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Application Notes

PQS

Design Rules for PFC Systems

Power Quality Solutions

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Application Notes

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Each issue focuses on a particular application topic, a specific solution or a topic of general interest. The aim is to share the extensive knowledge gained globally by EPCOS PFC experts with regional staff who deal with PFC and PQS. The authors of the PQS Application Notes have extensive experience in the field of PFC and PQS and a professional background as electrical/design engineers or product marketing managers throughout the world.

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Foreword

In view of the large number of suppliers of PFC products, it should be quite easy to design a customized and application-oriented PFC system. However, experience shows that this is not the case: the range of products is too broad and the risk of over or under-dimensioning is too high.

This application note gives some important design rules that should be observed to make a PFC system a customized and effective power-quality solution for each specific application. By following the simple instructions for measuring, evaluation and analysis stated in the following pages, you will obtain an appropriate design for a PFC system with optimal performance.

The rules and instructions given here are the result of long experience in the field of power factor correction and power quality. Their use is an important cornerstone for guaranteeing the success of a PFC system!

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Power Factor Correction

Design Rules for PFC Systems

Designing a PFC system is rather similar to treating a disease: if you have a health problem, you may read articles on the Internet or newspaper and talk to your family and friends to find a cure. But in the long run, only a thorough examination and check by your doctor will help to find the root cause and the right treatment in most cases. The same applies to the design of a PFC system. Once the **need for a PFC system** is evident, you can simply assemble some key components and see whether it works. It may work… but just like there is no medicine that will cure all diseases, there is no single all-purpose PFC system.

So it is mandatory to perform the equivalent to a medical X-ray examination prior to designing the final solution. The success of a PFC system is based on the measurements taken and on **evaluation and analysis** of the relevant values, combined with the observation of additional preconditions.

In this application note, we have collected some of the **most important key rules** which should be observed to achieve an optimum PFC solution. Please note that we are talking about rules, not recommendations - our experience shows that most failures in the field occur because these rules have been neglected. Please pay special attention to the following basic principles and rules!

1. Measurement of load and grid

- Disconnect all existing capacitors/systems.
- Determine the normal load operating conditions.
- Measure all electrical parameters of the installation including:
  - the power factor
  - the current
  - the active power
  - the reactive power
  - the real permanent voltage
  - THD-V%
  - THD-I%
  - the amplitude of each harmonic current/ voltage

Fig. 1: Detuned PFC system

Also, measure how quickly the need for reactive power changes in order to determine suitable step sizes and switching time constants, and to decide if a dynamic system may be necessary. Please note that **extraordinary events** appearing during special load conditions such as voltage sags, transients or flicker might not be identified by a measurement of short duration. Only **long-term monitoring** can identify such power-line disturbances. According to the standards the measurement should be not less than one week.

2. Dimensioning of the system

First determine the **necessary effective power** (kvar) of the capacitor bank in order to obtain the desired power factor.

Design the capacitor stages in such a way that the sensitivity of the bank is around 15 to 20% of the total available reactive power. There is no need to have a more sensitive bank that reacts with 5 or 10% of its total power, because this would lead to a high number of switching operations. This would burden the equipment unnecessarily when the real objective is to have a high average PF. Nevertheless the proper design depends on the size of the single loads in the system, and on the desired cos phi.

Try to design the bank with **standard kvar values** of effective power steps, preferably multiples of 25 kvar.

3. Choosing the right technology

The values of THD-V% and THD-I% are the major factors in determining the design.

- Measure the presence of harmonic currents in the main feeder cable of the system without capacitors under all possible load conditions.
- Determine the frequency and maximum amplitude for every harmonic that could exist.
- Calculate the Total Harmonic Distortion of the Current (THD-I) as a percentage of the base frequency current:
  $THD\text{-}I = 100 \cdot (SQRT[(I_3)^2+(I_5)^2+ \dots +(I_N)^2]) / I_1$
- Calculate every existing individual n_{th} harmonic value:
  $THD\text{-}I_n = 100 \cdot I_n / I_1$
- Measure the presence of harmonic voltages that might come from outside the system. If possible, measure the HV side.
- Calculate the Total Harmonic Distortion of the Voltage (THD-V) as a percentage of the base frequency voltage:
  $THD\text{-}V = 100 \cdot (SQRT[(U_3)^2+(U5)2+ \dots +(U_N)^2]) / U_1$
- Are there harmonics such as THD-I > 10% or THD-V > 3% (measured without capacitors)?
  If NOT: u could use standard PFC and do not consider harmonic filter reactors, but consider using $V_{CAP} > V_{REAL}$.
  If YES: use detuned harmonic filter reactors and consider the next question:
- Is there 3rd harmonic content,
  $I_3 > 0.2 \cdot I_5$
  If YES: use detuned PFC with a detuning factor of p = 14%
  If NOT: use detuned PFC with a detuning factor of p = 7% or 5.67 % and consider the following for the selection:
- If THD-V is 3 to 10%: use detuned PFC with a detuning factor of p = 5.67 or 7%
  If it is > 10 %: ask for filters of special design

Select suitable components using the recommendations in the tables of the EPCOS PFC Product Profile for detuned PFC. The selection requires the values of effective kvar filter output, the voltage and frequency of the particular power line and the determined detuning factor p, according to the dominant harmonic.

If all measurements lead to the conclusion that the grid is free of harmonics, a **standard PFC system** (without detuning reactors) can be chosen. In this case, however, the existing loads are of importance. For fast-changing loads, i.e. for applications which require a real-time response, a **dynamic PFC system** (switching of steps by thyristor modules) is the right solution.

Additionally, be aware that capacitors without reactors could form a **resonance circuit** together with the power-line inductance (mainly the input transformer). It should be carefully checked that the resonant frequency of this LC combination in every switching state of the PFC system does not lead to resonant current amplification.

Fig. 2: Harmonic filter reactors

4. Selection of rated capacitor voltage

The **real operating voltage** is the one that is measured when the capacitors are connected.

Industrial facilities usually have their own MV/LV substations. In this case the output voltage of the transformers is often set to a higher value than the rated voltage supplied by the power utility. This is usually done to obtain a good voltage level for loads in some distance from the transformer. It may also happen when only a few of the connected loads are operational.

Using capacitors with a rated voltage higher than the actual operating voltage will significantly **extend their life expectancy** under such conditions. The lower effective power of capacitors operated at less than the rated voltage can be compensated by selecting a higher kvar output capacitor at a higher rated voltage.

5. Use of forced ventilation

According to the IEC60831 international standard, class D capacitors should operate at an **average ambient temperatur**e of 35 °C, although they may operate at the maximum of 55 °C for a short time.

Operation at the maximum temperature is not recommended at all because it inevitably leads to a significant derating of life expectancy.

Any PFC system from 100 kvar onwards should have enough forced ventilation to keep the ambient operating temperature of the capacitors at about 35 °C.

In case of permanent high ambient temperatures, MKV capacitors from EPCOS should be chosen (temperature class -25 °C up to +70 °C).

Please note that the definition of ambient temperature is: “Measured at a distance of 20 mm from the upright can at two thirds of its height.” The capacitor surface temperature can exceed the forced ventilation value of 35 °C by approximately 10 °C.

6. Correct mounting of all components

Capacitors must only be mounted inside a PFC system following the **practical recommendations** given below. If possible, they should not be mounted inside the main board. Because the components inside a PFC system dissipate heat, it is very important to allow **effective cooling** of the capacitors. We recommend mounting the capacitors onto profiles and not onto flat metal sheets that would obstruct all cooling air-flows.

In general: Make sure that all components are mounted at **suitable distances** from each other to ensure effective cooling by an unobstructed air flow and to prevent additional heating by infrared radiation, contact or strong convection.

Harmonic filter reactors could operate close to or above 100 °C. If they are used in the PFC system, they shoul be mounted at a different height and as far away from the capacitors as possible. They also should be mounted onto metal profiles in order to use the cabinet as a heat sink and to prevent blocking the cooling air flow at the same time. Additionally it is of advantage to place the reactors as close to the cooling air exit as possible in order to avoid heat transfer to other components via the airflow.

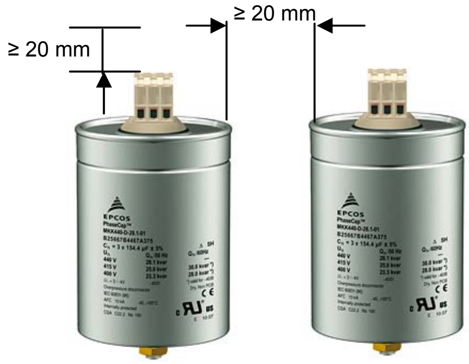

Fig. 3: Minimum distance between PFC capacitors of the PhaseCap series

Capacitor contactors are rated for a certain capacitor power at an max. operating temperature of 50 °C. If the operating temperature exceeds this value, their power switching capability decreases significantly. They have to be mounted so that they do not receive heat transferred from any other component in the system.

Always use high breaking capacity fuses dimensioned for 1.6 times the rated current!

Do not connect capacitors in parallel by making a bridge using the capacitors’ terminal block – it is designed for the current of only one capacitor.

If you need to **connect capacitors in parallel**, use separate cables to the terminals of the next component prepared to handle such capacitors together, such as a contactor or reactor.

Only use the recommended **cable cross sections**! Using smaller ones may lead to overheating of the capacitor terminals, causing a decrease of life expectancy. Also make sure to use high-quality cables of a high isolation class that emit little heat during operation.

Apply the **recommended torques** on the capacitor terminals and grounding/mounting studs.

7. Limitation of inrush currents

When capacitors are connected, inrush currents will always occur. They depend more on the short-circuit current of the point of connection than on the connected capacitor.

If not properly controlled, these inrush currents will inevitably shorten the expected lifetime of the PFC system and will worsen the **power quality of the whole installation**.

Fig. 4: Capacitor contactor

In standard PFC systems, capacitors must only be switched by capacitor contactors specially designed to switch capacitive loads and attenuate such inrush currents by pre-charging resistors.

It is important to bear in mind that even these capacitor contactors can only attenuate the inrush currents to a certain extent. They cannot prevent them completely. So it is better to reduce the number of switching operations as far as possible to avoid even these damped currents appearing too often and stressing the components of the PFC system.

Handmade coils made simply by wrapping the feeding cable are not sufficient to limit the inrush current!

Modern dynamic PFC systems use **thyristor modules** to switch capacitor steps without any inrush current transients at all. They allow an almost unlimited number of switching operations without any stress on the capacitors or any negative impact on the power quality.

Fig. 5: Thyristor module TSM series

For additional information, please see our application note: "Damping of inrush current" (ANo 113/V2, July 2008; www.epcos.com/pfc).

8. Correct configuration of the PFC system

As a rule, the PFC system should achieve an **average target cos-φ/power factor**. Please note that the emphasis is on average, which is not the same as an instantaneous or continuous adjustment.

Once the total required power of the PFC system has been determined, its **switching time constant** should not be configured too sensitively.

The **minimum step** should not be smaller than 10% of the total available capacitive power. Otherwise a slight change in the load will always cause switching. This would lead to an unnecessary high number of switching operations that significantly shorten the capacitor's life expectancy.

To reduce the number of switching operations, it makes sense to use **intelligent PF controllers**. They can register the number of switching operations and the operation time of every step. Use this information when sequencing the steps to get a fast response with a minimum switching number and achieve even stress on the capacitors at the same time.

Fig: 6: PF-controller of the BR6000 series

It will also be helpful to configure the system with two steps of the same minimum power. The minimum step is most highly stressed, because it performs the fine regulation. If there are two steps, the controller can distribute the stress between them.

Another important programmable parameter of the controller is the **discharge time**. This is the time that the controller has to wait before reconnecting the same capacitor to ensure it is discharged. The controller's default setting for the discharge time is usually 60 seconds. Setting the discharge time to at least 2 minutes will slow the system down and prevent an excessive number of switching operations while trying to reach the set target cos-φ.

9. Protecting the PFC system from transient overvoltages

Apart from other effects, almost all capacitor overload conditions ultimately increase the operating temperature of a capacitor. **Overcurrent** due to harmonics causes more internal losses that are converted to heat. Permanent **overvoltage** causes permanent overcurrent – and thus more heat. High ambient temperatures heat up the capacitors. And remember: higher operating temperatures means a shorter life or in the worst case a capacitor breakdown.

In addition, the **capacitor dielectric** is quite sensitive to voltage transients, and as its temperature increases, even smaller transient overvoltages can cause severe damage to the capacitor.

Plenty of transient overvoltages occur in an industrial installation as high-power inductive loads are switched. So highly effective and inexpensive protection is obtained by installing LV varistors from phase-to-ground. They really can spare the system significant stress.

10. Periodical preventive maintenance

Although PFC capacitors from EPCOS are maintenance-free, some preventive check-ups should be performed. A preventive **maintenance program** for a PFC system is quite simple:

- Verify that the system complies with all the above recommendations.
- After the first week of operation, tighten up all terminals.
- Verify the efficiency of the forced ventilation (35 °C ambient temperature), check ventilation filters for permeability.
- Verify that there is no evidence of overheating or electrical arcing.
- Keep the system clean and free of dust.
- Check the capacitors' RMS current, it should be between 0.9 and 1.2 I_{rated}.
- Repeat all these checks every 6 months.

11. High-quality high-tech PFC components

The power of a PFC system is comparable to that of a transformer, which means that a single cabinet contains as much power as all the distributed electrical equipment of the installation put together. It certainly deserves **special attention**, precautions and care.

With so much power involved, **reliability and safety** of the components are a must. Considering that all power electronic systems generate harmonics and transients, it is very important to use high quality and high technology in a 21st century PFC project.

EPCOS offers a **complete range** of products needed for successful power factor correction. All key components are carefully harmonized to each other – they are the basis for the **power quality solutions strategy** that EPCOS pursues to provide optimal products and services.

Fig. 7: PQS from EPCOS – all key components for PFC

12. Standards

The recommendations and proposals stated in this Application Note are based (amongst others) on several international standards for PFC capacitors, LV switchgear design and electrical systems:

- 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 Standard 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 in the standards and manufacturers' data sheets should always be observed.

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