

EXTENDING THE LIFE OF POWER FACTOR CAPACITORS

by

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Abstract: The addition of power factor improvement capacitors to individual motors or entire facility power systems is a traditional method of improving power factor, reducing energy consumption, making available more capacity from existing transformers, and reducing energy costs. Although capacitors are typically designed for twenty years life expectancy, why then do capacitors often fail in much less time? This paper discusses the common reasons for premature failure of power factor capacitors and proposes solutions that can extend capacitor life.

It is generally recognized that the life of a capacitor can be affected by its operating temperature terminal voltage or current. To maximize capacitor life, we should apply capacitors with consideration for actual terminal voltage, total (true) rms current and minimal operating temperature. To accomplish these goals, we must first identify those factors that could adversely affect capacitor voltage, current or temperature.

MPP Capacitors

Today's power factor capacitor systems have eliminated the use of PCBs and instead use Metallized Polypropylene (MPP) capacitors. MPP capacitors have a characteristic that is called self healing, which causes them to fail in a different manner than previous types of capacitors. Prior to the use of MPP, capacitors were either at 100% capability or were failed completely. There was no in between state. Upon failure, they would often blow a fuse or trip a circuit breaker, which might also serve to alert someone to the failure.

Capacitor Self Healing

When conditions such as voltage, current or temperature exceed the MPP capacitor specification, capacitors can experience localized insulation system breakdown, causing an internal short circuit. When they short out, the conductor area surrounding the shorted area vaporizes, thus removing the shorted circuit. The capacitor, considered "healed", continues operating, except with slightly lower capacitance. The self healing feature is convenient, but if the capacitors continue to be operated beyond their design constraints, they start to have multiple shorts and can lose capacitance more rapidly. This can change the resonant frequency of the filter network.

Why do capacitors lose capacitance?

The MPP dielectric system consists of polypropylene, having a thickness measured in microns, while the conductor is only measured in angstroms (hundred-millionth of a centimeter). When an internal short occurs, the failure is localized through the self healing process (described above), and therefore the capacitor loses a very small amount of capacitance, (perhaps less than 0.1%).

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A capacitor normally provides 100% of its nominal rated current unless it has been degraded through the self healing process. Since they remain “operative”, but with slightly reduced capacitance and current, quite often, no one notices the problem. As MPP capacitors continue to degrade, the leading current they provide to the circuit diminishes. In order to assure proper capacitor or filter performance, CAPACITORS MUST BE MEASURED TWICE PER YEAR and the values (capacitance and current) compared against those on the nameplate. If measured values are lower than rated values, they are already degrading.

Effect of temperature on capacitor life

MPP capacitor life follows the Arrhenius model, and is reduced by 50% for each 10 degrees Celcius above its rated operating temperature. Therefore, the half life of capacitors is typically expressed as 10 degrees Celsius. MPP capacitors that operate at temperatures above their rated temperature will experience reduced life, whereas capacitors operating below their rated temperature can experience extended life. Factors that will increase the operating temperature of capacitors include: excess current, excess terminal voltage, and ambient temperature.

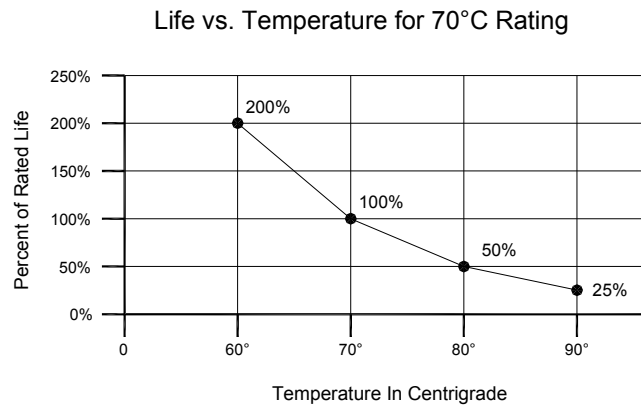


Fig. 1 Capacitor life vs. operating temperature

Fig. 1 demonstrates how a capacitor, rated for operation at 70 degrees Celsius, reacts to various operating temperatures. At 70C it experiences 100% life, and at 80C (10C higher than rated temperature) its life is reduced by 50%. At 90C operation, life is reduced by 75%. However, if temperature of this capacitor is reduced to 60C (10C less than rated temperature), it can experience 200% of normal life.

Effect of capacitor geometry on capacitor life

As demonstrated by El-Husseini, Venet, Rojat and Joubert in their article “Thermal Simulation for Geometric Optimization of Metallized Polypropylene Film Capacitors”, the physical geometry of a capacitor can have an impact on capacitor temperature, power loss and life. They demonstrated that for the same electrical stress, taller capacitors experienced higher temperature and losses than shorter capacitors. As stated in their article, in taller capacitors, the current must travel a longer distance through the very thin metal films, thus the total I^2R is higher compared to a short capacitor. The authors demonstrated that the total power loss in the capacitor is proportional to Equivalent Series Resistance (ESR) and to the square of the true rms current. ESR represents the eddy current and dielectric losses, which are affected by both frequency and

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current. If capacitor current is elevated, power loss increases. Likewise, power loss in a metallized film capacitor increases if the frequency of the current increases. Thus, harmonic current flowing in a metallized film capacitor, the power loss will be higher than if pure sinusoidal current were to flow. [1]

$$P_{\text{Total}} = \text{ESR} \times I_{\text{trms}}^2 \quad \text{Eq. 1}$$

When the capacitor cells are supplied as three phase units, it is difficult to see the physical shape and size of the capacitor cell, making it difficult to determine the suitability of the capacitor. But, whether a metallized film capacitor is used in a power factor correction system or harmonic filter, life expectancy can be increased simply by using a geometrically optimized capacitor rather than the taller capacitors. When the capacitor cells are supplied as three phase units, it is difficult for one to see the physical shape and size of the capacitor cell, making it difficult to determine the suitability of the capacitor.

Effect of terminal voltage on capacitor life

The effects of voltage on capacitor life expectancy, is much greater for metallized film capacitors than for aluminum electrolytic capacitors. Capacitor life expectancy is a function of (rated voltage divided by terminal voltage)⁷. For example, a capacitor rated for 480 volts, which has a terminal voltage of 504 volts (5% high) will have a life expectancy of $(480/504)^7 = 0.71$ times the rated life. At 10% over voltage, capacitor life is reduced to 51% of rated life. Fig. 2 illustrates the effect of voltage on capacitor life and that capacitor life can be doubled for a 10% reduction in terminal voltage. Capacitor life can be extended when the capacitor terminal is lower than the capacitor rated voltage.

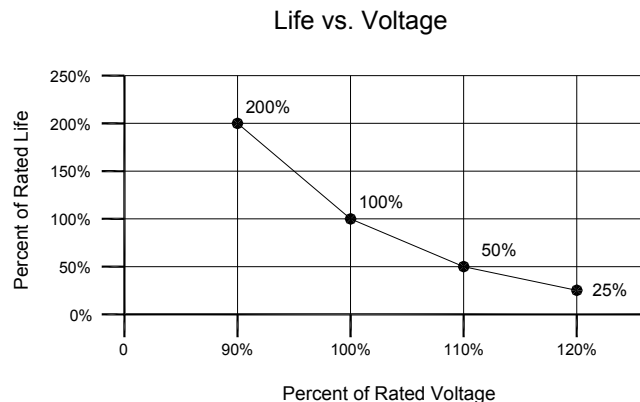


Fig. 2 Capacitor terminal voltage vs capacitor life

Effect of transients on capacitor life

Capacitors are sensitive to transient over voltages and may experience damage to the dielectric system. This can be experienced either due to transient over voltages on the power system as well as inrush current caused by either single or back to back switching transients. Under these conditions the capacitor terminals are exposed to elevated voltages as well as fast rising current

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IEEE-std 1036 demonstrates that peak capacitor inrush current can reach significant levels which can be ten times and greater than the normal capacitor (fundamental) current [2]. The peak inrush current is greatly affected by the available short circuit current as illustrated in equation Eq. 2.

$$I_{pk} = 1.414 \cdot \sqrt{I_{sc} \cdot I_1} \quad \text{Eq. 2}$$

Consider a capacitor application that involves available short circuit current of 10,000 amps and nominal capacitor rated current of 100 amps. In this case, capacitor inrush current can be over 1400 amps peak. The same capacitor on a system with 25,000 amps available short circuit current can experience peak inrush current of over 2200 amps. Capacitor inrush current can realistically reach levels that are as much as 30 times the rated capacitor current.

In cases where one capacitor bank is already energized and a second bank is to be switched onto the system, the second bank can experience much higher inrush current due to the discharging of the capacitors of the energized first bank. In this case, the peak current for 60 Hz systems may be calculated using equation Eq. 3.

$$I_{pk} = 1747 \cdot \sqrt{\frac{V_{L-L} \cdot (I_1 \cdot I_2)}{L_{eq} (I_1 + I_2)}} \quad \text{Eq. 3}$$

Where:

Leq = per phase inductance between capacitor banks (uH)

I₁, I₂ = capacitor current (amperes)

V_{L-L} = Line to line voltage (kV)

In this case, the magnitude of inrush current is a function of equivalent inductance that exists between the two capacitors. The greater the value of inductance, the lower is the peak inrush current. Consider a system with 4160 volt system with capacitor bank current of 100 amps and 5uH line inductance. In this case, the inrush current can be over 11,000 amps peak. If the total reactance between the two capacitor banks is 50uH, the peak inrush current is limited to less than 3600 amps, and for 100uH, the peak inrush current is limited to about 2500 amps. It is easy to see that capacitor inrush current can be limited by simply inserting a reactor in series with each capacitor bank.

For applications of multiple switched capacitor banks, peak inrush current can reach levels as high as 50 - 100 times rated capacitor current [3]. An inductance with a 60 Hz reactance as low as 0.5% - 1% of the 60 Hz capacitive reactance of the banks placed in series with the capacitor banks will greatly reduce the rate of rise and the peak value of inrush current [3].

Effect of elevated current on capacitor life

Capacitor temperature rise is a function of physical characteristics, thermal (true rms) current and the capacitor internal equivalent series resistance. Thermal current squared times internal equivalent series resistance is equal to watts (loss) which is dissipated as heat. Therefore, a 10% increase in capacitor current is reflected as a 21% increase in capacitor watts loss ($I^2 R = W$, so

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$1.1^2 \times R = 1.21 \times R$). Since watts loss has a direct effect on capacitor temperature rise, that same 10% increase in current can result in a 21% increase in temperature rise.

Consider a capacitor operating at 40C at rated current. If current is increased by 10%, perhaps due to the presence of harmonics, then watts loss and temperature rise increase by 21%. The capacitor sees this as an increase of operating temperature of more than 8°C, which can reduce the life expectancy as much as 50%.

It is clear to see that to achieve maximum life expectancy from a capacitor, several factors must be controlled. Capacitor temperature, voltage and current should be kept to minimum levels, and for longer life, for better life, short capacitors can be used in place of tall capacitors, resulting in lower ESR, power loss and internal temperature rise.

Impact of Capacitor Protection Reactors

The inductive properties of a series connected capacitor protection reactor, are beneficial for extending the life of power factor capacitors. Surprisingly enough, the use of reactors is not a new thought. One only needs to travel to Europe to see the widespread use of series connected reactors for protection of power factor capacitors.

When power factor capacitors are applied on a system that has harmonic producing loads, the network voltage becomes distorted. Distorted voltage is comprised of individual voltage sources at various (harmonic) frequencies. Each of these voltage sources will cause current to flow (at their respective frequency) into a capacitor. The true rms current which consists of the capacitor fundamental current and all harmonic currents is the thermal current that will drive the I^2R losses in the capacitor.

Since capacitive reactance (X_c) reduces as frequency increases (see Table 1), capacitors offer a very low impedance path for harmonics to flow. Their ability to attract harmonics causes additional current to flow in power factor capacitors when non-linear loads are connected to the same voltage source. Table 1 illustrates capacitive reactance (ohms) at various harmonic frequencies for both a 100 and 500 kVAR capacitor. The lower the ohms, the higher the magnitude of current flow at the respective frequency.

Table 1: Capacitive Reactance vs Harmonic Frequency

480V Capacitor	60hz Fundamental	300hz 5th harmonic	420hz 7th harmonic	660hz 11th harmonic	780hz 13th harmonic
100kVAR	2.304 ohms	0.4608 ohms	0.329 ohms	0.209 ohms	0.177 ohms
500kVAR	0.4608 ohms	0.0921 ohms	0.0658 ohms	0.0418 ohms	0.0354 ohms

Table 2 illustrates the impact of adding a capacitor protection reactor. The inductor/capacitor network impedance remains low for low frequencies allowing fundamental current to pass easily and increases exponentially for higher frequencies. This helps to restrict the flow of unwanted harmonics into the capacitor. Below the natural resonant frequency, the network looks capacitive (providing leading VARs) and above the resonant frequency it looks inductive (offering a high impedance to harmonics).

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Table 2: Network Impedance (LC) vs Harmonic Frequency

480V Capacitor	60hz Fundamental	300hz 5th harmonic	420hz 7th harmonic	660hz 11th harmonic	780hz 13th harmonic
100kVAr	2.143 ohms	0.345 ohms	0.800 ohms	1.564ohms	1.919 ohms
500kVAr	0.429 ohms	0.069 ohms	0.160 ohms	0.313 ohms	0.384 ohms

Fig. 3 compares the ohms (capacitive reactance) of a lone capacitor to the (LC) network impedance of a capacitor combined with a capacitor protection reactor (CPR). Without the CPR, capacitor ohms decrease rapidly as frequency increases, becoming attractive to any harmonics present on the power system. With CPR, the LC network impedance becomes higher as frequency increases, making it more difficult for harmonic currents to flow into the capacitor.

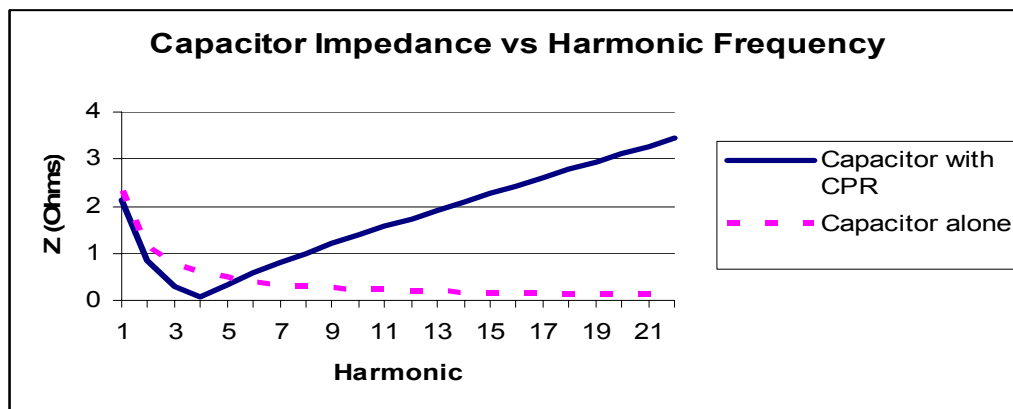


Fig. 3
Comparison of Impedance for Lone Capacitor vs. Capacitor with CPR.

As the capacitor kVAr rating increases, the capacitance in micro farads increases, while the capacitive reactance (ohms) decreases. Furthermore, the capacitor ohms decrease for higher harmonic frequencies. Fig. 4 illustrates the effect of harmonic voltage on capacitor current. This example demonstrates the magnitude of harmonic current that will flow in a capacitor when ten volts of an individual harmonic frequency is applied to the capacitor terminals. This harmonic current contributes to the true rms (thermal) current flowing in the capacitor. With a capacitor protection reactor installed in series with the capacitor, the LC network impedance is increased and therefore capacitor harmonic current is decreased. In addition, the steady state capacitor thermal current is reduced, power losses are reduced and the capacitor has improved protection against transients and inrush current.

One of the most destructive situations occurs when the capacitive reactance combines with system inductive reactance to form a tuned network having a natural resonant frequency at which harmonic energy is present. In this case, the combined impedance can be near zero and harmonic energy can be amplified, resulting in extremely high current flow into a capacitor. This calls for series inductance in the capacitor circuit to purposefully tune the capacitor bank near a frequency where harmonic energy is not present (often near the fourth harmonic).

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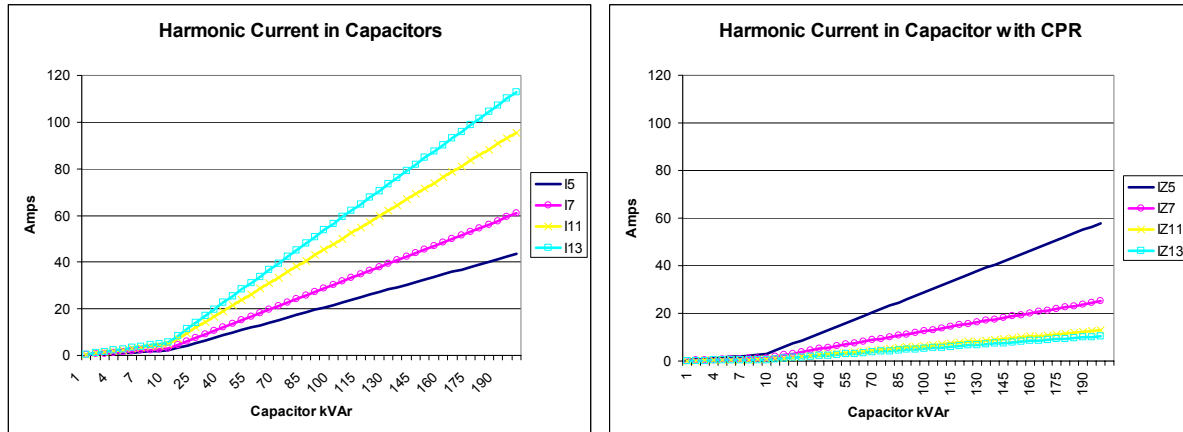


Fig. 4a and 4b Capacitor Harmonic Current for 10 volts at Specified Harmonic Frequencies, for cases without (4a) and with (4b) Capacitor Protection Reactor.

Transient protection offered by reactors

The presence of a series-connected capacitor protection reactor will offer protection against voltage and switching transients, further extending capacitor life. This is accomplished in that the reactor impedance and the nature of a reactor to slow down the rate of rise in current and to limit inrush current. In this sense, the capacitor protection reactor, intended to increase capacitor impedance at harmonic frequencies, also limits inrush current and reduces the effects of transient over voltage.

Voltage and kVAR boosting

When a reactor is connected in series with a power factor capacitor, the voltage at the capacitor terminals is increased due to the displacement between inductive and capacitive reactance. The voltage rise at the capacitor terminals may be calculated using equation Eq. 4.

$$V_{cap} = \left(\frac{n^2}{n^2 - 1} \right) \cdot V_{sys} \quad \text{Eq. 4}$$

where:

V_{cap} = capacitor terminal voltage

n = tuned harmonic number

Example: consider a 480 volt system, and a L-C network tuned to the 4th harmonic.

$$V_{cap} = [4^2 / (4^2 - 1)] \times 480V = 512 \text{ volts (+6.67\%)}$$

Since a reactor will increase capacitor voltage, it is necessary to use a capacitor with a suitable voltage rating or as seen earlier, the capacitor life can be significantly reduced. Due to capacitor terminal voltage boosting however, the addition of a reactor is not recommended as a retrofit to existing capacitors.

The fact that voltage at the capacitor terminals increases when a series reactor is added also provides the benefit of boosting actual kVAR of the capacitor. The new kVAR can be calculated by using equation Eq. 5.

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$$kVA_{r_{new}} = \frac{V_{sys}^2}{(X_C - X_L) \cdot 1000} \quad \text{Eq. 5}$$

Example: consider a 100kVA_r, 480V, 3-phase capacitor bank with 7% impedance capacitor protection (detuning) reactor. Then $X_C = 2.304$ ohms and $X_L = 2.304 \times 0.07 = 0.161$ ohms.

$$kVA_{r_{new}} = 480^2 / [(2.304 - 0.161) \times 1000] = 107.5kVA_r$$

The addition of a series-connected capacitor protection reactor not only protects the capacitor from adverse effects of harmonics and from excessively high inrush current or voltage transients, but also increases the usable kVA_r provided by the capacitor. In this particular case, the actual kVA_r provided by the LC network is 7.5% higher than the nameplate kVA_r rating of the capacitor.

Conclusion

Capacitor protection reactors can extend the life of power factor capacitor banks by restricting the flow of harmonics into the capacitor, limiting inrush current and absorbing transient over voltage. In addition to these levels of protection, the reactor also boosts the kVA_r supplied by the capacitor which can help to stabilize the system voltage and further improve power factor. Capacitor protection reactors should be considered for all capacitor banks that will be installed on a power system where harmonic-producing loads are connected. If you wish to forgo the addition of capacitor protection reactors initially, then consider specifying the capacitor voltage high enough to be suitable for the addition of reactors at a later date. This will enable you to add protective reactor to existing capacitors at a later time.

References:

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- [2] IEEE-std-1036 - 1992, IEEE Guide for Application of Shunt Power Capacitors.
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AUTHOR BIOGRAPHIES

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