Application Note

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Optimized Design of Power Factor Correction Systems

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Optimized Design of Power Factor Correction Systems

There is growing awareness of a need for application-specific power factor correction (PFC) systems of optimized design in line with the harsher conditions prevailing in industrial energy distribution systems. This means that conventional PFC systems that may previously have been sufficient have to be replaced by dynamic systems – ideally detuned ones.

When designing a PFC system for highly sensitive or polluting applications (such as welding equipment, cranes, elevators, steel presses, wind turbines as well as automotive and petrochemical equipment), it is mandatory not only to follow good engineering practice but also to carefully observe the rules and recommendations specified in the relevant design standards.

These Application Notes highlight some of the most common problems occurring in PFC systems and propose methods for their optimized design.

The Author

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Content

Power Factor Correction

Optimized Design of PFC Systems

Conditions in industrial energy distribution systems for PFC capacitors have become much harsher and therefore require new approaches and solutions to ensure safe and effective operation of the PFC system.

The demands made on PFC capacitors include:

- higher packing density of capacitors inside the cabinet
- strong load fluctuations
- increasing power-grid pollution, such as from harmonic loads (not only from typical net harmonics, but also from advanced PWM-based IGBT converters with frequency signals up to 20 kHz).

1. High packing density of capacitors in the cabinet

High temperatures

Lack of space inside PFC systems means higher specific power losses (W/cm^3) that result in higher operating temperatures of the capacitors inside the cabinet.

PFC capacitors heat up during operation due to resistive and dielectric losses. If the temperature rise is too high, e.g. the hot spot temperature exceeds a defined limiting value, the capacitor will break down or its life expectancy will be shortened.

Definition of temperature class -25/D

Typically, PFC capacitors are specified according to the highest temperature class (-25/D) specified in the IEC60831 or EN60831 standards. Class -25/D stands for the following temperatures:

- 55 °C maximum permissible peak temperature
- 45 °C maximum permissible average temperature during 24 hours
- 35 °C maximum permissible average temperature during one year.

These values apply to the temperature of the air surrounding the capacitor.

Hot-spot temperature

Polypropylene is typically used as the dielectric for PFC capacitors. Until a specific hot-spot temperature is reached, it has a high dielectric strength. However, this declines considerably as soon as the hot-spot temperature is exceeded. The operating life of a capacitor with polypropylene dielectric also depends strongly on the hot-spot temperature. A rule of thumb derived from the Arrhenius equation, which describes the temperature-dependent aging process, says that a temperature rise of 7 °C will shorten the operating life of MKK capacitors by 50 percent.

Overpressure disconnectors

If the specified temperature is exceeded, therefore, the life expectancy of the capacitor will be shortened due to a greater number of self-healing processes, which generate a small amount of gas. As the number of these processes increases, the internal overpressure rises and activates the overpressure disconnector. When a defined limiting temperature is reached, the self-healing capability fails and an irreparable breakdown occurs. In other words: exceeding the limiting temperature specified by the capacitor manufacturer or in the international IEC60831 standard will not only shorten the life expectancy of the capacitor but may also represent a safety risk.

Note: When the maximum operating temperature is exceeded, the internal safety device of the capacitor, the overpressure disconnector, stops functioning. In the worst case this leads to bursting of the capacitor with the risk of fire!

Fig. 1:
Conventional PFC system (without reactors) with natural air circulation. Generous ingress of air and a raised roof assure efficient cooling.

Design rules

When designing, constructing and operating a PFC system, it is mandatory to assure sufficient ventilation or cooling of the cabinet, or rather of the capacitor inside the cabinet. The high packing density may require forced cooling and enough space must be allowed between the capacitors. Sufficient distance should also be maintained to "warmer" components (such as wound parts, reactors and semiconductors). The parameters specified by the capacitor manufacturer must also be observed.

Fig. 2: Detuned PFC system with forced cooling and key components arranged under appropriate thermal conditions.

2. Strong load fluctuations and their consequences

Switching operations

Dynamic applications (such as automotive systems, cranes, welding machines, presses and wind turbines) involve a large number of switching operations. This means that the capacitors have to be switched on and off very frequently, sometimes with insufficient damping of the inrush current.

Capacitor contactors and inrush current

In conventional PFC systems, the capacitors are connected to the power line via electromechanical contactors (preferably with inrush current damping capability). The switching of capacitors causes high inrush currents, particularly when they are switched in parallel to others already activated in the power line and in the presence of high short-circuit powers on the line.

Depending on the contactor type and on the random time at which the capacitor is switched in relation to the instantaneous value of the sinusoidal half-wave (worst case at peak voltage value), high inrush currents with extremely high amplitudes will occur (described by the formula: peak current $\hat{I} = C*dV/dt$).

High inrush currents place greater stress on the capacitors due to strong electrodynamic forces, especially in the contact area of the metal-spraying layer and the electrode. This will influence the life expectancy of the capacitor significantly in addition to the power quality (transients, voltage sags) and the life expectancy of the contactor.

Limiting values to IEC60831

The life expectancy of metalized power capacitors is limited by the number of switching operations. According to capacitor standard IEC60831, the number of switching operations should not exceed 5,000 (with a defined amplitude). Today's high-quality power capacitors can normally cope with figures above this limiting value. Nevertheless, real cases have been reported where the switching operations rise to as many as 150,000 per year! Conventionally designed capacitors cannot handle values of this order.

The number of switching operations not only influences the capacitor's operating life directly, but also indirectly. Capacitor contactors with a pre-defined number of between 100,000 and 200,000 switching operations already reach their life expectancy after 1 to 2 years due to this high frequency. This typically results in destruction of their inrush current damping capability and also damages the contacts in the main power circuit. It is quite evident that these contactors can only attenuate the inrush current insufficiently if at all.

Burnt main contacts may also produce oscillation or "unclean" (re-bouncing) switching operations. This massive overload not only shortens the life expectancy of the capacitor, but also increases the risk of premature failure and in the worst case represents a potential safety risk.

Fig. 3: Burnt main contacts of a capacitor contactor.

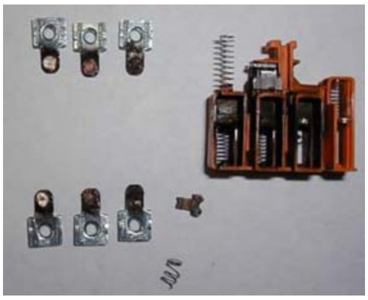

Fig. 4: Burnt pre-loading contacts of a capacitor contactor.

■ Dynamic PFC and thyristor modules

These kinds of fast-changing loads require technologies that act in real time. In dynamic PFC systems, electronic switches (thyristor modules) replace the slow-acting electro-mechanical switches. This not only means faster reactions but also increases the life expectancy, as thyristor modules do not suffer from mechanical wear.

Fig. 5: Thyristor module

TSM series for smooth switching.

Another advantage is the simultaneous prevention of high inrush currents. The thyristor module switches the capacitor at zero current passage, thus avoiding high inrush currents which can reach values of 200 times the nominal current with conventional contactors. This has a positive effect on the power quality: the life expectancy of the PFC system and capacitor increase, as does the safety level. The price difference between contactors and thyristor modules is amortized in two to three years. Considering that capacitor failures involve the risk of fire, this amortization period will effectively be shorter.

Dynamic PFC systems are increasingly becoming standard where heavily fluctuating loads are found – fortunately also in industrial applications!

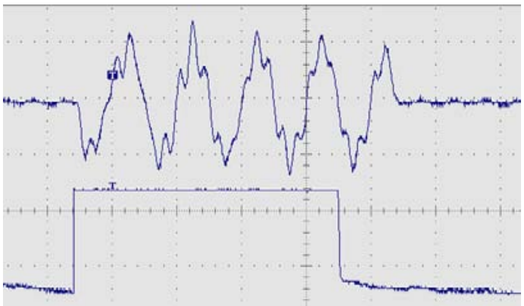

Fig. 6: No inrush current with thyristor module

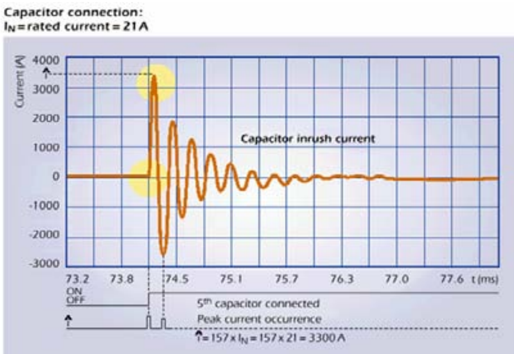

Fig. 7: Extreme inrush current (157 x nominal current) with capacitor contactor

3. Harmonics and their impact on the power line

■ Pollution by harmonics

The increasing number of power electronics applications in industrial, commercial and even private surroundings has a negative impact on the quality of the power line due to pollution by harmonics.

■ Resonances

System perturbations by harmonics and possible capacitor resonances in combination with inductances of the power line (strongly determined by transformer inductance) mean a possible stress potential for the PFC system. If the frequency of existing harmonics is equal to the natural resonant frequency of a L/C system, a more or less damped resonance with correspondingly high resonance currents will occur. Harmonics can either be triggered on the low-voltage side – known as parallel resonance – or on the medium-voltage side – known as series resonance.

Even without the occurrence of resonances, however, an additional current input and heating of the capacitor must be considered.

Note: Resonance effects can cause a multiple of the nominal current, with serious effects on distribution equipment such as fuses, contactors or capacitors!

■ Detuning of PFC systems with harmonic filters

Detuned PFC systems have almost become a standard in today's industrial applications. Their market penetration is around 90% in central Europe.

In a detuned PFC system, a harmonic filter reactor is connected to a capacitor in series. This L-C combination is designed to keep the filter frequency below the lowest harmonic frequency. The PFC system then behaves like an inductive circuit to all harmonic frequencies.

Detuning avoids resonances, keeps the stress on the capacitors within specified limits and simultaneously has a positive effect on the power quality. The decreased THD-V level also has a positive impact on the life expectancy of other electrical and electronic devices and thus reduces the investment required for maintenance.

A complex power structure has to cope with both parallel resonances (harmonic loads on the LV side) and series resonances (harmonic loads on the medium or high voltage sides). So a detuned PFC system offers a very solid technical solution for eliminating resonance problems (Fig. 8).

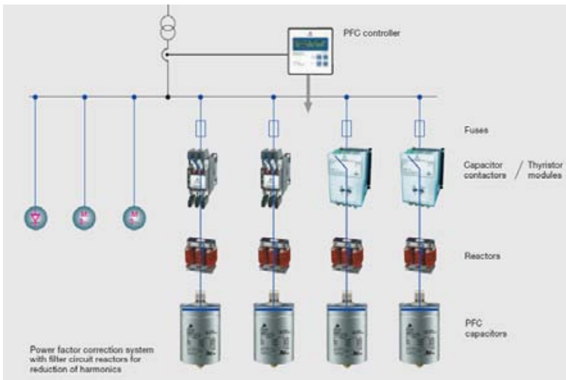

Fig. 8: Connection example for a detuned system – a hybrid solution with both capacitor contactors and thyristor modules.

4. Design of short circuit protection, e.g. HRC fuses and safety chains in general

As already mentioned, PFC capacitors with self-healing properties are normally equipped with overpressure disconnectors. These safety devices separate the capacitor electrically from the power line and avoid further current input at the end of their service life after a large number of self-healing processes and activation of the internal overpressure have taken place.

■ Short circuits and other breakdowns

Overpressure disconnectors are only activated in the event of gas production: this occurs as a result of overload leading to regeneration processes or a non self-healing breakdown. They will not work in the event of other failures, such as short circuits or breakdowns of the component which do not release any gas. Other protection devices are required in these cases.

■ HRC fuses and selection criteria

The principal way of protecting the circuit from short circuits is to connect HRC fuses directly in series. When choosing the HRC fuse, the following main criteria have to be observed (see also IEC61818).

- Nominal voltage: the nominal voltage should always exceed the grid voltage. This will guarantee safe extinction of the electric arc. Fuses with a nominal voltage of 690 V are often found, especially in wind turbine applications with a 690-V power grid. This is contrary to the recommendations of IEC61818.

- Nominal current: the technical literature recommends 1.6 – 1.8 times the nominal current
- $I^2 * t$ characteristic: to activate the fuse, the energy consumed has to be below the lowest threshold values of the burst energy of the capacitors and/or other downstream components. In other words, in the event of a failure, the fuse has to be activated before the energy consumed by the capacitor exceeds a certain value (burst energy). To verify the burst energy of the capacitor, the relevant manufacturer has to be contacted.
- Triggering characteristic
- Selectivity

HRC fuses are mainly used for short-circuit protection. They do not provide protection against overload. Under certain conditions, they must be able to control high inrush currents while also switching off quickly enough in the event of failure in order to limit the energy input. These two requirements are contradictory and therefore difficult to harmonize. It is recommended to contact the fuse supplier or capacitor manufacturer in each particular case.

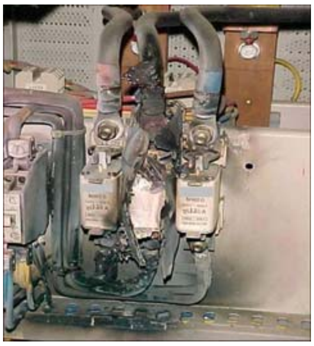

Fig. 9:
Fuse exploded due to resonances.

Capacitor protection relays

Capacitor protection relays are available to provide additional capacitor protection for medium-voltage PFC. These devices greatly exceed the requirements of normal short-circuit protection. Their additional protection functions include:

- short circuit to earth
- over-current depending on the number of connected capacitors
- unbalance
- under-current/over-current

The possible use of protection relays in low voltage applications is being evaluated.

5. Conclusions

Although the topics covered above reflect the major points required for the safe usage of PFC capacitors in industrial applications – they do not claim to be complete. Other conditions such as the exposed locations of wind turbines involving a higher risk of lightning strikes, over-voltage, phase opposition as well as isolated operation and audio remote frequencies must also be taken into account.

A customized specification is mandatory for an optimized design of PFC systems. It must include aspects such as location, application, surroundings and power stability. The particular components should be perfectly matched to each other. Principles of good engineering practice must not be ignored – sometimes a simple design is much better than an overly elaborate one!

In case of any doubts, please contact the supplier of the particular component before installation.

6. Standards

The recommendations and proposals stated in these Application Notes are based on several international standards, including those for PFC capacitors, LV switchgear design and electrical applications:

- IEC60831: LV-PFC Capacitor Standard
- IEC61921: Power Capacitors LV-PFC Banks
- DIN EN61921: Leistungskondensatoren Kondensatorbatterien zur Korrektur des Niederspannungsleistungsfaktors
- EN 50160: Voltage Characteristics of Electricity supplied by Public Distribution Systems
- Engineering Recommendation G5/4: Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom
- IEEE Std. 519-1992: IEEE Recommended practices and requirements for harmonic control in electrical power systems
- IEC60439-1/2/3: Low voltage switchgear and control gear assemblies

The specifications given in the standards and manufacturers' data sheets should always be observed.

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