TDK

Application Notes

PQS

Damping of Inrush Currents

Power Quality Solutions

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Foreword

Switching of capacitors means a tremendous stress for the complete PFC-system. Connecting PFC capacitors to a grid means a similar effect like a short circuit to the device if it is not protected by the appropriate switching device.

Capacitor contactors with damping resistors have become almost a must in PFC-applications.

EPCOS is offering a broad range of well-approved contactor series, covering a range from 12.5 to 100 kvar. Especially the new 100 kvar contactor means a significant cost reduction, as now just one device can be used instead of coupling two of 50 kvar each.

The Author

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Power Factor Correction

Damping of Inrush Currents in Low-Voltage PFC Equipment

1. General

The **market trend** to reduce losses in modern low-voltage power factor correction capacitors and the requirement for high output density results in reduced ohmic resistance in PFC capacitors.

Especially the **switching of capacitors** in parallel to others of the bank, already energized, causes extremely **high inrush currents** of up to 200 times the rated current, and is limited only by the ohmic resistance of the capacitor itself. According to the formula (Eq. 1), such a capacitor's AC resistance is very low and thus permits this high inrush current.

$$X_c = \frac{1}{2 * p * f * c}$$

Switching operation:

$$f \rightarrow \infty \rightarrow X_c \rightarrow 0 \rightarrow \hat{i} \rightarrow 200 * I_R$$

Eq. 1

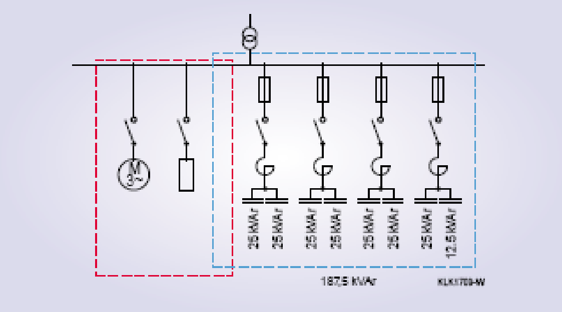


Fig. 1: High inrush current for grid, high balancing currents for capacitors

LV-PFC capacitor bank

Inrush current (pulse) is a factor of:

- Remaining capacitor voltage due to fast switching in automatic capacitor banks
- Short circuit power of supply transformer
- Output of capacitor switched in parallel to output of others already energized
- Fault level of supply network
- Ohmic resistance of capacitor itself, distribution switch gear and connection cables or conductors

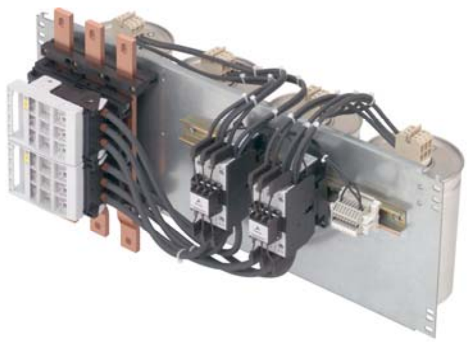


Fig 2: PFC-rack with capacitor contactors

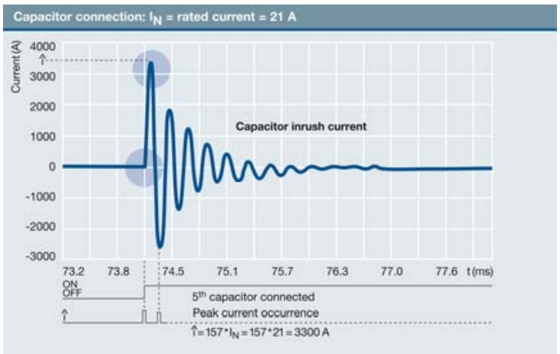


Fig. 3: Inrush current by connecting capacitors in parallel

2. The risks of high inrush current

Connecting LV-PFC capacitors without damping to an AC grid **stresses the capacitor** similar to a short-circuit. To avoid negative effects and to improve a capacitor's lifetime, **adequate damping** of inrush currents is highly recommended.

Influence of high inrush current and resulting distortion

- High stress on the capacitor reduces lifetime
- Welding or fast wear-off of the main contacts of contactors

- Negative effects on power quality (e.g. voltage transients)
- Overvoltage
  - Insulation problems
  - Defects of electronic equipment
  - Production stop
- Undervoltage/voltage zero crossing
  - Measurement failure
  - Problems with numeric controlled equipment
  - Production stops due to computer failure
- High cost of maintenance and production standstill

Fig. 4: Capacitors for Power Factor Correction: PhaseCap, PhaseCap HD, PhiCap, PoleCap, MKV

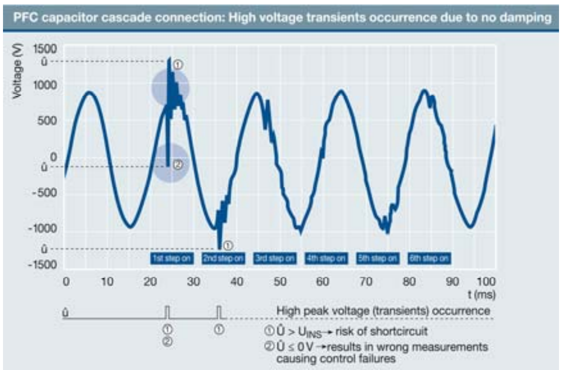


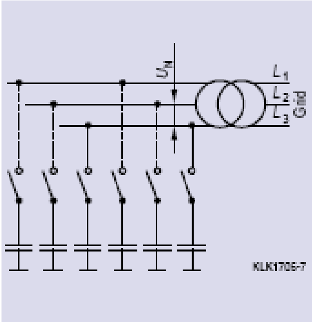
Fig. 5: Inrush measurement of capacitor steps; voltage at 0.69 kV-busbar

Switching of power factor correction (PFC) capacitors is not only related to high currents but also related to high voltage transients, causing further degradation of power quality, if the negative influence is not prevented by damping.

3. Inrush current calculation

Connecting a single capacitor:

Circuit and formula



$$\hat{I} = \sqrt{\frac{2 * Sk}{Q}} * I_R$$

Eq. 2

Terms

Peak inrush current	I_{peak}	[A]
Transformer shortcircuit power	Sk	[kVA]
Rated capacitor output	Q	[kvar]
Rated capacitor current	I_R	[A]
Rated voltage	U_R	[V]
Ohmic resistance = $3*U_R{}^{2}*(1/Q1+1/Q2)$	X_C	[Ω]
Grid impedance = ω * L (Ω) including	X_L	[Ω]

- contactor
- fuse
- busbars

Calculation example

Given parameters

Grid connection of a single 50 kvar capacitor, no other capacitor connected:

- Grid 400 V/50 Hz
- Transformer short-circuit voltage: 5%
- Transformer output: 1600 kVA
- Capacitor Q = 50 kvar; I_R = 72 A

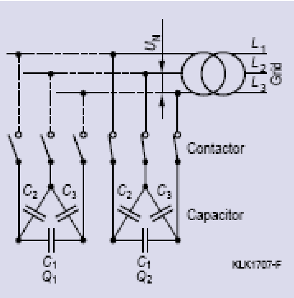
$$\hat{I} = \sqrt{\frac{2 * \frac{1600kVA}{0.05}}{50kvar}} * 72\ A = 2575\ A$$

The inrush current is approximately 35 times the rated current.

Result: Typical inrush currents are 10 – 40 times the rated current for single capacitors during connection.

Connecting a parallel capacitor:

Circuit and formula



$$\hat{I} = \frac{\sqrt{2} * U_R}{\sqrt{X_C * X_L}}$$

Eq. 3

Given parameters

Connection of a 50 kvar capacitor, other 300 kvar capacitors are already connected:

- Grid 400 V/50 Hz
- Transformer short-circuit voltage: 6%
- Transformer output: 630 kvar
- Q_1 = 50 kvar
- Q_2 = 300 kvar
- I_N = 72 A ; U_R = 400 V ; f = 50 Hz

$$X_C = 3 * U_R^{\ 2} * \left(\frac{1}{Q_1} + \frac{1}{Q_2}\right) = 11.2\ \Omega$$

L/phase = 0.4 µH (empirical)
$X_L = \omega * L = 2 * \pi * f * L = 0.125\ m\Omega$

$$\hat{I} = \frac{\sqrt{2} * 400V}{\sqrt{11.2\Omega * 0.125 * 10^{-3}\Omega}} = 15.118,6\ A$$

The inrush current is approximately 210 times the rated current.

Result: Typical inrush currents are 100 – 250 times rated current for single capacitors in parallel connection to other capacitors in operation.

4. Various solutions for limiting inrush current

4. 1 Detuning reactors

Series anti-harmonic reactors

In detuned capacitor banks the inductivity of filter circuit reactors provides an excellent damping effect for limiting inrush current. Fig. 7 and fig. 8 show the situation for connection of a detuned (reactor and capacitor) and standard system.

The peak current of a conventional capacitor is higher than 1000 A. The peak current of detuned capacitors is only approx. 100 A. The purpose of filter circuit reactors is of course not the damping of inrush current, but this example shows that in the case of detuned capacitors no additional damping measures are required.

Fig. 6: Harmonic filter reactor

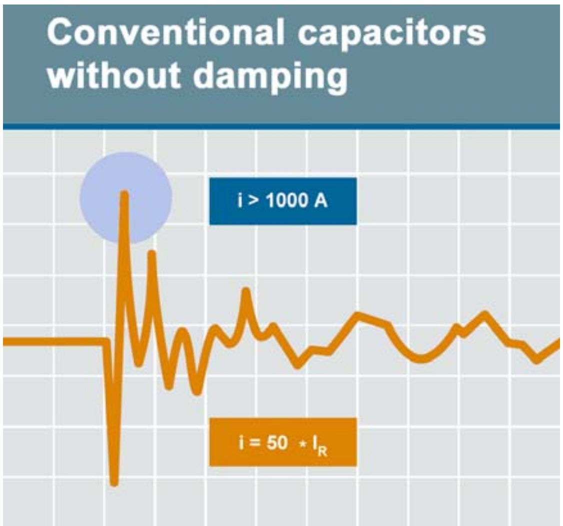


Fig. 7: 25 kvar (21 A/690 V),
vertical: 500 A/div, horizontal: 0.625 ms/div

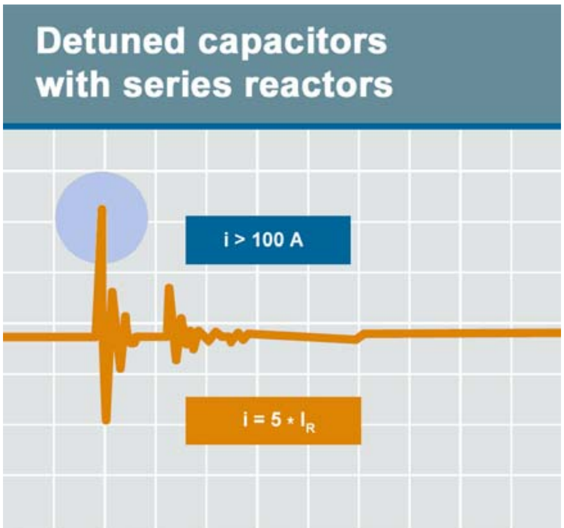


Fig. 8: 25 kvar (21 A/690 V),
vertical: 50 A/div, horizontal: 10 ms/div

4.2 Capacitor contactors with damping resistors

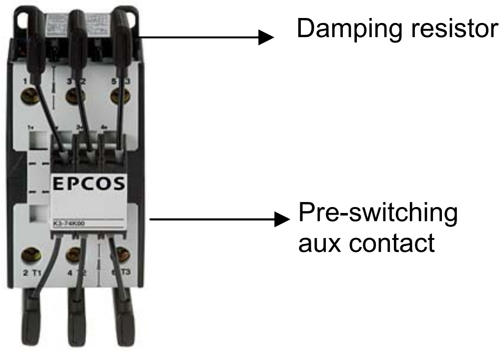


Fig. 9: Capacitor contactor 75 kvar

Fig. 10: New Capacitor contactor 100 kvar

How does it work?

The series damping resistors are switched by so called pre-contacts or auxiliary contacts. The pre-contact closes before main contacts and preloads the capacitor leading to

- Reduced voltage differences
- Limited peak current
- The resistor is temporarily in the circuit and has no thermal losses
- The total resistance of the resistor wires is mainly ohmic, its inductance can be neglected. The coiling up of the damping resistors is only a matter of construction.
- During operation (main contacts are closed) the resistor wires are disconnected or shorted out, and do not cause any permanent losses at all. Due to the very short operation time (a few milliseconds only) during switch-on of the contactor, a long life cycle of the damping resistors is ensured.

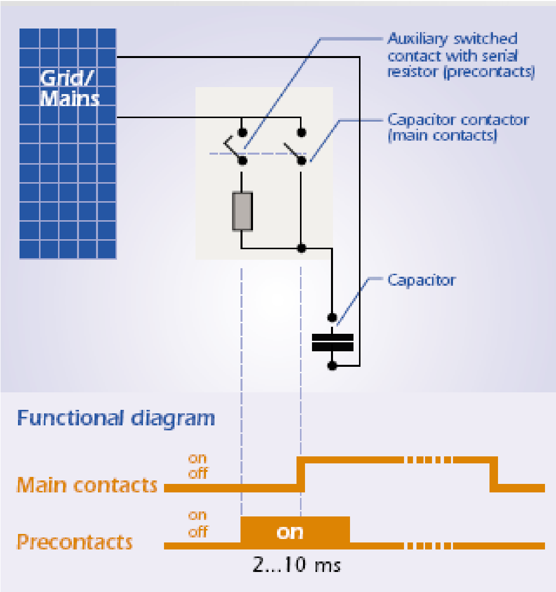


Fig. 11: Functional diagram

Due to pre-loading via aux. contacts the capacitor's voltage difference will be reduced. Consequently also the capacitor current according to the formula:

$$\hat{I} = C * \frac{d_V}{d_t}$$

Eq 4:

4.3 Thyristor switching modules

Thyristors are not subject to mechanical wear. Dispensing with mechanical contactors eliminates a further problem: high inrush currents. The thyristor modules switch the capacitors at the zero crossing of the current, thus avoiding inrush currents that can be as high as 200 times the rated current.

This problem can be remedied with thyristor modules that permit any **number of switching cycles** and offer short switching times for rapidly changing loads. As the capacitors are switched by the thyristor at current zero crossing, high inrush currents are avoided.

The thyristor **switches the capacitor virtually without delay.** As soon as the controller signal is applied to the thyristor, the current starts to flow through the capacitor and increases from zero to its peak value without any inrush current. As no inrush current peaks occur, no dangerous voltage transients are generated either.

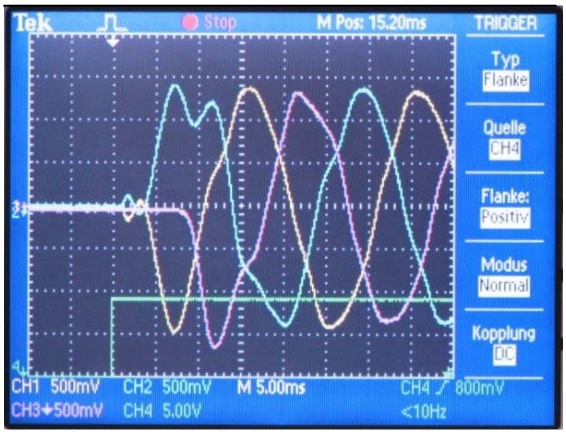


Fig. 12: Capacitor current switching by thyristor

Fig. 13: EPCOS product range TSM-modules

5. Comparison between some applications

The following three diagrams show the difference between a capacitor's inrush current without and with damping series resistors when a capacitor is switched in parallel to an already energized capacitor bank/unit:

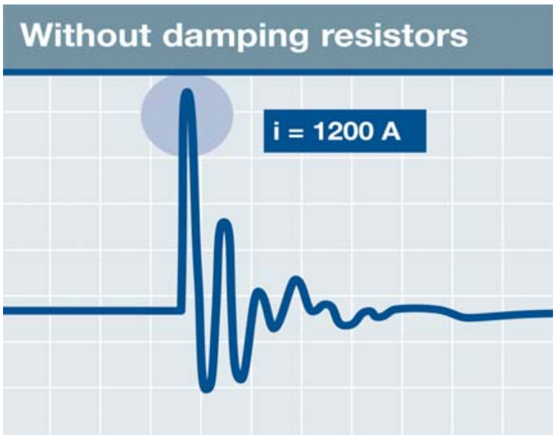


Fig. 14: 12.5 kvar (18 A/400 V),
vertical: 250 A/div, horizontal: 0.5 ms/div

Fig. 15: 12.5 kvar (18 A/400 V),
vertical: 250 A/div, horizontal: 0.5 ms/div

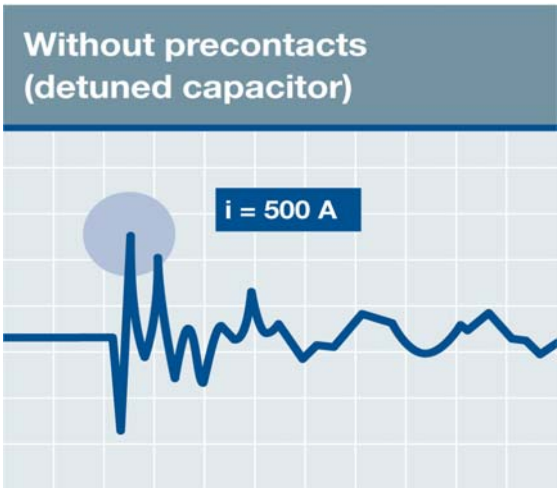


Fig. 16: 25 kvar (21 A/690 V),
vertical: 200 a/div, horizontal: 10 ms/div

Facts and conclusion

- Rated current of 12.5 kvar/400 V capacitor is 18 A
- Peak inrush current without series resistors is 1200 A
- Peak inrush current with series resistors is only 260 A
- 1200 A is equal to 66 times the rated current
- Inrush current with series resistors is only one fifth of that of the standard contactor
- Substantial difference also in terms of power (integrated area)
- Superior switching behavior of contactor with series resistors compared with a standard contactor, results in extended life cycle of contactors as well as of capacitor
- Improved power quality ensures trouble-free and safe operation of PFC-system and application

6. 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. These include:

- 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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