system that is doing this can be disconcerting for personnel unfamiliar with the phenomenon – I have seen more than one electrician make a rapid exit from the electrical room.

As a detuned capacitor starts to fail, the tuning point of the LC branch circuit shifts upwards and it actually draws more harmonics off of the network making it fail even faster. Harmonics generate a lot more heat on a per amp basis in the current path components so you see cable insulation failures, conductor transition failures (especially fuse holders cable lugs) and, worst case, capacitor catastrophic failures. Different switched stages will not fail the same leading to further complications of each stage having a different tuning point based on the remainder of Capacitance in its individual LC branch circuit. Odd interactions between stages can occur and stages that are operated for more hours can see higher rates of degradation over time. Rotational switching controls that try to balance stage usage can alleviate this somewhat but not completely.

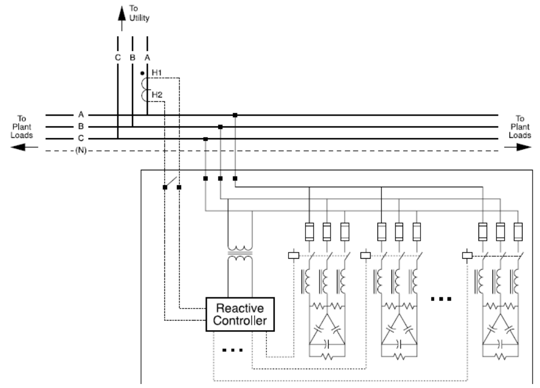

Figure 3: Detuned PFC System Three Line Diagram

Virtually all power capacitors in low voltage PFC applications use polypropylene film as their primary dielectric material and rely on the polypropylene to absorb transient, overvoltage and overcurrent stress, including harmonic overcurrent, by "arcing" which burns a small hole in the dielectric but does not theoretically propagate further. The industry calls this "self-healing" which is perhaps the worst example of marketing speak in the electrical equipment industry. Why? Low temperature incomplete combustion of polypropylene dielectric gives off multiple gasses including ethane and acetylene that can accumulate over time inside the capacitor housing with further voltage and current stress on the capacitor. That gas builds up in the capacitor and, if the mandatory pressure disconnect mechanism fails to operate properly, a small spark from future dielectric breakdown can cause ignition and fire. Once it gets going, polypropylene burns very hot and some capacitor manufacturers used, for many years, plastic housing materials such as polycarbonate that also burned nicely. See pictures below of what is left afterwards which makes forensic root cause determination near impossible.

Figure 4: Catastrophic Failures of a PFC Systems – Probably Preventable with Proper CBM

Many of the modes of PFC failures are be detectable with infrared and/or ultrasound inspection if you can "see" the components. Infrared scanning can detect hot connections and conductors while airborne ultrasound will detect arcing and tracking. However, unlike most other distribution equipment where the failures take months to get to a critical state, a capacitor bank can go into failure VERY quickly – like in a matter of days. I have witnessed cases where we did a complete check of a unit verifying everything was operating normally and less than two weeks later it caught fire and was a total write-off. For this reason, I believe that monthly Infrared and Ultrasound inspections should be performed on PFC equipment. Physical intervention maintenance including tightening conductor transitions at fuseholders, breakers, contactors, inductors and capacitor terminals can be then scheduled based on the IR inspection results. Measurements of stage currents and calculation of capacitive loss and resultant shifted tuning point can further determine when it is prudent to replace the capacitors.

Unfortunately, from a CBM perspective, PFC manufacturers are economically motivated to condense their systems into as little enclosure space as possible meaning that often, even with IR windows, it would be impossible to scan all the potential points of failure due to barriers to the inspector's field of view. And each stage of a PFC system can easily have over two dozen electrical connections that need regular scanning including fuse mounting in fuseholder (6 points), cable connections to fuses (6 points), contactor connections (6 points), reactor connections (6 points) and capacitor connections (6 or more points). Alternately, and especially if the site has a history of PFC failures, online temperature monitoring of capacitor banks in conjunction with an IR and Ultrasound program may be a more prudent CBM methodology to deploy.

I am not aware of any OEM that currently offers IR windows or ultrasound ports as a standard factory option as part of their design. Ten years ago, hardly any OEM offered IR windows on their switchgear either but now virtually every single OEM has this option so it will only be a matter of time for the PFC manufacturers to catch up. However, in the interim, this lack of an OEM option need not deter you from implementing a solution to allow for closed panel inspection of these existing assets at your facility. IRISS has the ability to manufacture fully UL Listed custom replacement panels and doors with IR windows built into them that will allow your personnel to perform these inspections without any special PPE required. In addition, IRISS has the Delta T Alert system of wireless temperature monitoring that can be retrofitted to any piece of switchgear or PFC equipment in less than 10 minutes for less than $300 per section. Delta T can give you 24/7 peace of mind that your PFC equipment is operating trouble free.

PFC systems provide a useful service on your electrical distribution system but require a well thought out CBM strategy to ensure their nominal life expectancy of 15-20 years can be practically achieved. A PFC system should not be something you install and forget about – regular checks of system performance and integrity should be part of your maintenance regimen or you risk getting a nasty surprise.

Want more information on implementing a CBM program for electrical assets at your facility? Need advice on choosing a PFC and/or harmonics mitigation strategy? Reach me at r.wodrich@iriss.com or call IRISS at 941 907-9128