FRAKO

MANUAL OF POWER QUALITY

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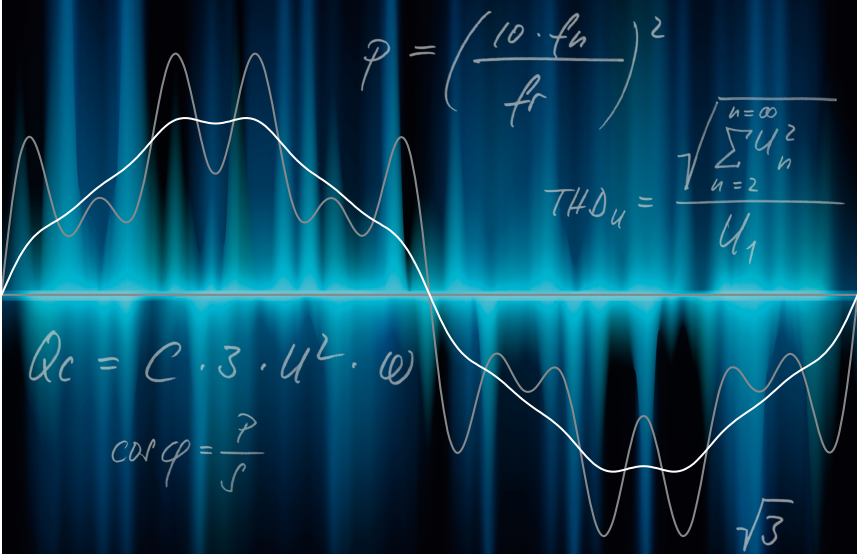

Information • Tables • Formulas

Everything to do with power factor correction and power quality for engineers and users

Cutting-edge technology for reliable power systems

At FRAKO our mission is to provide systems that are designed and optimized to meet the needs of our customers. We use our expertise and wealth of experience in development work and manufacturing to achieve this. The operational reliability of our products is as well known internationally as our track record in developing innovative solutions.

Every sphere, every activity and every operation of our company is hallmarked by quality. This bears fruit in FRAKO's renowned product quality as well as the quality of our advisory and field services. We value reliability, punctuality and transparency with the same commitment we have for product durability and performance. For this reason FRAKO is today a market leader worldwide in our business areas:

- High quality capacitors
- Individually specified power factor correction systems
- Efficient power quality instrumentation
- Intelligent energy management systems
- Dependable customer service before and after sales

Our customers and business partners know that FRAKO means quality, and that quality means safety and reliability. Because of this we can shoulder the responsibility for the performance, cost-effectiveness and environmental compatibility of our products and can guarantee their safety to life, limb and property. We are in a position to fulfil the most demanding requirements and develop innovative solutions to suit individual needs.

Our excellently trained and motivated employees have the technical competence and in-depth expertise to design and implement new installations successfully. We ourselves also take particular care to ensure that energy is used sparingly and efficiently in the manufacture and operation of our products. Our own energy consumption and the emissions generated are continuously monitored with our in-house energy management system to ensure that we achieve the highest levels of energy efficiency and environmental compatibility.

For the future we are committed to an ongoing and intensive effort to maintain our leading position and to justify the trust placed in us by our customers in the fields of power quality, energy cost minimization and energy efficiency.

The quality of our products and our expertise in their application are the basis for providing the best possible benefits to our customers. This manual describes the technical fundamentals, our manufacturing philosophy and our ongoing commitment for interested readers. It provides the basic knowledge needed to select, install and operate our power factor correction and power quality systems.

Teningen, January 2021

Dr. Matthias Sehmsdorf
Managing Director

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Section 1: Basic theory

Before venturing into the details in the design of power factor correction (PFC) systems, we would first like to present a brief refresher of basic alternating current circuit theory.

1.1: Active power

With a purely resistive load having no inductive or capacitive components, such as in an electric heater, the voltage and current curves intersect the zero coordinate at the same point (Fig. 1). The voltage and current are said to be 'in phase'. The power (P) curve is calculated from the product of the momentary values of voltage (V) and current (I). It has a frequency that is twice that of the voltage supply, and is entirely in the positive area of the graph, since the product of two negative numbers is positive, as, of course, is the product of two positive numbers.

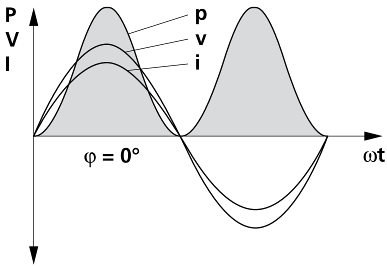


Fig. 1: Voltage, current and power for a purely resistive load (φ = 0°)

In In this case: $(-V) \cdot (-I) = (+P)$

Active or 'real' power is defined as that component of the power that is converted into another form (e.g. heat, light, mechanical power) and is registered by the meter. With a purely resistive (or 'ohmic') load it is calculated by multiplying the RMS* voltage [V] by the RMS current [I]:

$$\underset{[W]}{P} = \underset{[V]}{V} \cdot \underset{[A]}{I}$$

*RMS = root-mean-square

1.2: Active- and reactive power

In practice, however, it is unusual to find purely ohmic loads, since an inductive component is also present. This applies to all loads that make use of a magnetic field in order to function, e.g. induction motors, inductors and transformers. Power converters also require reactive current for commutation purposes. The current used to create and reverse the magnetic field is not dissipated but flows back and forth as reactive current between the generator and the load.

As Fig. 2 shows, the voltage and current curves no longer intersect the zero coordinate at the same points. A phase displacement has occurred. With inductive loads the current lags behind the voltage, while with capacitive loads the current leads the voltage. If the momentary values of power are now calculated with the formula $P = V \cdot I$, a negative product is obtained whenever one of the two factors is negative.

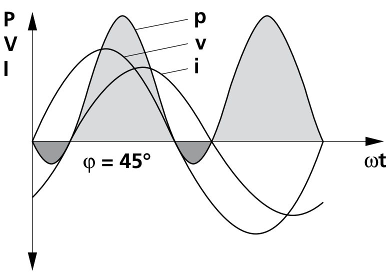


Fig. 2: Voltage, current and power for a resistive and an inductive load (φ = 45°)

In this example phase a displacement φ = 45° has been chosen. This corresponds to an inductive cos φ of 0.707. Part of the power curve can be seen to be in the negative area. The active power in this case is given by the formula:

$$\underset{[W]}{P} = \underset{[V]}{V} \cdot \underset{[A]}{I} \cdot \cos \varphi$$

1.3: Reactive power

Inductive reactive power occurs in motors and transformers when running under no-load conditions if the copper, iron and, where appropriate, frictional losses are ignored. With FRAKO power capacitors we can think in terms of virtually pure capacitive reactive power when these display extremely low losses (less than 0.05%).

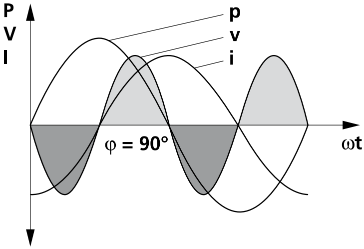


Fig. 3: Voltage, current and power for a purely reactive load (φ = 90°)

If the voltage and current curves are 90° out of phase, one half of the power curve lies in the positive area, with the other half in the negative area (Fig. 3). The active power is therefore zero, since the positive and negative areas cancel each other out. Reactive power is defined as the power that flows back and forth between the generator and the load at the same frequency as the supply voltage in order for the magnetic/electric field to build up and decay.

$$Q = V \cdot I \cdot \sin\varphi$$

[VAr] [V] [A]

1.4: Apparent power

Apparent power is critical for the rating of electric power networks. Generators, transformers, switchgear, fuses, circuit breakers and conductor cross sections must be adequately dimensioned for the apparent power that results in the system. The apparent power is the product obtained by multiplying the voltage by the current without taking into account the phase displacement.

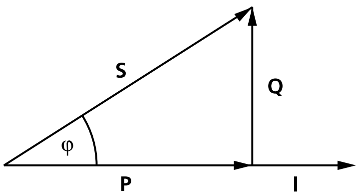


Fig. 4: Power diagram

$$S = V \cdot I$$

[VA] [V] [A]

The apparent power is also given by the Pythagorean addition of active power and reactive power:

$$S = \sqrt{P^2 + Q^2}$$

[VA] [W] [VAr]

1.5: Power factor (cos φ und tan φ)

The cosine (cos) of the angle φ of phase displacement ('phase angle') between current and voltage is a convenient parameter for calculating the active and apparent components of power, voltage and current. In electrical engineering practice, this parameter has come to be termed the 'power factor'.

The power factor at full load is normally given on the nameplates of electrical machines.

$$\cos\varphi = \frac{P}{S} \quad \text{[W]/[VA]}$$

The tangent (tan) of the phase angle φ is a convenient way of expressing the ratio of the reactive to the active power:

$$\tan\varphi = \frac{Q}{P} \quad \text{[VAr]/[W]}$$

These two equations show the relationship between the cosine and the tangent of the phase angle:

$$\cos\varphi = \sqrt{\frac{1}{1 + \tan\varphi^2}} \qquad \tan\varphi = \sqrt{\frac{1}{\cos\varphi^2} - 1}$$

As the power distribution system must be dimensioned to carry the apparent power, efforts are made to keep this as low as possible. If appropriately dimensioned capacitors are installed in parallel with the loads, the reactive current circulates back and forth between the capacitor and the loads. This means that the rest of the distribution network is not subjected to this additional current. If a power factor of 1 is achieved by this measure, the only current flowing in the distribution system is active current.

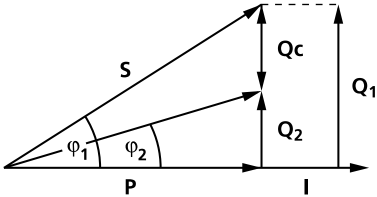


Fig. 5: Power triangle showing the effect of correction

The reactive power $\mathbf{Q_C}$ corrected by the capacitor is given by the difference between the inductive reactive power $\mathbf{Q_1}$ before correction and the reactive power $\mathbf{Q_2}$ after correction, i.e. $\mathbf{Q_C} = \mathbf{Q_1} - \mathbf{Q_2}$

$$Q_c = P \cdot (\tan \varphi_1 - \tan \varphi_2)$$

[VAr] [W]

1.6: Why correct the power factor?

The reactive current circulating between the utility company's generator and the consumer converts electrical energy into heat in the power distribution system, and there is an additional load on generators, transformers, cabling and switchgear. Energy losses and voltage drops are incurred. If there is a high proportion of reactive current, the installed conductor cross sections cannot be fully utilized for transmitting useful power, or must be correspondingly overdimensioned. From the standpoint of the utility company and supply network operator, a poor power factor increases the investment and maintenance costs for the power distribution system, and these additional costs are passed on to those responsible, i.e. those power consumers with poor power factors. A meter for reactive energy is therefore installed in addition to the one for active energy.

cos φ = 0.7

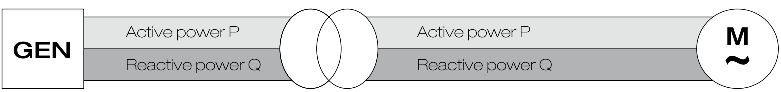
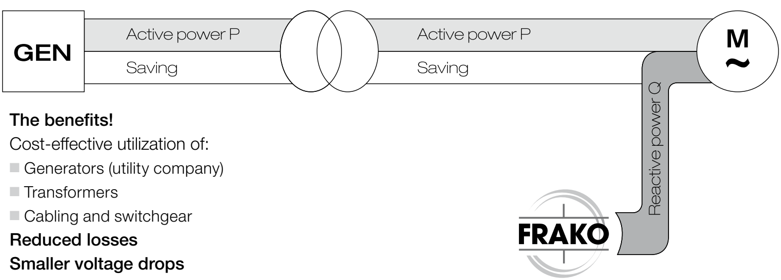


Fig. 6: Active and reactive power in the power distribution system: without PFC

cos φ = 1



The benefits!

Cost-effective utilization of:

- Generators (utility company)
- Transformers
- Cabling and switchgear

Reduced losses

Smaller voltage drops

hence:

Lower energy costs!

Fig. 7: Active and reactive power in the power distribution system: with PFC

Section 2: Power factor correction methods

2.1: Individual power factor correction

In the simplest case, an appropriately sized capacitor is installed in parallel with each individual inductive load. This completely eliminates the additional load on the cabling, including the cable feeding the compensated load. The disadvantage of this method, however, is that the capacitor is only utilized during the time that its associated load is in operation. Additionally, it is not always easy to install the capacitors directly adjacent to the machines that they compensate (space constraints, installation costs).

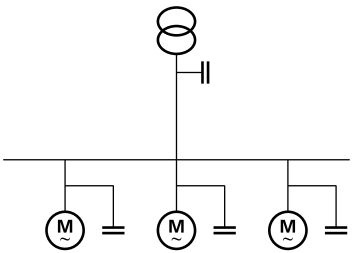


***Fig. 8**: Typical individual power factor correction*

Application:

- To compensate the no-load reactive power of transformers
- For drives in continuous operation
- For drives with long power supply cables or cables whose cross section allows no margin for error

Advantages:

- Reactive power is completely eliminated from the internal power distribution system
- Low costs per kVAr

Disadvantages:

- The PFC system is distributed throughout the entire facility
- High installation costs
- A larger overall corrective power is required as the coincidence factor cannot be taken into account

2.2: Group power factor correction

Electrical machines that are always switched on at the same time can be combined as a group and have a joint correction capacitor. An appropriately sized unit is therefore installed instead of several smaller individual capacitors.

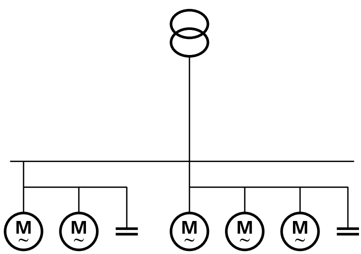


***Fig. 9**: Typical group power factor correction*

Application:

- For several inductive loads, provided that these are always operated together

Advantages:

- Similar to those for individual power factor correction, but more cost-effective

Disadvantages:

- Only for groups of loads that are always operated at the same time

2.3: Central power factor correction

The PFC capacitance is installed at a central point, for example at the main low voltage distribution board. This system covers the total reactive power demand. The capacitance is divided into several sections which are automatically switched in and out of service by automatic reactive power control relays and contactors to suit load conditions.

This method is used today in most instances. A centrally located PFC system is easy to monitor. Modern reactive power control relays enable the contactor status, cos φ, active and reactive currents and the harmonics present in the power distribution system to be monitored continuously. Usually the overall capacitance installed is less, since the coincidence factor for the entire industrial operation can be taken into account when designing the system. This installed capacitance is also better utilized. It does not, however, eliminate the reactive current circulating within the user's internal power distribution system, but if adequate conductor cross sections are installed, this need not be a disadvantage.

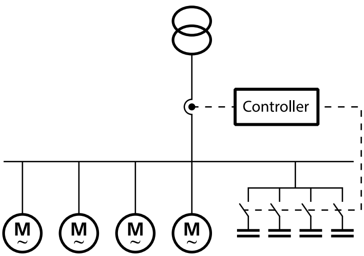


Fig. 10: Typical central power factor correction system

Application:

- Can always be used where the user's internal power distribution system is not underdimensioned

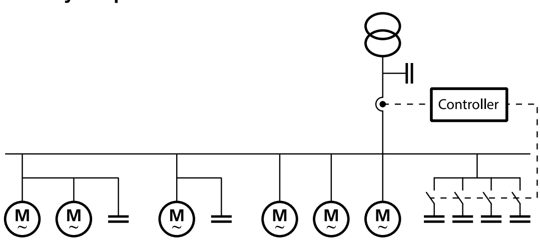
Advantages:

- Clear-cut, easy-to-monitor concept
- Good utilization of installed capacitance
- Installation usually relatively simple
- Less total installed capacitance, since the coincidence factor can be taken into account
- Less expensive for power distribution systems troubled by harmonics, as controlled units are simpler to detune

Disadvantages:

- Reactive currents within the user's internal power distribution system are not reduced
- Additional costs for the automatic control system

2.4: Hybrid power factor correction



Economic considerations often show that it is advantageous to combine the three methods described above.

Fig. 11: Typical hybrid power factor correction system

Section 3: Determination of required capacitance

3.1: Power tariffs

Utility companies as a rule have fixed tariffs for their smaller power consumers, while individual supply contracts are negotiated with the larger customers.

With most power supply contracts the costs for electrical power comprise:

- Power [kW], measured with a maximum demand meter, e.g. monthly or even annual maximum demand, as a rule over a 15 minute period.
- Active energy [kWh], measured with an active current meter usually split into regular and off-peak tariffs.
- Reactive energy [kVArh], measured with a reactive current meter, sometimes split into regular and off-peak tariffs.

It is normal practice to invoice the costs of reactive energy only when this exceeds 50% of the active energy drawn. This corresponds to a power factor cos φ = 0.9. It is not stipulated that the power factor must never dip below this value of 0.9. Invoicing is based on the power factor monthly average. Utility companies in some areas stipulate other power factors, e.g. 0.85 or 0.95.

With other tariffs the power is not invoiced as kW but as kVA, the costs for reactive energy therefore being included in the power price. To minimize operating costs in this case, a power factor cos φ = 1 must be aimed for. In general, it can be assumed that if a PFC system is correctly dimensioned, the entire costs for reactive energy can be saved.

3.2: Approximate estimates

Accurate methods for determining the required corrective power are given in a subsequent section. Often, however, it is desirable to estimate the approximate order of magnitude quickly. The situation may also occur where an engineer has performed an accurate calculation but is then not quite sure of the result, in case at some point a mistake has occurred in his or her reasoning. A rough estimate can then be used to verify that the results calculated are in the right order of magnitude.

Consumer	Capacitor corrective power
➛ Motors with individual PFC	➛ 35 – 40 % of motor rated power
➛ Transformers with individual PFC	➛ 2,5 % of transformer power rating ➛ 5 % for older transformers
➛ Central PFC	➛ 25 – 33 % of transformer power rating at target cos φ = 0.9 ➛ 40 – 50 % of transformer power rating at target cos φ = 1

***Table 1**: Approximate estimates for the required corrective power*

3.3: Listing the loads

When designing a new installation for a new plant or a section of a plant, it is practical to first make an approximate estimate of requirements. A more accurate picture is achieved by listing the loads to be installed, together with their electrical data, while taking into account the coincidence factor. In cases where a later extension may be considered, the PFC system should be designed and installed so that the extension will not involve great expenditure. The cabling and protected circuits to the PFC system should be dimensioned to cater for expansion, and space should be reserved for additional capacitor units.

3.4: Determination by measurements of current and power factor

Ammeters and power factor meters are often installed in the main low voltage distribution board, but clamp meters are equally effective for measuring current. Measurements are made in the main supply line (e.g. from the transformer) or in the line feeding the equipment whose power factor is to be corrected. Measuring the voltage in the power distribution system at the same time improves the accuracy of the calculation, or the rated voltage (e.g. 380 or 400 V) may simply be used instead.

The active power **P** is calculated from the measured voltage **V**, apparent current $\mathbf{I_S}$ and the power factor:

$$\underset{[kW]}{P} = \sqrt{3} \cdot \underset{[V]}{V} \cdot \underset{[A]}{I_S} \cdot \cos\varphi \cdot 10^{-3}$$

If the target power factor cos φ has been specified, the corrective power can be calculated from the following formula. It is, however, simpler to read off the factor „*f*" from Table 2 (on Seite 10) and multiply it by the calculated active power.

$$\underset{[VAr]}{Q_C} = \underset{[W]}{P} \cdot (\tan\varphi_{ist} - \tan\varphi_{soll})$$

or:

$$\underset{[VAr]}{Q_C} = \underset{[W]}{P} \cdot f$$

Example:

- Measured apparent current I_S: 248 A
- Measured power factor $\cos\varphi_{actual}$: 0.86
- Target $\cos\varphi_{target}$: 0.92
- Voltage V: 397 V

Calculation:

$$P = \sqrt{3} \cdot 397 \cdot 248 \cdot 0.86 \cdot 10^{-3}$$

$$P = 146.6\ kW$$

Read from Table 2:

Factor f = 0.17

Required corrective power:

$$Q_C = 146.6 \cdot 0.17 = \underline{24.9\ kVAr}$$

Note:

Measurements made as described above naturally only give momentary values. The load conditions can, however, vary considerably depending on the time of day and the season of the year. Measurements should therefore be made by someone who is familiar with the installation. Several measurements should be made, ensuring that the loads whose power factor is to be corrected are actually switched on. The measurements should also be made quickly - if possible reading all instruments simultaneously - so that any sudden change of load does not distort the results.

3.5: Determination by recording active and reactive power measurements

More reliable results are obtained with recording instruments, since variables can be recorded over a longer period of time, peak values also being included. The required corrective power is then calculated as follows:

Q_C: required corrective power
Q_L: measured reactive power
P: measured active power
tan φ_2: the value of tan φ corresponding to the target cos φ (can be obtained from Table 2, e.g. when cos φ = 0.92, the corresponding tan φ = 0.43)

$$\underset{[VAr]}{Q_C} = \underset{[VAr]}{Q_L} - (\underset{[W]}{P} \cdot \tan \varphi_2)$$

3.6: Determination by reading the meters

The active and reactive energy meters are read at the start of a shift. Eight hours later both meters are read again. If there has been a break in operation during this time, the eight hours must be extended by the duration of this break.

RM_1: reactive energy meter reading at start
RM_2: reactive energy meter reading at finish

AM_1: active energy meter reading at start
AM_2: active energy meter reading at finish

$$\frac{RM_2 - RM_1}{AM_2 - AM_1} = P \cdot \tan \varphi$$

Using this calculated value of tan φ and the target cos φ we can then obtain the factor ***f*** from Table 2. The required corrective power can then be calculated from the following equation, where ***k*** is the CT ratio of the current transformers for the meters:

$$Q_C = \frac{(AM_2 - AM_1) \cdot k}{8} \cdot f$$

Example:

The following meter readings have been obtained:

- Active energy meter: (AM_1) ... 115.3
  (AM_2) ... 124.6
- Reactive energy meter: (RM_1) ... 311.2
  (RM_2) ... 321.2
- Time between readings: 8 Stunden
- CT (current transformer) ratio k: 150/5 A (=30)

Calculation:

$$\tan \varphi = \frac{321.2 - 311.2}{124.6 - 115.3} = 1.08$$

For a target cos φ of 0.92,
Table 2 gives a Factor f 0.65.
The required corrective power is thus:

$$Q_C = \frac{(124.6 - 115.3) \cdot 30}{8} \cdot 0.65 = \underline{22.7\ kVAr}$$

Table 2: *Factor f* ($f = \tan \varphi_{actual} - \tan \varphi_{target}$)

Uncorrected	Target cos φ				← inductive (i)			capacitive (c) →			
tan φ ↔ cos φ	**0.80i**	**0.85i**	**0.90i**	**0.92i**	**0.95i**	**0.98i**	**1.00**	**0.98c**	**0.95c**	**0.92c**	**0.90c**
3.18 ↔ **0.30**	2.43	2.56	2.70	2.75	2.85	2.98	3.18	3.38	3.51	3.61	3.66
2.96 ↔ **0.32**	2.21	2.34	2.48	2.53	2.63	2.76	2.96	3.16	3.29	3.39	3.45
2.77 ↔ **0.34**	2.02	2.15	2.28	2.34	2.44	2.56	2.77	2.97	3.09	3.19	3.25
2.59 ↔ **0.36**	1.84	1.97	2.11	2.17	2.26	2.39	2.59	2.79	2.92	3.02	3.08
2.43 ↔ **0.38**	1.68	1.81	1.95	2.01	2.11	2.23	2.43	2.64	2.76	2.86	2.92
2.29 ↔ **0.40**	1.54	1.67	1.81	1.87	1.96	2.09	2.29	2.49	2.62	2.72	2.78
2.16 ↔ **0.42**	1.41	1.54	1.68	1.73	1.83	1.96	2.16	2.36	2.49	2.59	2.65
2.04 ↔ **0.44**	1.29	1.42	1.56	1.61	1.71	1.84	2.04	2.24	2.37	2.47	2.53
1.93 ↔ **0.46**	1.18	1.31	1.45	1.50	1.60	1.73	1.93	2.13	2.26	2.36	2.41
1.83 ↔ **0.48**	1.08	1.21	1.34	1.40	1.50	1.62	1.83	2.03	2.16	2.25	2.31
1.73 ↔ **0.50**	0.98	1.11	1.25	1.31	1.40	1.53	1.73	1.94	2.06	2.16	2.22
1.64 ↔ **0.52**	0.89	1.02	1.16	1.22	1.31	1.44	1.64	1.85	1.97	2.07	2.13
1.56 ↔ **0.54**	0.81	0.94	1.07	1.13	1.23	1.36	1.56	1.76	1.89	1.98	2.04
1.48 ↔ **0.56**	0.73	0.86	1.00	1.05	1.15	1.28	1.48	1.68	1.81	1.91	1.96
1.40 ↔ **0.58**	0.65	0.78	0.92	0.98	1.08	1.20	1.40	1.61	1.73	1.83	1.89
1.33 ↔ **0.60**	0.58	0.71	0.85	0.91	1.00	1.13	1.33	1.54	1.66	1.76	1.82
1.27 ↔ **0.62**	0.52	0.65	0.78	0.84	0.94	1.06	**1.27**	1.47	1.59	1.69	1.75
1.20 ↔ **0.64**	0.45	0.58	0.72	0.77	0.87	1.00	1.20	1.40	1.53	1.63	1.68
1.14 ↔ **0.66**	0.39	0.52	0.65	0.71	0.81	0.94	1.14	1.34	1.47	1.56	1.62
1.08 ↔ **0.68**	0.33	0.46	0.59	**0.65**	0.75	0.88	1.08	1.28	1.41	1.50	1.56
1.02 ↔ **0.70**	0.27	0.40	0.54	0.59	0.69	0.82	1.02	1.22	1.35	1.45	1.50
0.99 ↔ **0.71**	0.24	0.37	0.51	0.57	0.66	0.79	0.99	1.19	1.32	1.42	1.48
0.96 ↔ **0.72**	0.21	0.34	0.48	0.54	0.64	0.76	0.96	1.17	1.29	1.39	1.45
0.94 ↔ **0.73**	0.19	0.32	0.45	0.51	0.61	0.73	0.94	1.14	1.26	1.36	1.42
0.91 ↔ **0.74**	0.16	0.29	0.42	0.48	0.58	0.71	0.91	1.11	1.24	1.33	1.39
0.88 ↔ **0.75**	0.13	0.26	0.40	0.46	0.55	0.68	0.88	1.08	1.21	1.31	1.37
0.86 ↔ **0.76**	0.11	0.24	0.37	0.43	0.53	0.65	0.86	1.06	1.18	1.28	1.34
0.83 ↔ **0.77**	0.08	0.21	0.34	0.40	0.50	0.63	0.83	1.03	1.16	1.25	1.31
0.80 ↔ **0.78**	0.05	0.18	0.32	0.38	0.47	0.60	0.80	1.01	1.13	1.23	1.29
0.78 ↔ **0.79**	0.03	0.16	0.29	0.35	0.45	0.57	0.78	0.98	1.10	1.20	1.26
0.75 ↔ **0.80**	-	0.13	0.27	0.32	0.42	0.55	0.75	0.95	1.08	1.18	1.23
0.72 ↔ **0.81**	-	0.10	0.24	0.30	0.40	0.52	0.72	0.93	1.05	1.15	1.21
0.70 ↔ **0.82**	-	0.08	0.21	0.27	0.37	0.49	0.70	0.90	1.03	1.12	1.18
0.67 ↔ **0.83**	-	0.05	0.19	0.25	0.34	0.47	0.67	0.88	1.00	1.10	1.16
0.65 ↔ **0.84**	-	0.03	0.16	0.22	0.32	0.44	0.65	0.85	0.97	1.07	1.13
0.62 ↔ **0.85**	-	-	0.14	0.19	0.29	0.42	0.62	0.82	0.95	1.05	1.10
0.59 ↔ **0.86**	-	-	0.11	**0.17**	0.26	0.39	0.59	0.80	0.92	1.02	1.08
0.57 ↔ **0.87**	-	-	0.08	0.14	0.24	0.36	0.57	0.77	0.90	0.99	1.05
0.54 ↔ **0.88**	-	-	0.06	0.11	0.21	0.34	0.54	0.74	0.87	0.97	1.02
0.51 ↔ **0.89**	-	-	0.03	0.09	0.18	0.31	0.51	0.72	0.84	0.94	1.00
0.48 ↔ **0.90**	-	-	-	0.06	0.16	0.28	0.48	0.69	0.81	0.91	0.97
0.46 ↔ **0.91**	-	-	-	0.03	0.13	0.25	0.46	0.66	0.78	0.88	0.94
0.43 ↔ **0.92**	-	-	-	-	0.10	0.22	0.43	0.63	0.75	0.85	0.91
0.40 ↔ **0.93**	-	-	-	-	0.07	0.19	0.40	0.60	0.72	0.82	0.88
0.36 ↔ **0.94**	-	-	-	-	0.03	0.16	0.36	0.57	0.69	0.79	0.85
0.33 ↔ **0.95**	-	-	-	-	-	0.13	0.33	0.53	0.66	0.75	0.81
0.29 ↔ **0.96**	-	-	-	-	-	0.09	0.29	0.49	0.62	0.72	0.78
0.25 ↔ **0.97**	-	-	-	-	-	0.05	0.25	0.45	0.58	0.68	0.73
0.20 ↔ **0.98**	-	-	-	-	-	-	0.20	0.41	0.53	0.63	0.69
0.14 ↔ **0.99**	-	-	-	-	-	-	0.14	0.35	0.47	0.57	0.63
0.00 ↔ **1.00**	-	-	-	-	-	-	-	0.20	0.33	0.43	0.48

3.7: Determination from the utility company's invoice

The required corrective power can be determined relatively easily and accurately from the power supply company's monthly invoice. If power consumption is constant throughout the year, the annual electricity consumption, or any desired monthly invoice (but not for the month in which the annual shutdown occurs), may be taken as a basis. If seasonal variations are apparent, an invoice from the 'high season' must of course be selected. If regular and off-peak tariffs are measured separately, the regular tariffs are usually used for calculation purposes. It can be assumed that the corrective power thus derived will be adequate to cover the reactive current flowing at off-peak times. In special cases, however, where the less expensive off-peak power is used predominantly, the off-peak consumption may not be neglected.

3.7.1: Kilowatt-hour tariff

With the kilowatt-hour tariff, **maximum potential demand, active energy** and **reactive energy** are invoiced as separate items. With most power supply contracts, no charge is made for reactive energy if its magnitude is up to 50% of the active energy. Only amounts that exceed this figure must be paid for. This corresponds approximately to a cos φ of 0.9. It is recommended, however, to use a slightly higher figure, e.g. 0.92, for calculation purposes, in order to have a small margin of reserve in the corrective power available.

Specimen calculation using figures from the utility company's invoice:

- Active power: 99 kW
- Active energy (regular tariff): 17,820 kWh
- Reactive energy (regular tariff): 19,245 kVArh

$$\tan\varphi = \frac{\text{Reactive energy}}{\text{Active energy}} = \frac{19{,}245\ \text{kVArh}}{17{,}820\ \text{kWh}} = 1.08$$

The actual value of cos φ can now be obtained from Table 2, since the calculated tan φ of 1.08 corresponds to a cos φ actual of 0.68. For a target cos φ of 0.92 a factor f = **0.65** is now obtained from Table 2.

The required corrective power is then calculated, i.e. active power x factor f:

$$99\ \text{kW} \cdot 0.65 = 64.35\ \text{kVAr}$$

In this case a capacitor rating of 75 kVAr must be selected. If a possible future expansion of the facility is also to be taken into account, then a somewhat larger capacitance (e.g. 100 kVAr) could be selected.

3.7.2: Demand tariff

With this tariff the utility company bases its invoice on the maximum amount of power drawn by the user during the given month. As it is not the active power but the apparent power that is measured for this purpose, it is advisable to select a corrective power that will achieve a cos φ of 1.

Specimen calculation using figures from the utility company's invoice:

- Maximum active power: 104 kW
- Power factor cos φ_{actual}: 0.62

$$\frac{\text{Maximum active power}}{\cos\varphi} = \frac{104\ \text{kW}}{0.62} = 168\ \text{kVA}$$

From Table 2, with an uncorrected cos φ_{actual} = 0.62 and a target cos φ_{target} = 1, a factor f of **1.27** is read off. The required corrective power is then calculated:

active power x factor f

$$104\ \text{kW} \cdot 1{,}27 = 132{,}08\ \text{kVAr}$$

For this duty a power factor correction system with a corrective power of 150 to 175 kVAr arranged in finely adjustable stages is suitable.

Section 4: Applications

4.1: Power factor correction for discharge lamps

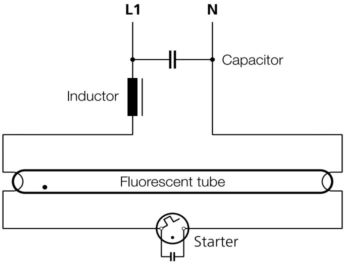


Fig. 12: Individual correction with the capacitor in parallel with the lamp (shunt capacitor with 230 V rating)

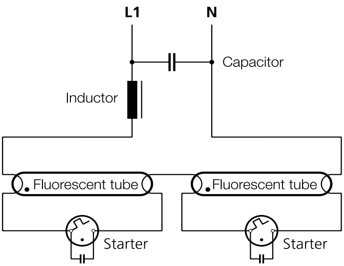


Fig. 13: Two lamps connected in tandem with the capacitor in parallel with them (shunt capacitor with 230 V rating)

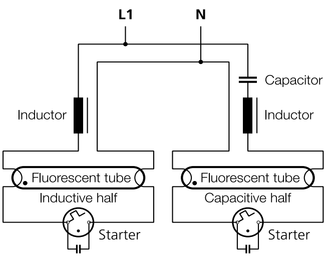


Fig. 14: Dual (lead-lag) circuit with the capacitor in series with one lamp, (series capacitor with 450 V rating)

Discharge lamps must be operated with a ballast to limit the current flowing through them. High-reactance transformers are used mainly for low pressure sodium vapour lamps, while all other discharge lamps are fitted with inductors as ballast. This inductive reactance results in a power factor cos φ of about 0.5 with inductors and about 0.3 with high-reactance transformers.

Single-phase capacitors can be connected in parallel or in series to correct the reduced power factor caused by inductive ballast.

In a single-lamp circuit and a series circuit with two lamps in tandem the capacitor is connected in parallel with the lamp(s). The capacitor voltage rating of 230 V is the same as the supply voltage.

Note: Capacitors arranged in parallel with the power supply form together with the network impedance an oscillating circuit. This can amplify any harmonics that are present and cause interference in audiofrequency remote control systems (described separately on page 42).
The so-called lead-lag circuit is particularly cost-effective and needs only one capacitor for two lamps. One lamp circuit remains purely inductive while the second ballast is in series with a capacitor. This capacitor must be designed for a higher rated voltage (450 V), since its being in series with the inductor increases the voltage across it. Disturbances due to resonance, such as experienced with capacitors arranged in parallel, do not occur. In addition, the ripple effect of the two individual lamps is improved, thus reducing the risk of a dangerous stroboscopic effect on rotating machinery. This is why many power supply companies stipulate that users arrange the capacitor and ballast in series, and this method is generally recommended.

Electronic ballasts for fluorescent lamps or **power supply** units for LED lamps **do not require power factor correction.** However, their nonlinear current draw, especially when a large number of lamps are installed, means that increased levels of harmonics must be expected (see the section on power quality, from page 32 onwards).

4.1.1: Selection table for discharge lamps

This table indicates the capacitors suitable for the various types of lamps.

Note: In the case of low-loss ballasts, smaller capacitors than specified in the table are arranged in series. The recommended capacitance can vary from one lamp manufacturer to the next, but the capacitance stated on the inductor is always definitive.

These are the commonest capacitors used in series with low-loss ballasts:

- 18 W 2.7 µF / 480 V
- 36 W 3.4 µF / 450 V 3.5 µF / 450 V
- 58 W 5.3 µF / 450 V 5.4 µF / 450 V

Lamp rating in W	Shunt capacitor capacitance in µF	Series capacitor capacitance in µF
Fluorescent lamps		
4 to 16	2.0 / 230 V	-
18 to 20	4.5 / 230 V	2.9 / 450 V
36 to 40	4.5 / 230 V	3.6 / 450 V
58 to 65	7.0 / 230 V	5.7 / 450 V
Metal-halide lamps		
35	6.0 / 230 V	-
70	12.0 / 230 V	-
150	20.0 / 230 V	-
250	32.0 / 230 V	-
400	35.0 / 230 V	-
1000	85.0 / 230 V	-
2000	60.0 / 380 V	-
3500	100.0 / 380 V	-

Lamp rating in W	Shunt capacitor capacitance in µF
High pressure mercury lamps	
50	7.0 / 230 V
80	8.0 / 230 V
125	10.0 / 230 V
250	18.0 / 230 V
400	25.0 / 230 V
700	40.0 / 230 V
1000	60.0 / 380 V
Low pressure sodium lamps	
18	5.0 / 230 V
35	20.0 / 230 V
55	20.0 / 230 V
90	25.0 / 230 V
135	45.0 / 230 V
150	20.0 / 230 V
180	40.0 / 230 V
High pressure sodium lamps	
50	8.0 / 230 V
70	12.0 / 230 V
100	12.0 / 230 V
150	20.0 / 230 V
250	32.0 / 230 V
400	50.0 / 230 V
1000	100.0 / 230 V

4.1.2: Group power factor correction for discharge lamps

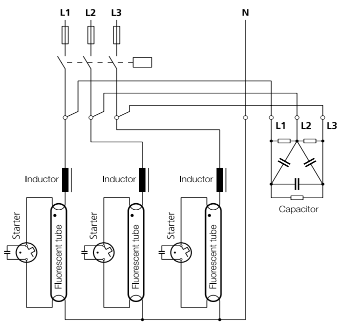


Fig. 15: Group correction for discharge lamps distributed between the three phases (e.g. with type LKT power capacitor)

If several discharge lamps are switched on and off together and they are arranged symmetrically, a common 3-phase capacitor assembly with a rated voltage of 440 V can be used.

Corrective power:

$$Q_C = n \cdot C \cdot 0.015$$

- Q_C: Corrective power in kVAr
- n: Number of lamps, distributed between the three phases
- C: Shunt capacitance per lamp in µF

Example: 24 fluorescent lamps each rated at 58 W

$$24 \cdot 7\ \mu F \cdot 0.015 = 2.52\ kVAr$$

■ 4.2: Individual power factor correction for transformers

The utility company regulations for the allowable size of capacitors permanently connected to a transformer vary according to region. Before installing a PFC system of this type, it is therefore advisable to consult the utility company concerned. The modern design of transformer features core laminations that only require a small amount of power for reversal of magnetization. If the corrective power is too high, overvoltage conditions may occur during no-load operation.

Capacitors with built-in fuse switch-disconnectors are well suited for this duty. If capacitors with fuse switch-disconnectors are connected directly to the transformer terminals, the designer should be aware of the fact that the lines to the capacitor must be dimensioned for the full short-circuit power.

Transformer rated power [in kVA]	**Corrective power** [in kVAr]
100 – 160	2.5
200 – 250	5.0
315 – 400	7.5
500 – 630	12.5
800	15.0
1000	20.0
1250	25.0
1600	35.0
2000	40.0

Table 3: *Approximate corrective power requirements for the individual power factor correction of transformers as specified by the German Association of Energy and Water Industries (BDEW)*

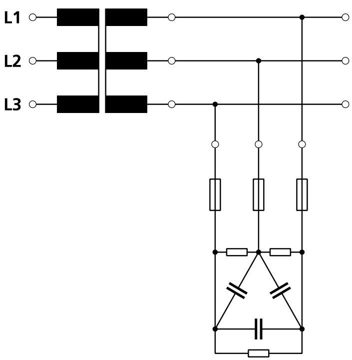


Fig. 16: *Typical transformer with permanent power factor correction*

The capacitor with a fuse switch-disconnector can be directly connected to the terminals of the transformer. This means that the lines to the capacitor must be dimensioned for the full short-circuit power.

Note: These fuse switch-disconnectors are operated under purely capacitive load. They must therefore never be withdrawn when under load or dangerous arcing may otherwise occur!

If it is desired to disconnect the capacitor even when the transformer is switched on, a power capacitor with an automatic circuit breaker must be used.

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4.3: Individual power factor correction for motors

The corrective power should be some 90% of the motor apparent power under no-load conditions.

Required corrective power:

$$\underset{[\mathrm{kVAr}]}{Q_C} = 0.9 \cdot \sqrt{3} \cdot \underset{[\mathrm{V}]}{V} \cdot \underset{[\mathrm{A}]}{I_0}$$

I_0 = No-load motor current

This achieves a power factor of about 0.9 under full load and 0.95 - 0.98 under no-load conditions. The German Association of Energy and Water Industries (BDEW) recommends the approximate capacitor ratings in Table 4 below for induction motors running at 1500 min^{-1}. The values given in the table should be increased by 5% for motors running at 1000 min^{-1}, or by 15% for motors running at 750min^{-1}.

Motor rated power [in kW]	**Corrective power** [in kVAr]
1 to 1.9	0.5
2 to 2.9	1.0
3 to 3.9	1.5
4 to 4.9	2.0
5 to 5.9	2.5
6 to 7.9	3.0
8 to 10.9	4.0
11 to 13.9	5.0
14 to 17.9	6.0
18 to 21.9	7.5
22 to 29.9	10.0
30 to 39.9	approx. 40% of motor power
40 or over	approx. 35% of motor power

Table 4: *Approximate values specified by the BDEW for individual power factor correction of motors*

Note: In the case of electrical machines with individual power factor correction, where the capacitor is directly connected to the motor terminals, the corrective power must on no account be overdimensioned. This applies in particular if the motor has a high centrifugal mass with the tendency to run on after it is switched off. The shunt capacitor can then excite the machine to act as a generator, producing dangerous overvoltages. These can cause damage not only to the capacitor but also to the motor.

In the simplest case, the capacitor is directly connected to the motor terminals. There is no need to provide special overcurrent protection for the capacitor, because the protection of the motor also covers the capacitor. If a motor protective switch is installed, it is advisable to readjust the current trip setting to a lower value.

Note: Variable-frequency drives require little or no reactive power, depending on the technology employed. As no sinusoidal power is drawn from the supply by these electronic devices, they give rise to considerable harmonic currents, which are fed back into the supply system (see the section on power quality, from page 32).

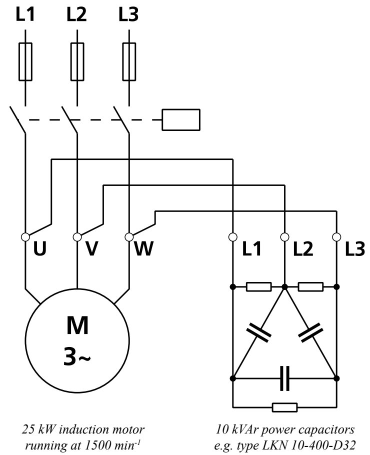


***Fig. 17**: Typical permanently installed power factor correction for a motor*

Reduced trip current:

$$I_{th} = \frac{\cos \varphi_1}{\cos \varphi_2} \cdot I_n$$

where

- I_{th}: new current trip setting [in A]
- I_n: motor rated current as per nameplate [in A]
- $\cos \varphi_1$: $\cos \varphi$ as per nameplate
- $\cos \varphi_2$: $\cos \varphi$ with PFC (approx. 0.95)

The 3-phase capacitor discharges directly through the low ohmic resistance of the motor windings. Discharge resistors are therefore not absolutely necessary.

4.3.1: Individual power factor correction for elevator and hoist motors

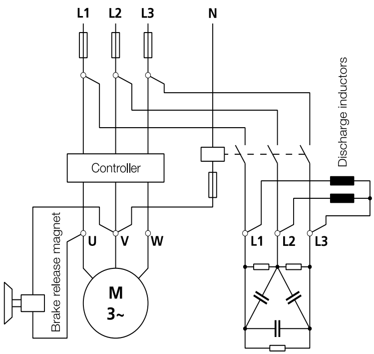


***Fig. 18**: Elevator motor with its own capacitor switching contactor and rapid discharge device*

Elevator and hoist motors work with safety devices, such as the brake release magnet, which actuates a quick-acting brake if power failure occurs.

If the 3-phase capacitor were directly in parallel with the motor, its residual energy could delay this emergency braking or even prevent it from being effective. The capacitor must therefore only be connected to the circuit **before** the switchgear!

A separate contactor should be provided for the capacitor, which should have its own rapid discharge device, realized either by discharge inductors connected directly to the capacitor or by rapid discharge resistors switched in by the capacitor contactor.

An interlock must be incorporated in the control system to prevent the capacitors being switched in again before the discharge time has expired. Because of the frequency of switching and the resultant wear and tear of the contactors, it is advisable to use capacitor stages with solid-state switches. These switch the capacitors in and out at zero current, response times in the order of milliseconds being attainable.

4.3.2: Star-delta switches

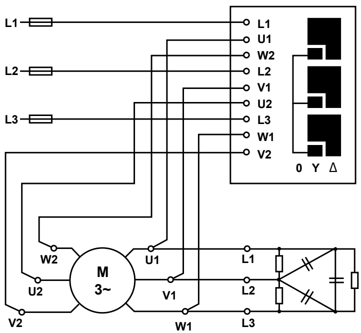


Fig. 19: Manually operated star-delta switch: special version for motors with individual power factor correction

If manually operated star-delta switches are to be used with three-phase power capacitors, a version designed to control motors with individual power factor correction must be selected.

The contact bridges must be designed so that, while switching from star to delta, **no** short interruption occurs to switch the capacitor into 'phase opposition'.

This would involve excessively high recharging currents, which could damage not only the capacitor but also the switch.

When the switch is in the OFF position (motor switched off), the star contact bridge must not be closed, so that the capacitor is not short-circuited.

4.3.3: Star-delta contactor groups

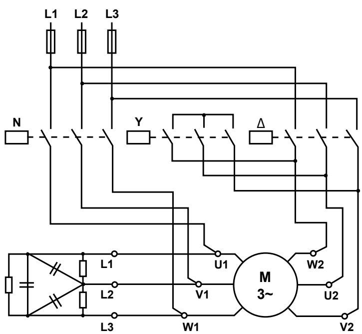


Fig. 20: Motor with individual power factor correction and star-delta contactor

With star-delta contactor groups it must be ensured, just as with star-delta switches, that no short interruption occurs during the changeover from star to delta, i.e. the line contactor must remain energized. When the motor is switched off, the star contact bridge must be open. The capacitor can be connected to the load side of the line contactor or to the terminals U, V and W of the motor, not however to its terminals X, Y and Z, since these are short-circuited by the star contact bridge.

Note: The corrective power must on no account be overdimensioned. This applies in particular if the motor has a high centrifugal mass with the tendency to run on after it is switched off. The shunt capacitor can then excite the machine to act as a generator, producing dangerous overvoltages. For this reason when star-delta starting is used, the star contact bridge should not remain closed when the switch is OFF. If the machine is excited as a generator with the star connection made, even higher voltages than those with the delta connection are to be expected.

4.4: Power factor correction systems

PFC systems consist of the following components:

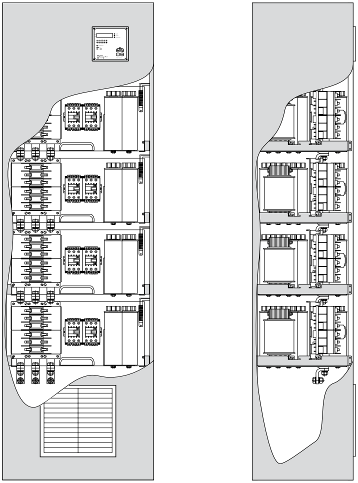


__Fig. 21__: Typical modular design of a PFC system

- Reactive power control relay
- Banks of capacitors switched in and out by contactors or solid-state switches
- Filter reactors (inductors), if detuning required
- Group overcurrent protection
- Thermostatically controlled ventilation system, if detuning installed

The components can either be assembled on a mounting plate or, if a modular system capable of being extended at a later date is called for, in a control cabinet.

PFC systems are installed in power distribution networks where the reactive power demand fluctuates constantly. The capacitor corrective power is divided into several stages that can be switched in and out by an automatic reactive power control relay via contactors or steady-state switches to suit load conditions.

A centralized PFC system is easy to monitor. State-of-the-art reactive power control relays enable switch status, cos φ, active current, reactive current and the harmonics present in the system to be monitored continuously. Usually the total capacitor power rating can be less than with individual power factor correction since the coincidence factor can be taken into account when designing the complete industrial facility. Optimum use is thus made of the installed capacitor corrective power.

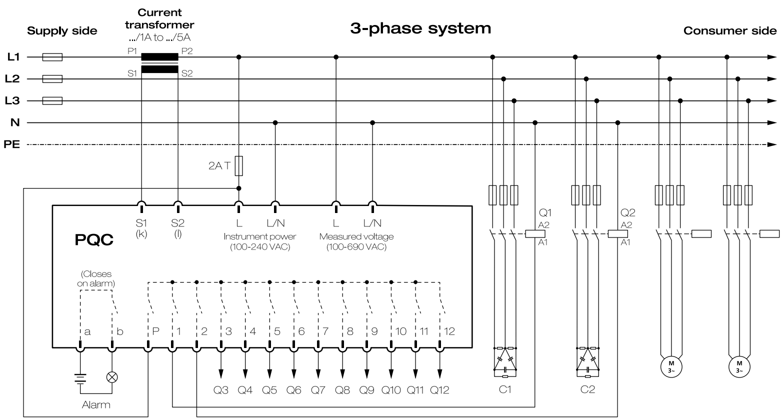


__Fig. 22__: Typical circuit diagram for a power factor correction system

Section 5: Product features

5.1: Power capacitors

Manufactured in Germany in our own factory, **FRAKO** power capacitors are the optimum core components for made-to-order fixed capacitor banks and automatic power factor correction systems. The fourfold safety features in their design maximize safety and reliability. Worldwide, our power capacitors are the first choice whenever reactive power demand is to be reduced, system power quality improved and charges for reactive energy avoided.

Key benefits of our power capacitors:

- High overload capability
- Long service life
- Maximum safety and dependability

In addition, the patented contact ring design has enabled FRAKO to manufacture a lead-free capacitor, yet another contribution to improved reliability. FRAKO power capacitors are available in 4 versions, Basic, Standard, Premium and Heavy Duty, to give you the ideal capacitor to meet your specifications for current-carrying capacity, ambient temperature and service life.

Every FRAKO power capacitor is uniquely identified by its individual serial number, which incorporates data relevant to its manufacture and links it to the test and measurement results from the quality assurance inspection.

Four safety design features ensure uninterrupted operation

The reliability of power capacitors is crucially important for the problem-free operation of power factor correction systems and passive filters. FRAKO's measures taken to ensure this are fourfold:

- **Safety factor 1:**
  Self-healing polypropylene film

  Its self-healing property ensures that the dielectric film automatically isolates any puncturing that may occur.

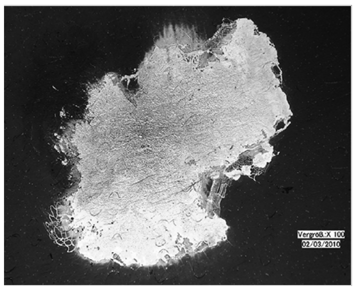


Fig. 23: Self-healing polypropylene film

- **Safety factor 2:**
  Solder-free connections

  The innovative contact ring patented by FRAKO totally eliminates the potential risk of damaging the winding as in conventional capacitor designs. In addition, the winding is spot-welded to the internal wiring, creating a permanent connection, vital for the action of the mechanical fuse that protects against excessive internal pressure (see safety factor 3).

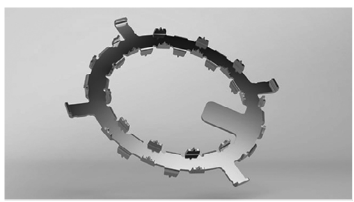


Fig. 24: Patented contact ring

- **Safety factor 3:**
  Mechanical fuse against excessive pressure

  The mechanical fuse disconnects the capacitor safely and without disruption to the power supply if excessive internal pressure develops due to overloading or at the end of its service life.

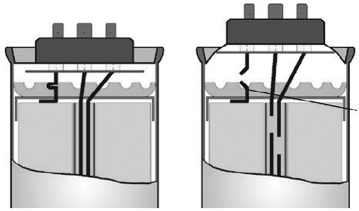


Fig. 25: Mechanical fuse action under excess pressure

- **Safety factor 4:**
  Segmented metallization

  The segmented film is a valuable supplement to the self-healing property and the mechanical fuse. If several punctures occur in a greater area of metallized film, the amount of energy involved could be too much for the self-healing action alone to cope with. In this case, the segmented film provides an EXTRA fail-safe function, since the severely overloaded segment is completely isolated from the power supply.

Fig. 26: Segmented metallization

Special technical features

In our ongoing development work on FRAKO power capacitors, we always focus on those attributes that are called for in present-day applications. The three following requirements are particularly important:

- Overvoltage tolerance
- Current-carrying capacity
- Thermal endurance

Overvoltage tolerance

As required by the standards IEC 60831-1 & -2, also by EN 60831-1 & -2, all FRAKO power capacitors are designed to withstand the following overvoltages.

- 8 hours daily: 1.10 x capacitor nominal voltage
- 30 minutes daily: 1.15 x capacitor nominal voltage
- 5 minutes: 1.20 x capacitor nominal voltage
- 1 minute: 1.30 x capacitor nominal voltage

The following table shows a selection of nominal voltage ratings and maximum overvoltages.

Capacitor nominal voltage	240 V	400 V	440 V	480 V	525 V	600 V	690V	760V	800V
8 hours daily	264 V	440 V	484 V	528 V	578 V	660 V	759 V	836 V	880 V
30 minutes daily	276 V	460 V	506 V	552 V	604 V	690 V	794 V	874 V	920 V
5 minutes	288 V	480 V	528 V	576 V	630 V	720 V	828 V	912 V	960 V
1 minute	312 V	520 V	572 V	624 V	683 V	780 V	897 V	988 V	1040 V

Current-carrying capacity

All over the modern world, harmonics are polluting electricity supply systems. The increasing use of devices such as frequency converters has a growing impact on capacitors. If these are operated in a power supply system contaminated by harmonics, dangerous resonances can result, which in turn significantly increase the currents that the capacitors must withstand.

The applicable standards call for a continuous current-carrying capacity of at least 1.3 times the nominal current to be catered for in power capacitors. In reality, however, even this value can be exceeded under conditions with extreme levels of harmonics. For this reason, all FRAKO power capacitors are designed for a continuous current-carrying capacity from at least 1.5 times up to 2.7 times the nominal current, depending on the capacitor version.

Thermal endurance

Excessive temperatures also have a negative impact on the service life of a capacitor. Storage or operation of capacitors above their permitted temperature limits results in a drastic shortening of their service life. Power capacitors are assigned to different temperature classes according to the permitted maximum ambient temperature as follows:

Temperature classes	Maximum ambient temperatures		
	Absolute maximum temperature	Average over 1 day	Average over 1 year
B	45 °C	35 °C	25 °C
C	50 °C	40 °C	30 °C
D	55 °C	45 °C	35 °C

The temperatures stated above refer to the direct environment of the capacitors. This means the internal temperature in the enclosure or control cabinet that houses them. Experience shows that the limits given in the table for the temperature classes can easily be exceeded in practice. Higher temperatures are to be expected in particular in the case of power factor correction systems fitted with filter reactors.

FRAKO power capacitors in the Standard, Premium and Heavy Duty versions are therefore designed for continuous ambient temperatures of at least 60 °C.

This continuously rated thermal endurance is helped by the compact construction of the capacitors, which is conducive to optimum heat dissipation.

Maintenance-free capacitor connector

The AKD connector is based on the tried-and-tested WAGO CAGE CLAMP®. These use a special spring clamp design that ensures a simple, vibration-resistant and maintenance-free electrical contact with the capacitor. They can be used to connect single-core, stranded or fine-filament copper cables. AKD connectors meet IP20 (EN 60529) requirements and therefore provide protection against objects such as fingers inadvertently touching live conductors.

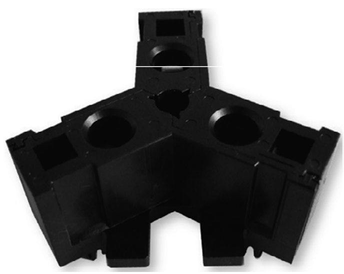


***Fig. 27**: Patented capacitor connector block*

5.2: Reactive power control relays

Fig. 28: *PQC Power Quality Controller*

- FRAKO reactive power control relays are intelligent instruments programmed to adjust themselves to suit the power factor correction system and the power supply system to be corrected, thus automatically avoiding faulty configuration.
- Incorrect connections or wrongly located instrument transformers are automatically identified and displayed, thus making time-consuming, labour-intensive troubleshooting unnecessary.
- Universal control characteristic curves offer power factor correction strategies for every conceivable requirement in all 4 control quadrants. In addition to forestalling the costs of reactive energy, these instruments provide other benefits, such as:
  - Reducing losses in the consumer's installation and the power supply system
  - Increasing the output of power generation facilities
  - Minimizing wear of the electrical equipment.

The intelligent operating principle ensures that the target power factor is achieved and maintained with as few switching cycles as possible. This minimizes wear of the power factor correction system and reduces supply-side distortion. Some versions of these instruments protect the correction system from excessively high harmonic levels by shutting it down. The user-friendly operation of the instruments is also highly valued by our customers.

Reactive power control relay with power quality monitoring

The PQC Power Quality Controller adds powerful new functionality to the proven strengths of FRAKO reactive power control relays to meet the challenges posed by state-of-the-art power quality systems.

With its built-in microprocessor, the PQC handles tasks over and above classical power factor correction. In particular, new protective mechanisms have been incorporated to safeguard not only the installation itself but also the system that corrects its power factor. The PQC thus monitors the relevant variables that can cause disruptions in the network, and gives alarms if they go beyond the limits set to ensure compliance with technical standards. In addition, the PQC also protects the power factor correction system responsible for the network, shutting it down if it becomes overloaded. This significantly reduces the risk of upsets occurring within that system. Defective or partially defective capacitor stages are identified and withdrawn from the power factor correction process. An extremely flexible alarm management function ensures that alarm notifications appropriate to the event are sent to where they are needed. The ability to configure each individual controller enables the PQC to be used anywhere, making it the best possible instrument for controlling power quality in contemporary industrial supply systems.

The PQC is characterized by user-friendly features such as simple installation, intuitive operation and the automatic start-up already well known from FRAKO reactive power control relays. Its integrated self-monitoring function improves long-term operational reliability, thus helping to reduce costs and minimize the risk of system disruptions.

Key features

- Single or 3-phase measurements
- 4-quadrant control
- 6 or 12 control outputs + 1 alarm contact
- 5 configurable control characteristic curves
- Plain language menu (German, English or French) with graphical user dialogue
- Integrated monitoring of system variables with data processing in alarm management

Recommended applications

The PQC is suitable for 4-quadrant power factor correction in:

- Consumer power systems
- Generator networks
- Low and medium voltage networks
- PFC systems with or without detuning

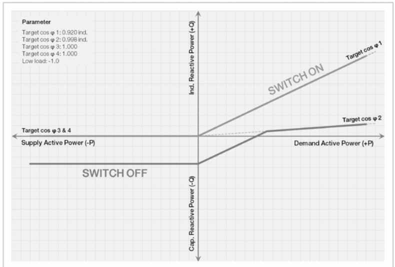


***Fig. 29**: Typical control characteristic curve for reduced-wear power factor correction with target cos φ inductive when importing power but capacitive when exporting power.*

Operating the PQC

The PQC has a backlit monochrome LCD screen with 128 x 64 pixels, together with 5 keys for navigating through the plain language (German, English or French) menus.

The menus are structured in an intuitive way that makes it easy to configure the instrument. An overview of the PQC in the display shows the key information for the individual phases together with the switching status of the control outputs. The operator is thus given all relevant information on the state of the power factor correction system at a glance. An intelligent alarm management function alerts the operator to critical conditions, either by notifications in the display or via the alarm contact.

Commissioning the PQC

When first started up, the PQC automatically determines the system configuration to which it is connected plus the control outputs in use with their respective capacitance ratings (corrective power in kVAr). The operator selects the appropriate characteristic control profile for the application or configures the PQC to meet the required specifications. Five control profiles - specially developed for the most frequently encountered applications - are saved in the instrument before it leaves the factory. On completion of the start-up procedure, the PQC switches the connected capacitor stages in or out according to the selected control curve.

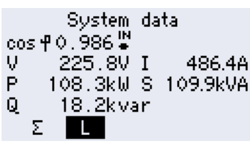


***Fig. 30**: PQC display of system variables*

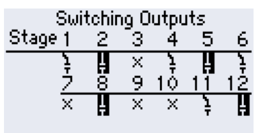


***Fig. 31**: PQC display of control output status*

Section 6: Installation

6.1: Current transformers

A current transformer is necessary to operate PFC systems. This is not included in the scope of supply, but can be provided with the system after clarification of user requirements. The primary current in the transformer is determined by the user's current input, i.e. this unit is designed for the maximum current loading or the installed load connected to the power transformer. The reactive power control relay current circuit is designed for a .../1 A to .../5 A current transformer with a 5 VA rating and Class 3 accuracy. If ammeters are installed in series with the control relay, the rating of the current transformer must be increased to suit. The internal power consumption in the control relay current circuit amounts to some 1.8 VA for a current transformer with a 5 A secondary current rating.

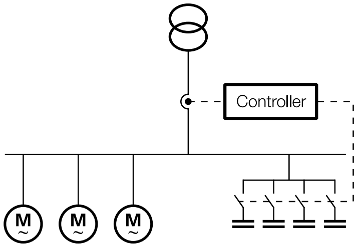


*__Fig. 32__: **Correctly** installed current transformer registers load current and capacitor current.*

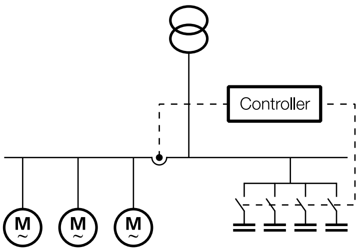


*__Fig. 33__: **Incorrect!** The current transformer only registers the load current: the capacitor bank is switched in but not out again (no capacitor current can be measured)!*

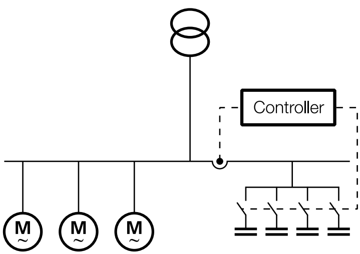


*__Fig. 34__: **Incorrect!** The current transformer only registers the capacitor current: the capacitor bank is not switched in (no current in transformer circuit)!*

If further instruments need to be powered from the same current transformer, this must be taken into account when specifying its rating (output load).

Losses also occur in the current transformer wiring, and these must also be taken into account if there are long lengths of cable between the current transformer and the reactive power control relay.

Power losses in copper conductors

from a current transformer with 5 A secondary current:

Cross section in mm^2	Losses per metre of two-wire line in VA
2.5	0.36
4.0	0.22
6.0	0.15
10.0	0.09

The **formula for dimensioning** current transformers is given on page 31.

Note: The current transformer must be installed in one of the three phases so that the entire current to the loads requiring PFC plus the capacitor current flow through it (as shown in the diagrams on the left). The terminal P1 (K) is connected to the supply side, terminal P2 (L) to the load side.

Caution: When the primary circuit is broken, voltage surges occur which could destroy the current transformer. The terminals S1 (k) and S2 (l) must therefore be short-circuited before the transformer circuit is broken.

6.2: Overcurrent protection and cables

When installation work is carried out, the regulations VDE 0100 and VDE 0105 of the German Association for Electrical, Electronic & Information Technologies, the general guidelines of the BDEW (German Association of Energy and Water Industries) and the conditions of supply of the utility company concerned must be complied with. VDE 0560 Part 46 states that capacitor units must be suitable for a continuous RMS current of 1.3 times the current that is drawn at the sinusoidal rated voltage and nominal frequency. If the capacitance tolerance of 1.1 x C_N is also taken into account, the maximum allowable current can reach values of up to 1.38 x I_N. This overload capability, together with the high in-rush current to the capacitors, must be taken into account when dimensioning protective devices and cable cross sections.

Note: FRAKO power capacitors offer a current-carrying capacity of up to 2.7 × I_N.

__Table 5__: Overcurrent protection (OCP) and supply cable cross sections according to VDE 0298, Part 4, layout method C

	400 V/50 Hz			525 V/50 Hz			690 V/50 Hz		
Power in kVAr	Current in A	OCP in A	Cross section in mm^2	Current in A	OCP in A	Cross section in mm^2	Current in A	OCP in A	Cross section in mm^2
2.5	3.6	10	4 x 1.5	2.7	10	4 x 1.5	2.1	10	4 x 1.5
5	7.2	10	4 x 1.5	5.5	10	4 x 1.5	4.2	10	4 x 1.5
6.25	9.0	16	4 x 2.5	6.9	10	4 x 1.5	5.2	10	4 x 1.5
7.5	10.8	16	4 x 2.5	8.2	16	4 x 2.5	6.3	10	4 x 1.5
10	14.4	20	4 x 2.5	11.0	16	4 x 2.5	8.4	16	4 x 2.5
12.5	18.0	25	4 x 4	13.7	20	4 x 2.5	10.5	16	4 x 2.5
15	21.7	35	4 x 6	16.5	25	4 x 4	12.6	20	4 x 2.5
17.5	25.3	35	4 x 6	19.2	35	4 x 6	14.6	25	4 x 4
20	28.9	50	4 x 10	22.0	35	4 x 6	16.7	25	4 x 4
25	36.1	50	4 x 10	27.5	50	4 x 10	20.9	35	4 x 6
27.5	39.7	63	4 x 16	30.2	50	4 x 10	23.0	35	4 x 6
30	43.3	63	4 x 16	33.0	50	4 x 10	25.1	35	4 x 6
31.25	45.1	63	4 x 16	34.4	50	4 x 10	26.1	50	4 x 10
37.5	54.1	80	3 x 25/16	41.2	63	4 x 16	31.4	50	4 x 10
40	57.7	80	3 x 25/16	44.0	63	4 x 16	33.5	50	4 x 10
43.75	63.1	100	3 x 35/16	48.1	80	3 x 25/16	36.6	63	4 x 16
45	65.0	100	3 x 35/16	49.5	80	3 x 25/16	37.7	63	4 x 16
50	72.2	100	3 x 35/16	55.0	80	3 x 25/16	41.8	63	4 x 16
52.5	75.8	125	3 x 50/25	57.7	80	3 x 25/16	43.9	63	4 x 16
60	86.6	125	3 x 50/25	66.0	100	3 x 35/16	50.2	80	3 x 25/16
62.5	90.2	125	3 x 50/25	68.7	100	3 x 35/16	52.3	80	3 x 25/16
67.5	97.4	160	3 x 70/35	74.2	125	3 x 50/25	56.5	80	3 x 25/16
68.75	99.2	160	3 x 70/35	75.6	125	3 x 50/25	57.5	80	3 x 25/16
75	108.3	160	3 x 70/35	82.5	125	3 x 50/25	62.8	100	3 x 35/16
87.5	126.3	200	3 x 95/50	96.2	160	3 x 70/35	73.2	125	3 x 50/25
93.75	135.3	200	3 x 95/50	103.1	160	3 x 70/35	78.4	125	3 x 50/25
100	144.3	200	3 x 95/50	110.0	160	3 x 70/35	83.7	125	3 x 50/25
112.5	162.4	250	3 x 120/70	123.7	200	3 x 95/50	94.1	160	3 x 70/35
125	180.4	250	3 x 120/70	137.5	200	3 x 95/50	104.6	160	3 x 70/35
150	216.5	315	3 x 185/95	165.0	250	3 x 120/70	125.5	200	3 x 95/50
175	252.6	400	2x 3 x 95/50	192.5	315	3 x 185/95	146.4	250	3 x 120/70
200	288.7	400	2x 3 x 95/50	219.9	315	3 x 185/95	167.3	250	3 x 120/70
225	324.8	500	2x 3 x 120/70	247.4	400	2x 3 x 95/50	188.3	315	3 x 185/95
250	360.8	500	2x 3 x 120/70	274.9	400	2x 3 x 95/50	209.2	315	3 x 185/95
275	396.9	630	2x 3 x 185/95	302.4	500	2x 3 x 120/70	230.1	400	2x 3 x 95/50
300	433.0	630	2x 3 x 185/95	329.9	500	2x 3 x 120/70	251.0	400	2x 3 x 95/50
350	505.2	800	2x 3 x 240/120	384.9	630	2x 3 x 185/95	292.9	500	2x 3 x 120/70
375	541.3	800	2x 3 x 240/120	412.4	630	2x 3 x 185/95	313.8	500	2x 3 x 120/70
400	577.4	800	2x 3 x 240/120	439.9	630	2x 3 x 185/95	334.7	500	2x 3 x 120/70
500	721.7	1000	3x 3 x 185/95	549.9	800	2x 3 x 240/120	418.4	630	2x 3 x 185/95

Table 6: **Outer diameters of cables and conductors**

Cross section in mm²	NYM ∅ in mm	NYY ∅ in mm	NYCY/NYCWY ∅ in mm	H05VV-F ∅ in mm	H07RN-F ∅ in mm
2 x 1.5	9.0	11.0	12.0	10.5	11.5
2 x 2.5	10.5	13.0	14.0	12.5	13.5
3 x 1.5	10.0	11.0	13.0	11.0	12.5
3 x 2.5	11.0	13.0	14.0	13.0	14.5
3 x 4.0	12.5	15.0	16.0	-	16.0
3 x 6.0	14.0	16.0	17.0	-	20.0
3 x 10.0	17.0	19.0	18.0	-	25.5
3 x 16.0	20.0	21.0	21.0	-	29.0
4 x 1.5	10.5	13.0	14.0	12.5	13.5
4 x 2.5	12.0	14.0	15.0	14.0	15.5
4 x 4.0	14.0	16.0	17.0	-	18.0
4 x 6.0	15.0	17.0	18.0	-	22.0
4 x 10.0	18.0	20.0	20.0	-	28.0
4 x 16.0	23.0	23.0	23.0	-	32.0
4 x 25.0	27.5	27.0	28.0	-	37.0
4 x 35.0	31.0	30.0	29.0	-	42.0
4 x 50.0	-	35.0	34.0	-	48.0
4 x 70.0	-	40.0	37.0	-	54.0
4 x 95.0	-	45.0	42.0	-	60.0
4 x 120.0	-	50.0	47.0	-	-
4 x 150.0	-	53.0	52.0	-	-
4 x 185.0	-	60.0	60.0	-	-
4 x 240.0	-	71.0	70.0	-	-
5 x 1.5	11.0	13.5	15.0	13.5	15.0
5 x 2.5	13.0	15.0	17.0	15.5	17.0
5 x 4.0	15.0	16.5	18.0	-	19.0
5 x 6.0	18.0	19.0	20.0	-	24.0
5 x 10.0	20.0	21.0	-	-	30.0
5 x 16.0	24.0	23.0	-	35.0	-
7 x 1.5	-	13.5	-	-	-
10 x 1.5	-	17.0	-	-	-
12 x 1.5	-	17.5	-	-	-
14 x 1.5	-	18.0	-	-	-
16 x 1.5	-	19.0	-	-	-
24 x 1.5	-	23.0	-	-	-

NYM: Light plastic-sheathed cable
NYY: Cable with polymer sheath
NYCY: Cable with concentric conductor and polymer sheath
NYCWY: Cable with concentric, waveconal conductor and polymer sheath
H05VV-F: Ordinary rubber-sheathed flexible cable (NLH. NMH)
H07RN-F: Heavy rubber-sheathed flexible cable (NSH)

Table 7: **Cable entry with cable glands**

Metric thread	**PG**	**Cable outside diameter** in mm	**Hole diameter** in mm
M 16 x 1.5	11	6.5 - 10.5	19.0
-	13.5	8.0 - 12.5	21.0
M 20 x 1.5	16	10.0 - 15.0	23.0
M 25 x 1.5	21	12.0 - 20.0	29.0
M 32 x 1.5	29	19.0 - 26.5	38.0
M 40 x 1.5	36	29.0 - 34.0	48.0
-	42	34.0 - 41.0	55.0
M 50 x 1.5	48	40.0 - 45.0	60.0

6.3: Ingress protection

The standard EN 60529 specifies the degree of protection for electrical enclosures by means of two letters and a two-digit number. IP stands for ingress protection.

The following are the most frequently encountered combinations:

Table 8: **Common ingress protection codes**

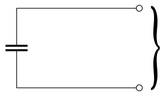
Protection	Against accidental contact	Against solid objects	Against liquids
IP00	none	none	none
IP10	against accidental or inadvertent contact	over 50 mm diameter	none
IP20	against fingers and objects up to 80 mm long	over 12.5 mm diameter	none
IP30	against tools and wires thicker than 2.5 mm	over 2.5 mm diameter	none
IP31	against tools and wires thicker than 2.5 mm	over 2.5 mm diameter	drops of water falling vertically
IP40	against wires or strips thicker than 1 mm	over 1 mm diameter	none
IP41	against wires or strips thicker than 1 mm	over 1 mm diameter	drops of water falling vertically
IP42	against wires or strips thicker than 1 mm	over 1 mm diameter	drops of water falling at up to 15° from the vertical
IP43	against wires or strips thicker than 1 mm	over 1 mm diameter	water sprayed at up to 60° from the vertical
IP54	complete protection	dust deposits	water splashed from all directions
IP65	complete protection	dust ingress	water jets from all directions

Section 7: Calculation formulas

Symbols:

Q_C = Corrective power in VAr
V = Voltage in V
f_n = Supply frequency in Hz
n = Number of capacitors
C = Capacitance of a capacitor in F (farads)
π = Pi (3,1415926...)
p = Detuning factor

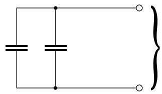
Corrective power, single phase



$$Q_C = C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n$$

Example: 83 µF at 400 V / 50 Hz
0.000083 · 400² · 314.16 = 4,172 VAr = 4.17 kVAr

Corrective power, single phase, *n* capacitors, in parallel



$$Q_C = n \cdot C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n$$

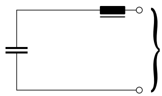
Example: 2x83 µF at 400 V / 50 Hz
2 · 0.000083 · 400² · 314.16 = 8,344 VAr = 8.34 kVAr

Corrective power, single phase, *n* capacitors, in series

$$Q_C = \frac{C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n}{n}$$

Example: 2x83 µF at 400 V / 50 Hz
0.000083 · 400² · 314.16 / 2 = 2,086 VAr = 2.09 kVAr

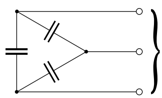
Corrective power, single phase, detuned



$$Q_C = \frac{C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n}{1 - p}$$

Example: 171.3 µF at 400 V / 50 Hz, with 14% detuning
0.0001713 · 400² · 314.16 / 0.86 = 10 kVAr

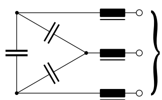
Corrective power, 3-phase, delta-connected



$$Q_C = 3 \cdot C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n$$

Example: 3x332 µF at 400 V / 50 Hz
3 · 0.000332 · 400² · 314.16 = 50 kVAr

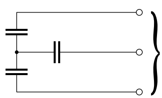
Corrective power, 3-phase, delta-connected, detuned



$$Q_C = \frac{3 \cdot C \cdot V^2 \cdot 2 \cdot \pi \cdot f_n}{1 - p}$$

Example: 3x332 µF at 400 V / 50 Hz, with 7% detuning
3 · 0.000332 · 400² · 314.16 / 0.93 = 53.8 kVAr

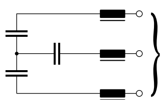
Corrective power, 3-phase, star-connected



$$Q_C = C_{3\text{-}phase} \cdot V^2 \cdot 2 \cdot \pi \cdot f_n$$

Example: 3x1x124.4 µF at 400 V / 50 Hz
0.0001244 · 400² · 314.16 = 6.25 kVAr

Corrective power, 3-phase, star-connected, detuned



$$Q_C = \frac{C_{3\text{-}phase} \cdot V^2 \cdot 2 \cdot \pi \cdot f_n}{1 - p}$$

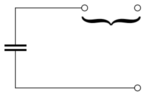
Example: 3x1x115.7 µF at 400 V / 50 Hz, with 7% detuning
0.0001157 · 400² · 314.16 / 0.93 = 6.25 kVAr

Symbols:

V = Voltage in V
I = Phase current in A
P = Active power in W
Q = Reactive power in VAr
S = Apparent power in VA
Q_C = Corrective power in VAr

f_n = Supply frequency in Hz
f_r = Series resonant frequency in Hz
p = Detuning factor in %
l = Conductor length (2-core cable) in m
q_{cu} = Conductor cross section in mm²
P_v = Conductor power loss in VA

Capacitor current in phase conductor, single phase

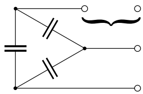


$$Q_C = I \cdot V \qquad \underline{\text{oder:}} \qquad I = \frac{Q_C}{V}$$

Example: 25 kVAr at 400 V

25,000 / 400 = 62.5 A

Capacitor current in phase conductor, 3-phase



$$Q_C = I \cdot V \cdot \sqrt{3} \qquad \underline{\text{oder:}} \qquad I = \frac{Q_C}{V \cdot \sqrt{3}}$$

Example: 25 kVAr at 400 V

25,000 / (400 · 1.73) = 36 A

Power factor and relationship between cos φ and tan φ

$$\cos\varphi = \frac{P}{S} \qquad \underline{\text{or:}} \quad \cos\varphi = \sqrt{\frac{1}{1+\tan\varphi^2}} \qquad \underline{\text{or:}} \quad \cos\varphi = \sqrt{\frac{1}{1+\left(\frac{Q}{P}\right)^2}}$$

$$\tan\varphi = \frac{Q}{P} \qquad \underline{\text{or:}} \quad \tan\varphi = \sqrt{\frac{1}{\cos\varphi^2} - 1} \qquad \underline{\text{or:}} \quad \tan\varphi = \sqrt{\frac{1}{\left(\frac{P}{S}\right)^2} - 1}$$

Series resonant frequency (f_r) and detuning factor (p) of detuned capacitors

$$f_r = f_n \cdot \sqrt{\frac{1}{p}} \qquad \underline{\text{or:}} \qquad p = \left(\frac{f_n}{f_r}\right)^2$$

Example: p = 0.07 (7% detuning) in 50 Hz system

$f_r = 189\,Hz$

Current transformer Power loss calculation (output load)

$$P_v = \frac{I^2 \cdot l \cdot 2}{q_{cu} \cdot 56}$$

Example 1 CT ratio: ... / 5A

20 m copper measurement cable (2-core), 2.5 mm²

Control relay with 1.8 VA power draw at measurement input:

(5² · 40 / 2.5 / 56) + 1.8 = 8.94 VA = transformer: 10 VA

Example 2 CT ratio: ... / 1A

150 m copper measurement cable (2-core), 2.5 mm²

Instrument with 1.2 VA power draw at current input:

(1² · 300 / 2.5 / 56) + 1.2 = 3.34 VA = transformer: 5 VA

Section 8: Power quality

8.1: What are harmonics?

Modern low voltage systems increasingly have loads installed that draw non-sinusoidal currents from the power distribution system. These load currents cause voltage drops through the system impedances, distorting the original sinusoidal supply voltage. Fourier analysis can be used to separate these superposed waveforms into the basic oscillation (supply frequency) and the individual harmonics. The frequencies of the harmonics are integral multiples of the basic oscillation and are denoted by the ordinal number ‘n’ or ‘ν’. (Examples: supply frequency = 50 Hz ➛ 5th harmonic = 250 Hz; supply frequency = 60 Hz ➛ 5th harmonic = 300 Hz).

Linear loads are:

- Ohmic resistances (electric heating elements, incandescent bulbs, etc.)
- 3-phase motors
- Capacitors

Non-linear loads (harmonics generators) are:

- Transformers and inductors
- Electronic power converters
- Rectifiers and converters, especially when controlling variable-speed induction motors
- Induction and electric arc furnaces, welding equipment
- Uninterruptible power supplies (UPS systems)
- Single-phase switched-mode power supply (SMPS) units for modern electronic loads such as televisions, battery chargers, computers, monitors, printers, telefax machines, electronic ballasts, energy-saving lamps, power supply units for LED lamps, etc.

Every periodic signal with a frequency *f* (regardless of the waveform) consists of the sum of the following:
- The sine component of the frequency *f*, known as the fundamental component or h_1
- The sine components of the integral multiples of the frequency *f*, known as the harmonics h_n
- Any DC components that in some cases may also be present.

$$y_{(t)} = h_{1(t)} + h_{3(t)} \ldots$$

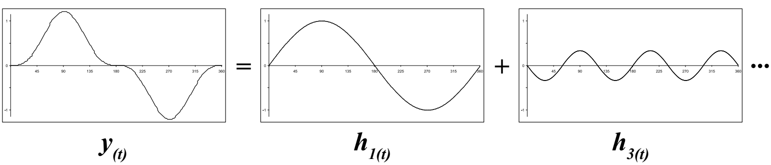


Fig. 35: *Analysing a periodic signal into its component harmonics*

Harmonics can be divided into:

- **Even harmonics** (2nd, 4th, 6th, etc.)
  These occur due to sudden load variations or faults in converters
- **Odd harmonics** (3rd, 5th, 7th, etc.)
  - ➛ **Harmonics divisible by 3** (3rd, 9th, 15th, etc.)
    These occur due to asymmetrical loads and single-phase sources of harmonics
    Typical sources: Office buildings, hospitals, software companies, banks, etc.
    Factories with 2-phase welding equipment
    Problem: These harmonic currents in the neutral conductor are cumulative!

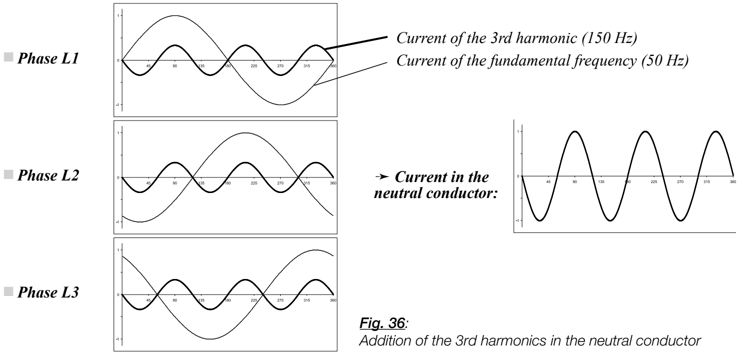
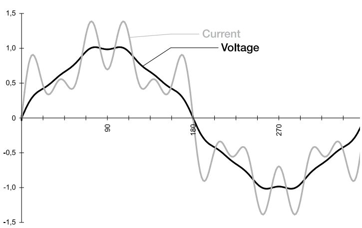


__Fig. 36__:
Addition of the 3rd harmonics in the neutral conductor

  - ➛ **Harmonics not divisible by 3** (5th, 7th, 11th, 13th, etc.)
    These occur due to 3-phase sources of harmonics.
    5th and 7th harmonics: from 6-pulse converters
    11th and 13th harmonics: from 12-pulse converters
    Problem: The harmonics are transmitted via the transformer!

The total harmonic distortion **THD** is the result of the vector addition of all harmonics present, and is as a rule expressed as a proportion of the fundamental frequency, thus providing a quick overview of network power quality.

Each harmonic can be considered as an individual system with its own phase angle! This results in a basic difference between **cos** φ (fundamental frequency) and **PF** (or λ, i.e. the power factor as the vector sum over all the harmonics).



Harmonics are generated not only in industrial installations, but also increasingly in private households.

As a rule, the devices generating these harmonics only feed in the odd orders, so that it is only the 3rd, 5th, 7th, 9th, 11th, etc. harmonics that are encountered.

__Fig. 37__: Network current and voltage superposed with the following harmonics: 5% of the 5th harmonic, 4% of the 7th harmonic and 2.5% of the 11th harmonic

8.2: Where are harmonics produced?

In industrial low voltage systems, especially when variable-speed drives are installed, and in every household: in every television, computer and compact energy-saving lamp with electronic ballast. The sheer number of these loads in the evenings with the currents in phase often gives rise to high levels of harmonics in medium voltage networks.

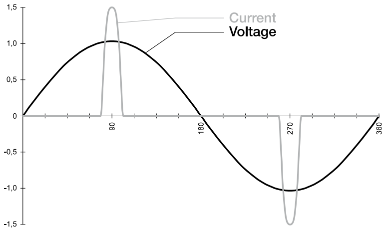


Fig. 38: *Current and voltage in an SMPS unit*

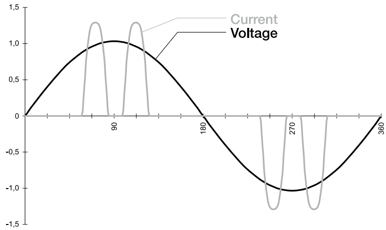


Fig. 39: *Current and voltage in a B6 converter*

8.3: What is the level of these harmonics if no PFC system has yet been installed?

a) In a facility's own low voltage system:

it depends on the power of the installed converters and rectifiers.

If, for example, a large 6-pulse converter is installed in the system and its power rating is 50% of the transformer nominal rating, this gives rise to about

- 4% of the 5th harmonic (250 Hz) and
- 3% of the 7th harmonic (350 Hz)

It is more usual, however, for several small converters that are not linked to each other to be installed in a system. The fact that the currents to the individual rectifiers are not all in phase means that the resulting harmonic voltages are less than in the above case.

If, for example, several rectifiers with a combined power of some 25% of the transformer nominal rating are installed, this gives rise to about

- 1 - 1,5% of the 5th harmonic and
- 0,7 - 1% of the 7th harmonic.

These are approximate values to help in the initial assessment of whether a detuned PFC system needs to be installed.

b) In the medium voltage network:

Nowadays, most of these systems are affected predominantly by the devices in private households (mainly television sets) that produce harmonics. This is readily apparent when the daily curve for the 5th harmonic is examined:

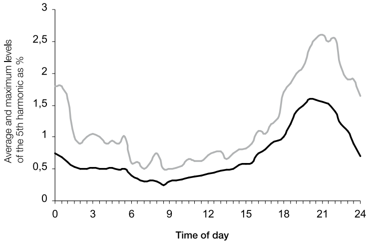


***Fig. 40**: Average and maximum levels of the 5th harmonic as % in a municipal medium voltage network*

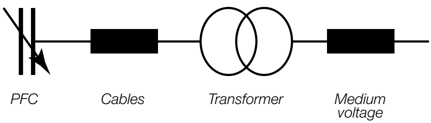
The level of harmonics in the medium voltage system of a municipal power supply with industrial loads on weekdays is shown in the chart.

These average and maximum levels were determined in a series of measurements carried out from 1985 to 1987 by FGH, a German power supply industry research organization, and must certainly be much higher today. The increase in the evenings is due to the numerous televisions and other non-linear loads in private households.

In densely populated areas in the evenings, frequencies of over **4% 250 Hz** and up to about **1.5% 350 Hz** can be superposed on the medium voltage supply system. The higher harmonics are usually negligible. Harmonic levels can only be predicted with limited accuracy!

8.4: What effect does a PFC system have on a network with harmonics?

A PFC system with no detuning forms an oscillatory circuit with reactive line impedances. The resonant frequency is given by a simple rule of thumb:



$$f_r = 50\,Hz \cdot \sqrt{\frac{S_{sc}}{Q_c}}$$

f_r: Resonant frequency
S_{sc}: Short-circuit power at the point where the correction system is connected
Q_c: PFC corrective power

The short-circuit power S_{SC} at the point where the PFC system is connected is

- determined essentially by the transformer (S_{SC} / v_{SC}),
- reduced by some 10% by the impedance of the medium voltage system
- possibly greatly reduced by long lengths of cable between the transformer and the PFC system.

Example:

- Transformer 1000 kVA, v_{SC} = 6%
- Short-circuit power of the medium voltage system 150 MVA, $S_{SC} \approx 2.6$ MVA
- PFC system 400 kVAr in 8 stages, not detuned

PFC corrective power (Q_c)	**Resonant frequency** (f_r)
100 kVAr	562 Hz
250 kVAr	355 Hz
400 kVAr	281 Hz

When the capacitor stages of the correction system are switched in, the system resonant frequency f_r changes considerably and is sometimes close to the frequency of a system harmonic.

If the natural resonance of this oscillatory circuit is near to a system harmonic that is present, it is to be expected that resonance will increase the harmonic voltages. Under certain conditions, these may be multiplied by an amount approaching the system Q factor (in industrial systems about 5-10!):

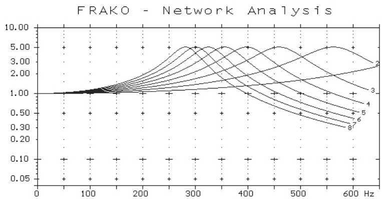


***Fig. 41**: Amplification factor for harmonic voltages in a PFC system without detuning in a low voltage network*

8.5: When can dangerous network resonances occur?

From the above chart it can be seen that it is possible to assess whether resonance problems can occur with harmonics. Simple rules suffice for this:

1.) If the resonant frequency is
- 10 % below/above a network harmonic, the latter will be **amplified** in a network with a high Q factor (e.g. in the evenings and at night) **by a factor of up to 4**.
- 20 % above a network harmonic, the latter will be amplified in a network with a high Q factor **by up to 2.5 times**.
- 30 % above a network harmonic, the latter will be amplified only slightly, **by a factor of up to about 1.7**.

2.) In a network with no harmonic generator of its own, but with pronounced harmonics present in the medium voltage system, the following can occur
- at a resonant frequency below 400 Hz: resonance peaks of the 7th harmonic,
- **at a resonant frequency below 300 Hz: dangerous resonance peaks of the 5th harmonic** (250 Hz).

8.6: What effect does the system configuration have on the problem of harmonics?

The system short-circuit power determines the resonant frequency and, where harmonic generators are present in that network, the amplitude of the harmonics in the network voltage.

- If the **system short-circuit power** at the point where the PFC system is connected is **too low**, this causes problems.
- If the **short-circuit power is changed radically** due to altered switching conditions, this causes problems.

Example:
In many large commercial facilities continuity of power supply is achieved by connecting the low voltage distribution points via a ring circuit. This system has a high short-circuit power even with large PFC systems and heavy rectifier loads with hardly any harmonics problems arising, since the resonant frequency is high and the harmonic currents are dissipated with low voltage drops into the medium voltage system. If a break is made in the ring circuit, for example for maintenance work, the short-circuit power can decrease considerably under certain conditions, so that the resonant frequency can fall below 300 Hz!

8.7: Voltage and current loads in PFC systems without detuning

When resonance occurs, the network RMS voltage only increases slightly, but the RMS value of the capacitor current increases considerably. In the case of resonance with the 5th harmonic, this can reach a level of, say, 15% in which case:

- The system RMS voltage increases by 1%
- The crest working line voltage increases by 10-15% (depending on phase angle)
- **The RMS value of the capacitor current increases by 25%!**

In the case of resonance with the 11th harmonic, this can reach a level of, say, 10%, in which case:

- The system RMS voltage increases by 0.5%
- The peak value of the supply voltage increases by 6-10%
- **The RMS value of the capacitor current increases by 50%!**

For this reason a high **current-carrying capacity** is one of the most important quality characteristics for a capacitor!

FRAKO capacitors can withstand an overcurrent up to **2.7 times the rated current** as a continuous load!

Section 9: Designing for systems with harmonics

■ 9.1: What must be done if resonance is possible but rather unlikely?

A considerable proportion of installations being designed today fall into this category, e.g.:

- No internal harmonic generators installed in the network, no harmonics in the medium voltage system, but a resonant frequency below 400 Hz.
- If changes are made in the network configuration, for example, during maintenance work, the resonant frequency can fall below 400 Hz. Harmonics are present in the medium voltage distribution system.
- It is planned to build installations with rectifiers at a later date.

To protect an installation without detuning from the occurrence of resonance, even if this may only happen occasionally, it is highly advantageous to use a FRAKO **supply network monitoring instrument**. These devices monitor all three phases of the power supply system, shut the installation down if a dangerous level of harmonics is exceeded and switch it automatically in again when this level falls below the critical value. The peak values that have occurred are stored, however, and can be retrieved via a bus interface.

For distribution systems that are symmetrically loaded, a FRAKO **reactive power control relay** can also be installed. These instruments monitor the system to detect any resonance that may occur. They determine the harmonic voltages in the measured phase(s) and calculate the RMS current to the capacitors. If a programmed maximum limit is exceeded, the installation is shut down and switched in again when the level falls below its critical value.

■ 9.2: Planning for PFC systems in networks with harmonics

The best information on the operational characteristics of a planned PFC system is obtained by a combination of two planning activities:

- Measuring the harmonic voltages and currents over several days with no PFC system installed.
- Theoretical calculation of the network resonance characteristics.

In dem gemessenen Netz sind dann folgende Oberschwingungspegel zu erwarten:

Maximum value of the measurement without PFC multiplied by the resonance factor from the system analysis

Example:

An average-size low voltage system with a 1000 kVA transformer. The installation, complete with the PFC system, is connected via two 20 m long cables laid in parallel (equivalent to the impedance of a 10 m cable). Only purely ohmic loads may be taken into account as equipment such as induction motors have no damping effect on harmonics. With a 400 kVAr installation and all capacitor stages switched in, the 5th harmonic (250 Hz) is amplified by a factor of about 3. At 250 kVAr the 7th harmonic is amplified by a factor of about 4!

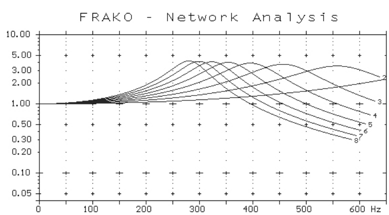


***Fig. 42**: Amplification of harmonic voltages as a function of the number of capacitor stages switched in*

During the day, with increased network damping, these factors are lower, but in the evenings and at weekends the amplification factor for the 7th can be higher.

9.3: Measures to counteract expected resonances

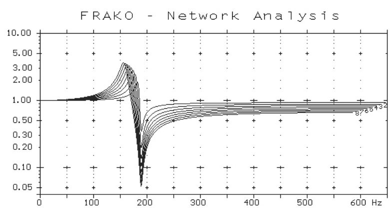
If harmonics with high voltage levels, such as:

4.0%	of the 3rd harmonic (150 Hz)
5.0%	of the 5th harmonic (250 Hz)
4.0%	of the 7th harmonic (350 Hz)
3.0%	of the 11th harmonic (550 Hz)
2.1%	of the 13th harmonic (650 Hz)

due to resonance-induced amplification are anticipated when a PFC system is planned, serious disruptions can occur in the low voltage distribution system:

- Problems with IT systems and CNC machines
- Damage to rectifiers and/or converters
- Uncontrolled tripping of switchgear and circuit breakers
- Shutdown of PFC systems without detuning
- Voltage peaks in the distribution system
- Increased eddy current losses in transformers and induction motors

If the level of individual harmonics with no PFC system amounts to more than 1.5% (7th and higher harmonics) or 2% (5th harmonic) and the resonant frequency of the network can be close to these harmonics, then it must be assumed that these permissible limits will be exceeded by resonance-induced amplification. In situations of this type, only detuned PFC systems should be used in order not to jeopardize the reliability of the low voltage distribution system.



Detuning reduces the resonant frequency to a value below 250 Hz. All harmonics above the resonant frequency of the detuned system are attenuated.

Fig. 43: Damping of harmonic voltages as a function of the number of detuned capacitor stages

A detuned capacitor consists of a capacitor in series with a filter reactor (inductor). Its series resonant frequency is adjusted by appropriate design of the filter reactor so that it is below the frequency of the 5th harmonic (250 Hz). This combination therefore has an inductive characteristic for all frequencies above the series resonant frequency. Resonance between the capacitors and the reactive network impedances is no longer possible. A detuned system suppresses some of the harmonic currents. To prevent overloads due to the 5th harmonic still present in the network, it is present-day practice to adjust the resonant frequency of the detuned circuit to 189 Hz or less.

The detuned circuit is characterized either by the capacitor-reactor resonant frequency f_r or by the ratio p between the voltage drop across the reactor and that across the capacitor.
These two parameters are related by the following formula:

$$f_r = f_n \cdot \sqrt{\frac{1}{p}}$$

Example: p = 0.07 (7% detuning) in 50 Hz system
$f_r = 189\,Hz$

The impedance of the detuned capacitor at 250 Hz is smaller than the impedance of the capacitor without detuning by a factor x.

The detuned PFC system has the following characteristics for the 5th harmonic:
- Acceptor circuit characteristics when $x > 1$
- Rejector circuit characteristics when $x < 1$

With strong acceptor circuit characteristics (series resonant circuit), the maximum allowable level of the 250 Hz harmonic must be limited so as not to overload the filter reactor.

➛ p = 5.7%	fr = 210 Hz	x = 2.4	➛ **$v250_{max}$ = 4%**
➛ p = 7 %	fr = 189 Hz	x = 1.33	➛ **$v250_{max}$ = 5%**
➛ p = 8 %	fr = 177 Hz	x = 1.0	➛ **$v250_{max}$ = 5%**
➛ p = 14 %	fr = 134 Hz	x = 0.42	➛ **$v250_{max}$ = 5%**

Example: If 4% of the 5th harmonic is superposed on the network voltage, a detuned PFC system attenuates the 5th harmonic as follows:

➛ at 7 %	detuning:	by 4% × 5 (=250 Hz/50 Hz) × 1.33 = **0.27 × I_n**
➛ at 5.7%	detuning:	by 4% × 5 (=250 Hz/50 Hz) × 2.40 = **0.48 × I_n**
➛ at 14 %	detuning:	by 4% × 5 (=250 Hz/50 Hz) × 0.42 = **0.08 × I_n**

(I_n = system rated current at 50 Hz)

When a detuned PFC system is designed, the following factors must always be taken into account:

- Capacitors with and without detuning must never be operated in parallel in the same low voltage system.
- Parallel operation of filter circuit systems with different detuning factors (p) is possible, but the loading of the filter circuits is different and should be accurately analysed for high levels of harmonics.
- If the low voltage systems are electrically isolated from each other (transformers not capable of being coupled at the low voltage side), then, if required, one system can be detuned while the other system has a power factor correction without detuning.
- The type of installation selected must comply with the requirements of the utility company concerned.

9.4: Maximum permissible harmonic levels

A number of standards can be consulted when assessing power quality, the relevant standard depending on the particular application. For normal low voltage supplies connected to public distribution networks, two standards are generally applicable:

- **EN 50160** 'Voltage characteristics of electricity supplied by public electricity networks' covers harmonic voltages up to the 25th order.
- **EN 61000-2-2** 'Compatibility levels for low frequency conducted disturbances and signalling in public low voltage power supply systems' covers harmonic voltages up to the 50th order.

__Table 9__: Comparison of maximum permissible harmonic levels according to EN 50160 and EN 61000-2-2

	EN 50160	EN 61000-2-2		EN 50160	EN 61000-2-2
Even harmonics:					
2nd (100 Hz)	2.00 %	2.00 %	**Odd harmonics:** (divisible by 3)		
4th (200 Hz)	1.00 %	1.00 %	3rd (150 Hz)	5.00 %	5.00 %
6th (300 Hz)	0.50 %	0.50 %	9th (450 Hz)	1.50 %	1.50 %
8th (400 Hz)	0.50 %	0.50 %	15th (750 Hz)	0.50 %	0.40 %
10th (500 Hz)	0.50 %	2.50 %	21st (1050 Hz)	0.50 %	0.30 %
12th (600 Hz)	0.50 %	2.13 %	27th (1350 Hz)	-	0.20 %
14th (700 Hz)	0.50 %	1.86 %	33rd (1650 Hz)	-	0.20 %
16th (800 Hz)	0.50 %	1.66 %	39th (1950 Hz)	-	0.20 %
18th (900 Hz)	0.50 %	1.50 %	45th (2250 Hz)	-	0.20 %
20th (1000 Hz)	0.50 %	1.38 %			
22nd (1100 Hz)	0.50 %	1.27 %	**Odd harmonics:** (not divisible by 3)		
24th (1200 Hz)	0.50 %	1.19 %	5th (250 Hz)	6.00 %	6.00 %
26th (1300 Hz)	-	1.12 %	7th (350 Hz)	5.00 %	5.00 %
28th (1400 Hz)	-	1.05 %	11th (550 Hz)	3.50 %	3.50 %
30th (1500 Hz)	-	1.00 %	13th (650 Hz)	3.00 %	3.00 %
32nd (1600 Hz)	-	0.95 %	17th (850 Hz)	2.00 %	2.00 %
34th (1700 Hz)	-	0.91 %	19th (950 Hz)	1.50 %	1.76 %
36th (1800 Hz)	-	0.88 %	23rd (1150 Hz)	1.50 %	1.41 %
38th (1900 Hz)	-	0.84 %	25th (1250 Hz)	1.50 %	1.27 %
40th (2000 Hz)	-	0.81 %	29th (1450 Hz)	-	1.06 %
42nd (2100 Hz)	-	0.79 %	31st (1550 Hz)	-	0.97 %
44th (2200 Hz)	-	0.76 %	35th (1750 Hz)	-	0.83 %
46th (2300 Hz)	-	0.74 %	37th (1850 Hz)	-	0.77 %
48th (2400 Hz)	-	0.72 %	41st (2050 Hz)	-	0.67 %
50th (2500 Hz)	-	0.70 %	43th (2150 Hz)	-	0.63 %
The same for both standards:			47th (2350 Hz)	-	0.55 %
- Total harmonic voltage distortion **THDv: max. 8%** - Total harmonic current distortion **THDi: max. 20%** recommended.			49th (2450 Hz)	-	0.52 %

Section 10: Designing for networks with audiofrequency remote control systems

10.1: Power factor correction in networks with audiofrequency remote control systems

Audiofrequency (AF) remote control systems are installed in utility company supply networks in order to perform switching functions (such as tariff changeover) by means of special receivers in the consumer's circuit. To do this, control voltages at a high frequency (AF pulses) are superposed on the power distribution system. These frequencies are usually in the range of 166 to 1350 Hz.

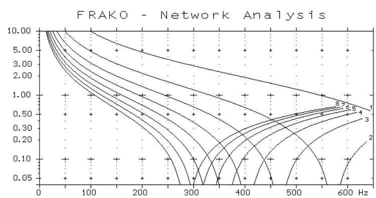
In order not to interfere with the functioning of these remote control systems, the control voltage level must not be unduly disrupted by the customer's installation. To ensure this, members of the German Association of Energy and Water Industries (BDEW), the Association of Austrian Security Companies (VSÖ) and the Association of Swiss Electricity Companies (VSE) produced joint recommendations for preventing impermissible disturbances in AF remote control systems.

An impedance factor α^* is used for the assessment of networks with PFC systems installed.
At an impedance factor $\alpha^* \geq 0.5$ no interference is to be expected with remote control systems!

The impedance factor α* is the ratio of the impedance of the consumer's installation (load plus PFC system) at the remote control frequency to the transformer's rated impedance.

10.2: Effect of PFC systems without detuning

A PFC system without detuning together with the reactive network impedances constitutes an oscillatory circuit whose resonant frequency f_r decreases with increasing PFC corrective power. Near to the resonant frequency, the impedance of the oscillatory circuit is at a very low value and can considerably attenuate the voltage level of the AF control system.



When the PFC system is fully switched in, an impedance factor $\alpha^* \geq 0.5$ can only still be achieved for a remote control frequency of 166 Hz.

__Fig. 44__: Impedance factor α as a function of the number of switched-in capacitor stages*

If the impedance factor cannot be maintained, a detuned system must be selected. The installation of an AF rejector circuit in series with the PFC system to increase the impedance can no longer be recommended for modern systems plagued with harmonics!

10.3: Effect of detuned PFC systems

Detuning PFC systems reduces the resonant frequency (as already described in more detail from Seite 43 onwards) to a value below 250 Hz. All harmonics above the resonant frequency of the detuned circuit are no longer amplified but attenuated. This gives adequate values of the impedance factor α* for remote control frequencies sufficiently far away from the resonant frequency of the detuned circuit.

Depending on the exact design of the circuit, remote control frequencies can be reliably blocked when using detuned PFC systems even without needing an AF rejector circuit.

In view of the maximum reliability required of PFC systems and the interference-free transmission of remote control signals called for by utility companies, we recommend the following designs for a correction factor (ratio of transformer power to PFC corrective power) of up to 50%:

Utility remote control frequency (in Hz)	**PFC design** (detuning factor)	... the most important **Main advantages and disadvantages**
≥ 166	p = 14% (fr = 134 Hz)	Only offers blocking effect on harmonics, suitable for systems with harmonics of orders divisible by 3, but cost-intensive installation.
≥ 216.67	p = 8% (fr = 177 Hz)	Moderate extraction effect on harmonics, not suitable for systems with harmonics of orders divisible by 3, relatively cost-intensive installation.
≥ 228	p = 7% (fr = 189 Hz)	Inexpensive installation, adequate extraction effect on harmonics, not suitable for systems with harmonics of orders divisible by 3.
≥ 270	p = 5.67% (fr = 210 Hz)	Extraction effect on harmonics often too great, not suitable for systems with harmonics of orders divisible by 3, not recommended without prior system analysis.

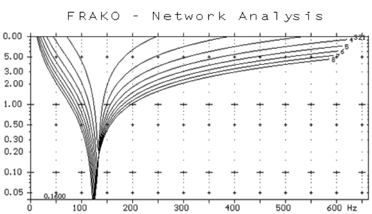


Fig. 45: *Impedance factor α* as a function of the number of switched-in capacitor stages, with 14% detuning*

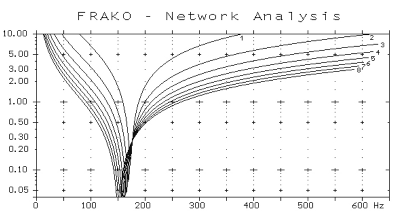


Fig. 46: *Impedance factor α* as a function of the number of switched-in capacitor stages, with 8% detuning*

These recommendations are based on many years of practical experience and are in line with the recommendations for preventing impermissible disturbances in AF remote control systems drawn up jointly in 1993 by members of the German Association of Energy and Water Industries (BDEW), the Association of Austrian Security Companies (VSÖ) and the Association of Swiss Electricity Companies (VSE).

10.4: Versions of detuned PFC systems

12.5 to 14% detuning:
A version with 12.5 to 14% detuning is suitable, even with no AF rejector circuit, for distribution systems with remote control frequencies from 166 Hz upwards. The disadvantages of this version are the higher costs of the inductors and capacitors, and its very low extraction capability for industrial harmonics. In low voltage networks with high levels of the 5th harmonic, the use of these versions should not be considered, especially for systems > 200 kVAr. Instead, a version with p = 7% or 8% should be selected. Low voltage networks with extremely high levels of the 3rd harmonic (150 Hz) are, however, an exception. The 3rd harmonic is produced as a rule by a highly asymmetrically loaded low voltage system or a large number of single-phase harmonic generators, often found in sites such as office complexes, banks, hospitals and department stores. To avoid resonance at this frequency, a detuned system with a resonant frequency below 150 Hz must be installed in such cases, versions with 14% detuning being the most suitable. In general, versions with 7 or 8% detuning must not be used for these systems.

7 and 8% detuning:
PFC systems with 7% detuning have a proven track record for most industrial applications. The resonant frequency is at an optimum level to suppress the harmonics (mainly the 5th and 7th) encountered in industry, while at the same time offering enough margin so as to not become overloaded. For industrial networks that are more or less symmetrically loaded, with normal levels of harmonics and remote control frequencies above 228 Hz, this is the ideal solution! Versions with 8% detuning are for networks using a remote control frequency of 216.67 Hz.

5 to 5.67% detuning:
As a rule these versions are used because of their increased extraction of harmonics. If, however, a high level of harmonics from the medium voltage distribution network is fed to the system, the use of the 5 to 5.67% detuned version should not be considered, in order to prevent overload conditions, and instead a version with p = 7% should be selected. At extreme levels of harmonics, specially customized filter circuits can also be designed. See Section 12.1, **Passive filter systems**, on page 51.

Combined detuning:
This PFC system variant is constructed with filter circuit stages of different resonant frequencies (as a rule 12.5 / 14% and 5 / 5.67%). The number and ratings of the filter circuit stages are selected so that the power ratio approaches1:1. Combined detuned circuits were formerly used in networks with utility company remote control frequencies in the range 166 to 190 Hz as a simpler variant instead of using detuned systems with AF rejector circuits. Today, on account of control system limitations, the different thermal loads on individual stages and the acute risk of overloading in networks plagued by harmonics, combined detuning is no longer recommended.

Inductive PFC systems:
In systems with a capacitive power factor (e.g. solar parks, networks where switched-mode power supplies predominate, etc.) inductances are required instead of capacitors. FRAKO has also developed controlled systems to meet this need. More information about this is given in the featured topic **Inductive power factor correction** on page 59.

■ 10.5: Monitoring PFC systems in operation

The maintenance of PFC systems after their installation is just as important as the planning and design work beforehand. Once a PFC system has been commissioned, it is frequently forgotten about. The user is usually not reminded of the fact that the capacitor contactors are components subject to wear until the unpleasant effects of contactor failure have been experienced. **Contactors are subject to high stress levels when switching capacitive loads**. Chattering switching contacts result in high charging and discharge currents in the capacitors and heavy wear and tear of the switching contacts themselves. Replacing the contactors in good time considerably prolongs the service life of the PFC system. **Switching cycle counters** have been integrated into FRAKO's state-of-the-art reactive power control relays in order to give **early information** on the wear of the contactors. The reactive power control relay indicates the optimum point in time when the contactors should be replaced and thus helps to cut costs. For preventive maintenance purposes, the user can display the cumulative total of switching cycles for each individual stage.

Changed conditions in the network can also result in disturbances in the entire low voltage power system. The purpose of system monitoring is to identify these disturbances at an early stage. FRAKO's power quality monitoring instruments offer the option of early alarms before the system or system components fail. All parameters relevant to safety and reliability in medium- and low voltage systems, the temperatures of sensitive system components and the consumption of active and reactive energy are registered, analysed, monitored and reported.

■ 10.6: What must be done if the harmonic levels are high, but the reactive power demand is low?

In such cases there are several solutions to limit harmonic currents caused by the operation of loads that generate them.

The most well-known measures to solve this problem are by means of:

- Several passive filters tuned to work together (tuned filter circuits) or
- Assigning highly non-linear loads and sensitive consumers into separate groups, feeding each group through a separate transformer.

However, these solutions involve two main disadvantages:

- Improvement of the system disturbance characteristics applies only to the particular installation involved. Each subsequent extension can mean that the initial investment becomes worthless.
- It is often very difficult to implement these solutions in practice for an existing installation.

For problems with:

- Excessively high levels of the 3rd, 9th and 15th harmonics and the high neutral conductor current they give rise to, or
- The demand for tuned acceptor circuits to maintain the harmonic current returned to the medium voltage system under a specified limit or
- Low demand for reactive power but high harmonic currents, for example, due to a large proportion of converter-controlled induction motors,

active harmonic filters or combinations of filter circuit systems with FRAKO active filters often present the optimum solutions.

Section 11: Power quality measurement and analysis

Analysis implementation and reporting requirements regarding network power quality and equipment loads (Sourced from the publication Recommendations for Harmonic and Power Measurements in Electrical Networks by ZVEI, the 'German Electrical and Electronic Manufacturers' Association).

11.1: Introduction

Germany has one of the world's most reliable networks when it comes to the supply of electrical power. But high service reliability is not necessarily synonymous with high power quality, which is affected by deviations in network voltage from the purely sinusoidal waveform, or network voltage fluctuations. Ensuring the supply of power in sufficient quality therefore plays a major role in industrial and increasingly also in public distribution networks. The number and variety of electronic power converters has significantly increased in recent years – from switched-mode power supplies to powerful rolling mill drives. In addition, new HVDC lines are being used, both on the mainland and for connecting offshore wind farms. Consequently, power electronics account for a large proportion of all electrical energy generated and consumed. Today, power quality measurements have become an essential tool for operating and/or designing power networks. These recommendations are intended to establish minimum requirements for technical reports dealing with the measurement and analysis of power quality and power rating.

11.2: Power quality

The term power quality is often used to describe the different types of disturbances that affect the quality of supply such as:

- Harmonics up to 2.5 kHz in the supply voltage and/or supply current
- Rapid voltage changes (e.g. flicker) as well as slow voltage changes and voltage band violations
- Commutation notches, which are sometimes only discernible together with cable resonance oscillations
- Interharmonic voltages and currents up to 2.0 kHz and supraharmonic voltages and currents (> 2.0 kHz)
- Current and voltage imbalances
- Audiofrequency signals

11.3: Power components

When measuring the power quality, it is necessary to differentiate between the fundamental frequency component (e.g. 50 Hz in Germany) and higher harmonic components or other elements caused by imbalance or modulation such as:

- Active power, displacement reactive power and distortion reactive power
- Reactive power caused by imbalance/modulation
- Reactive power (includes all of the above forms of reactive power and is always positive)
- Fundamental apparent power
- Apparent power taking into account all of the above power components
- Power factor λ and displacement power factor $\cos \varphi$

10-minute intervals should be selected for recording harmonics. Modern measurement instruments often also provide the option to log additional intervals. In many cases, it is necessary to analyse the 10-minute mean values to check for the presence of highly dynamic events in the electrical network. For this reason, measurement instruments provide maximum value data over 10 and/or 200 ms periods, depending on the type of device. This must be evaluated with regard to its impact on the power quality.

11.4: Evaluation basis

Power quality and power component ratio measurements are usually analysed according to the following standards or guidelines:

- IEC 61000 for power quality limits in public and industrial medium and low voltage power supply systems (voltages only)
- EN 50160 for public networks supplying high, medium and low voltage electricity (voltages only)
- D-A-CH-CZ Technical rules for the assessment of network disturbances (voltages and currents)
- VDE application guides 41XX for high, medium and low voltage electricity (voltages only)
- IEC 60871 for HV power capacitors
- IEC 60831 for LV power capacitors
- DIN EN 61800 for variable-speed drives
- Other global standards: IEEE 519, GB/T 15543, GOST 13109, Engineering Recommendations G5/4-1 and P28
- Network connection contract detailing the displacement power factor cos φ and other conditions agreed

The measured values must be within the set limits during 95 or 100 percent of the measurement time (usually one week), depending on the standard concerned.

11.5: Measurement tasks

The following information must be recorded in the final report after measuring the power quality of an electrical network:

- Exact name of the company, location and substation
- Measurement reason (routine check, disturbance, basis for network expansion or plant design)
- Exact measurement period
- Circuit diagram (simplified or detailed) specifying the measuring point and switching state
- Load conditions (normal load or deviating conditions)
- Exposed consumer (e.g. drive converter or welding machine), specifying data and possibly the load profile
- PFC equipment and relevant switching states
- Network filters
- Power generation equipment and emergency power systems
- Measurement analysis basis (standards, guidelines)
- Who performed which measurement
- Name of distribution network operator

11.6: Suitability of measurement equipment

It is essential to hold a technical meeting with the customer to determine the underlying conditions for the necessary measurements. Based on the outcome of the meeting, conclusions can be drawn about the measurement equipment to be used.

A distinction must be made between simple measurement tasks with measurement instruments for recording statistical data and measurements for technically demanding network analyses with instruments that have a frequency resolution from 20 to 150 kHz and can record triggerable faults. This is particularly essential for the latest generation of converters and network resonances due to the instruments' capacitances (e.g. non-detuned PFC systems, input filters, power cables).

Measurement of power quality
For power quality measurements, Class A instruments as defined in IEC 61000-4-30 must always be used. This ensures that the measurement results comply with the relevant standards and are suitable for unrestricted use. To evaluate the connection point in public networks, a 10-minute time interval should be used for the measurement. For analysing the load characteristics, this interval can be reduced or oscillograms can be created, for example to detect commutation notches. To determine the correct flicker values, the relevant nominal supply voltage must be stated in the measurement parameters.

Audiofrequency signals
Prior to setting the measurement parameters, it is necessary to find out and enter the audiofrequency signals used in the network from the customer or distribution network operator. The signal frequency and level are important when it comes to specifying the measures necessary to reduce the harmonics.

Measurement of current
Currents can be measured with split core current transformers or Rogowski coils, the transformer ratio and phase angle with respect to the relevant voltage being taken into account. If the instrument features a phasor diagram, this should be used to avoid measurement errors. Modern measuring instruments also offer possibilities for data post-processing if faulty parameter settings are identified.

Measurement of power
In many cases, power measurements with a time resolution corresponding to a meter polling interval of 15 minutes should be selected. The transmission characteristics of the voltage transformers must be taken into account, especially in medium and high voltage networks. Depending on the transformer, significant distortions of measured values may occur from 1.0 kHz upwards due to internal resonances in the inductive transformer. Today, power electronics devices that generate even harmonics and interharmonics are increasingly in use. For this reason, the relevant analysis modes of the measuring instruments must be evaluated and, if necessary, presented in the report. The accuracy of the measured results should always be assessed before or after the measurements, taking into account the accuracy class, the transformer and the technical data of the measurement instruments. The physical position of the Rogowski coils, for example, also greatly affects the accuracy and can cause errors of up to 20 percent.

11.7: Measurement implementation

Before the measurements commence, the necessary load variations or switching states must be clarified with the system operator. These must be documented by the network operator if this information is not clearly evident from the measurement results.

The duration of the measurements, which should normally cover all load conditions, can also be based on this information. Only then can appropriate measures be derived for the operational management of a network—for example if the limits set by standards are reached or exceeded.

Triggers for switching operations or load changes may be required if measurements of random disturbances are taken.

For longer, unsupervised measurements, only approved equipment, instrument cables and adapters are to be used to prevent personal injury.

11.8: Format of report and recommendations

There are two options for the technical reports that present the measurement results:

- Executive summary with selected measurement results
- Comprehensive report with a theoretical section (explaining the occurrence of phenomena such as flicker, harmonics, voltage dips), a section describing the measurement procedures and various attachments for the individual measurement points

In both cases, it should be ensured that the measurements are evaluated with regard to their compliance with the standards or specifications of the network operator or their going outside the set limits. Thus the person commissioning the network analysis, who is often not a proven expert in the field of power quality, is given the opportunity to evaluate the measurements performed and to draw conclusions for the operation of his or her electrical network.

If set limits are exceeded, e.g. for harmonics, flicker (rapid voltage fluctuations) and reactive power, the report must always contain recommendations for remedial measures to be taken by network operators and consumers:

- Increasing the short-circuit power by changing the transformer power or increasing the network connection capacity
- Changing the pulse rate of power converter systems
- Changing from diode to active front end in the supply-side circuit
- Capacitive PFC systems with contactor control or low voltage semiconductor switches for high load dynamics, but sometimes also inductive systems
- Passive filter circuits (paying attention to capacitive reactive power)
- Active power filters
- Dynamic filter systems that can generate inductive and capacitive reactive power

It is also necessary to address future changes in the customer's network (increase in demand, installation of more converter drives, etc.). However, the recommendations should only provide an objective description of the effectiveness of the individual supply-side or consumer-side measures as well as the economic aspects, such as power losses, while maintaining a vendor-neutral position.

11.9: Measurement report checklist

- ❑ Exact company name, location, substation and measurement point
- ❑ Reason for the measurement
  - Operational measurement/routine check
  - Fault diagnosis/troubleshooting
  - Data acquisition for designing new installations/expansion
- ❑ Measurement period
- ❑ Information about the measurement instrument used
- ❑ Information about the standards and guidelines used, and requirements of the distribution network operator, if specified
- ❑ Circuit diagram indicating the measurement point and switching states (open/closed switches)
- ❑ Information about loads
  - Non-linear loads (with active components and non-sinusoidal current draw, e.g. all types of power converters and power supply units)
  - Linear loads (with passive components and sinusoidal current draw)
  - In-house generation (emergency power generators, CHP, PV systems)
  - PFC systems/filters (active/passive)
- ❑ Load conditions (with timing specification)
  - Shift operation
  - Maintenance shifts
  - Load conditions deviating from normal
- ❑ Report detailing the results and their evaluation
- ❑ Conclusions and any recommended actions

FRAKO is there to help you!

We are always more than willing to visit your premises and listen to your concerns and issues with subjects such as power quality, reliability of the installation, disturbances during operation, energy efficiency, utilities management and reduction of energy costs. Working together with you, our technicians and engineers are certain to devise solutions for your problems.

We offer complete system measurements and analyses, or provide instruments on loan for this purpose from our equipment pool. When the instrument is returned to us, our specialists prepare a detailed written analysis of the results, including suggestions for improving your system.

More information is available on our website, where analysis instruments can also be reserved when required: www.frako.com/en/service/consulting/

Section 12: Harmonic filter systems

■ 12.1: Passive filter systems

Passive filters - also known as series resonant circuits or tuned filters - are tuned directly for individual harmonics. They are not installed primarily to correct reactive power but to extract the harmonics. As only little capacitive reactive power is required in modern industrial installations, the challenge is to filter out as many harmonics as possible while having as little reactive power as possible. FRAKO passive filters have a rating of some 300 A for only 100 kVAr reactive power and therefore offer an excellent cost-benefit ratio!

This extreme harmonics mitigation effect harbours a high risk of overloading the system if the latter's conditions change. To obtain optimum harmonics mitigation while overcoming the risk of system overload, innovative filter systems are equipped with an automatic device to detune individual load stages. This makes it possible to strengthen or weaken the extraction effect, the system thus adjusting itself to the optimum degree of detuning.

A passive filter system with automatic detuning consists essentially of the following components:

- Load circuit with several **filter stage** modules (power capacitors, inductors, switchgear, overcurrent protection)
- Up to 3 **detuning stages** per filter stage (detuning capacitors, switchgear, overcurrent protection)
- A higher level **control system** (system analysis instrument with controller function)

The higher level control system analyses and saves the data on power quality and the loading of the filter stages. On the basis of the analysed data it controls the filter and detuning stages, the usual controlled variables being the harmonic levels and the system loading.

***Fig. 47**: Passive filter system with up to 400 A current rating*

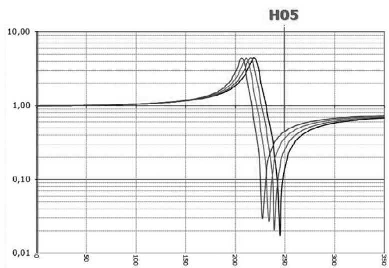


***Fig. 48**: Impedance curve for four controlled degrees of detuning*

If the reactive power of the system results in undesirable capacitive power factors, or the system is already capacitive, active filter systems must be installed; see Section 12.2, **Active filter systems**, on page 52.

■ 12.2: Active filter systems

The crucial advantage of an active filter is that it mitigates the harmonics without the undesirable side effect of impacting on the power factor at 50 Hz. In addition, the correction of network disturbances still remains effective if subsequent extensions are made to the installation. The modular design of the FRAKO active filter means that the required nominal rating can be selected quite simply to suit updated needs, extensions to the installation being catered for at any time by the addition of more filter modules. This means that the initial investment in equipment is not squandered!

Operating principle of active harmonic filters

The active filter is installed in parallel to the harmonic generators. It analyses the harmonic current produced by the nonlinear loads and supplies a 180° out-of-phase compensating current, either over the entire spectrum from the 2nd to the 50th harmonic or for a specially targeted harmonic. This action neutralizes the harmonic currents concerned completely at the point of connection, provided that the system has been appropriately dimensioned.

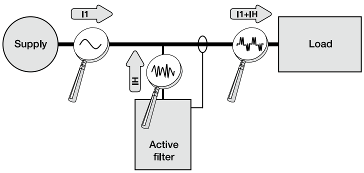


__Fig. 49__: Operating principle of the active filter
I1: Fundamental current
IH: Harmonic current

The combination of harmonic filter and harmonic load appears to the network as an overall linear load drawing a sinusoidal current. Installation is quite simple. A 3-phase feeder with or without a neutral conductor needs to be available. The current transformer is then installed in the line to the non-linear load.

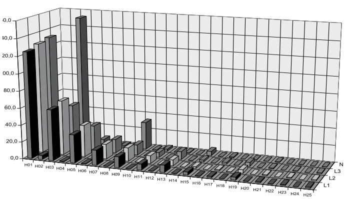


__Fig. 50__: Harmonics measured ***without*** *filter*

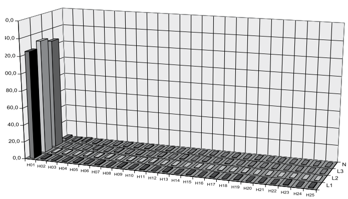


__Fig. 51__: Harmonics measured ***with*** *filter*

Typical applications are in:

- Low voltage systems with many converters that are under an obligation to return only limited harmonic currents to the preceding network, where, for example, long spur lines to remote installations are involved with correspondingly low short-circuit power.
- Modern converter drives that return high levels of harmonics to the distribution system, but with only a low demand for reactive power.
- Low voltage networks with a high proportion of the 3rd harmonic due to the installation of single-phase harmonics-generating devices. See the description of problems in the neutral conductor on page 33.

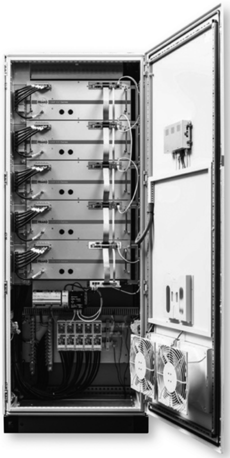
In addition to neutralizing harmonics, FRAKO active filters possess other functions, such as **dynamic power factor correction** and **load balancing**.

Special highly dynamic, voltage-controlled systems mitigate harmonics up to the 100th order by means of the system impedance. See the featured topic **Active filters** (voltage-controlled) from page 57 onwards.

Section 13: Featured topics

13.1: Featured topic: Active filters (current-controlled) 'Active against harmonics'

Power consumers have been offered to date hardly any means of minimizing harmonics in their distribution systems at reasonable cost. The usual method has been to try to eliminate or attenuate the harmonics at the device that generates them by installing passive elements in the circuit. This means, however, that a tuned acceptor circuit with inductance and capacitance must be installed for each harmonic in order to reduce its undesirable effects. The problem can now be solved more conveniently with the help of an active harmonic filter.



Active harmonics filter in modular enclosure system

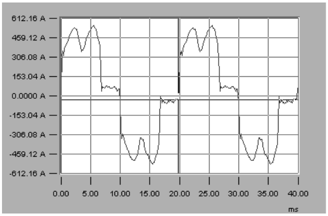
All integral multiples of a fundamental frequency are known as harmonics. It is common practice to label each individual harmonic with the ordinal number n. When the mains frequency is 50 Hz, the 5th harmonic thus has a frequency of 250 Hz. Mathematical analysis has revealed that any complete and repetitive waveform is made up of a set of numerous purely sinusoidal frequencies. These harmonics are generated when operating with loads in the consumer circuit that do not draw current sinusoidally. The waveform for the current drawn by these loads determines the number and amplitude of the harmonics. The greater the deviation from the sinusoidal ideal, the more harmonics are returned by the consumer to the supply network and the greater the amplitude of the individual harmonics. The mathematical technique of Fourier analysis is used to divide the complex waveform into a set of harmonics, each of which is assigned the appropriate value of n and its amplitude.

A simple method for determining individual harmonics is by measuring with a clamp meter that can filter out and display individual harmonics from the measurement signal. Although only one harmonic at a time can be displayed with this method, it is relatively quick and simple to obtain a rough overview of the amplitudes of the individual harmonics. There is a variety of symptoms that indicate the presence of harmonics in a system: PCs crash, hard disk errors occur, monitors flicker, the neutral conductor overheats, damage occurs to PFC systems or corrosion is detected in other parts of the installation.

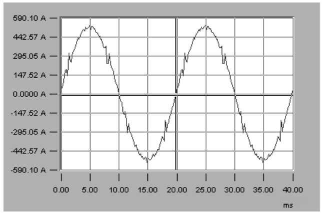
Operating principle of a harmonic filter

The underlying concept of the harmonic filter is the use of an active correction function. This is done not by extracting currents, but by injecting additional currents whenever required. A current transformer first measures the current being drawn momentarily by the load. The control unit in the harmonic filter then analyses this current for amplitude and harmonics. It consequently feeds a current into the supply system whose amplitude and individual harmonic number is exactly equal to the current drawn by the load, but 180° out of phase with it. The harmonic currents thus cancel each other out and the supply network only has to supply the fundamental frequency and is not contaminated with harmonics. One great advantage of the active filter compared to conventional techniques is its flexibility in adapting the corrective power. Depending on requirements, the filter can supply more or less corrective current. Even if overloading occurs, the filter does not switch off but assumes a current-limiting mode, i.e. the filter supplies its maximum current and in so doing neutralizes a large proportion of the harmonics. Interaction with other system components, such as detuned PFC systems or UPS units is therefore reduced to a minimum that is not critical. It is no problem to extend the system or install a combination of several filters. If operating or network conditions change, the filter automatically adapts to the new conditions within the scope of its nominal rating.

■ Significance of the electrical installation



*Current waveform **without** harmonic filter*



*Current waveform **with** harmonic filter*

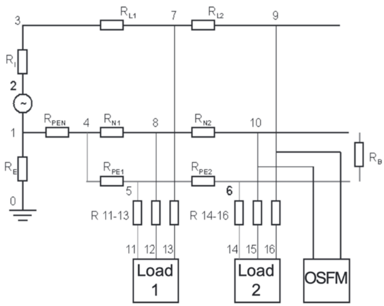
Correct installation of the electrical system is of fundamental importance for the satisfactory functioning of a harmonics mitigation unit. Both the type of system and the way it has been installed can not only detract from the effectiveness of the harmonic filter but can also encourage or even cause disturbances in the electric power supply. Every electrical installation relies fundamentally upon its earthing. An effective and consistently applied earthing system is the basis of every power supply installation. If there is a 'gremlin' in the earthing system, ideal conditions are brought about for parasitic voltages, for electromagnetic disturbances and, of course, for harmonics to be propagated without hindrance. The main function of the earthing system is to ensure that, if a fault occurs, no dangerous voltages can arise where contact can cause injury or death, and that the current can flow to earth unimpeded. This is the only way to ensure that an overcurrent protection device in the supply current can respond and trip out the circuit within the prescribed time limit. In addition, the earthing system is there to maintain the various items of electrical apparatus at a uniform potential that is as low as possible and to correct any differences in potential that might otherwise arise.

■ Strict separation of N and PE

If this separation is not achieved, for example because load currents are flowing in the PE conductor, electromagnetic fields are then formed around the earthing and potential equalization conductors, which can have considerable negative effects. Since these fields could also be formed in the shielding of data cables, the interference produced could result in data being lost. Connecting the PE conductor to other conductive systems such as water, gas or central heating installations causes additional load currents in these parts of the system. The consequences are parasitic voltages and corrosion.

For this reason it is a major requirement for modern power supply systems that attention be paid as early as possible to ensure that there is a clear separation between N and PE conductors, and that they always remain isolated from each other once work on their installation has started.

In one specific case, telephones were disrupted and monitor screens caused to flicker due to the effects of harmonics. Measurement of these harmonics revealed a heavy proportion of the third harmonic, amounting to up to 35% of the nominal current; not only in the N conductor but also in the PE conductor.



Schematic of a simulated single-phase system

Before measures can be taken to counteract harmonics in such cases, the wiring must be optimized to comply with the foregoing criteria. Unfortunately, the regulations in force in Germany in 2001 did not categorically prescribe the separation of N and PE. There are only recommendations stemming mainly from the IT and telecommunications industry and from VdS (a subsidiary of GDV, the German Insurance Association) for supply cables to consistently use the 5-wire system. Filter currents cannot, of course, be avoided in the PE conductor, but they can be tolerated provided that no load currents or harmonics are also present. The present-day EMC directives mean that the designers of both electrical installations and devices have to contend with a technical trade-off. On the one hand, the instruments and installations should feed as little interference as possible into the network; on the other hand, they themselves must function interference-free and any interference currents generated should be dissipated. This is achieved mainly by leakage through filter capacitors directly to the earth conductor. With permanently connected systems this leakage can also be to the neutral conductor. However, this is not possible with devices fitted with German earthed plugs, since they can be turned through 180°, and their polarity is therefore not defined.

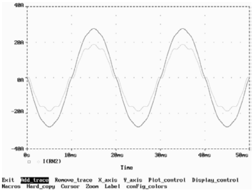
■ A typical example

A conventional PC with a 250 W AC adapter has a leakage current of about 1 mA. This is composed of a 50 Hz fundamental component and various harmonics. The leakage currents ‘contaminate’ the PE conductor which, in general, is not critical for the reliability of a system. With 100 PCs this therefore gives rise to a leakage current of about 0.1 A. Assuming that the resistance of the PE conductor is about 1 Ω, the resultant voltage drop is 0.1 V. The entire earthing system usually has a low resistance. (A conductor with a cross-sectional area of 10 mm^2 has a resistance of 0.0012 Ω per metre). By contrast, however, in a system having a rated load current of 100 A, the third harmonic can easily result in a harmonic current of 40 A, thus giving rise to a voltage drop of no less than 40 V.

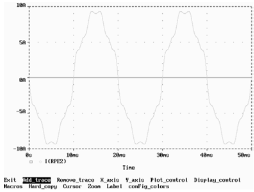
This is a classical application for an active harmonic filter. By compensating for loads that generate heavy harmonic currents, the filter removes harmonics from the distribution system and protects other consumers from the effects of the harmonics. This can only work, however, if there is a strict separation of N and PE conductors. In practice it has been shown that the use of active filters enables the harmonics to be reduced from over 30% to about 5%. This was achieved with loads having highly distorted current input curves and in addition subject to current peaks.

Simulation of different conditions in distribution systems can give a clear picture of the effect on harmonics content. For the sake of simplicity, it suffices to illustrate this with a single-phase network with N and PE conductors. Two loads are connected to the system, with the first of these returning harmonics to the power supply system, the second load, however, either generating no harmonics or else these being neutralized by a harmonic filter. In the ideal case, the only current flowing in the PE conductor consists of the load filter currents caused, for example, by switched-mode power supply units or network input filters.

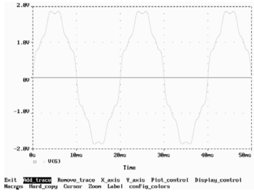
Harmonics are, of course, also discharged to the PE conductor via these filters. In order to carry out the simulation under conditions that were as realistic as possible, the amplitude and harmonic number of each component were adopted from a system analysis.



Current in R_{N2} with and without bridge resistor R_B



Current in R_{PE2} with and without bridge resistor R_B



Potential in PE conductor at load 2 relative to earth

The profile of the current curve is an approximation to the conditions actually occurring in a power supply system under load. The filter leakage current is in the order of milliamperes, despite the presence of harmonics, and therefore has only a slight negative impact on the functioning of the PE conductor. If the strict separation of N and PE is now removed, for example, by installing a jumper between the N and PE busbars in a subdistribution board, then load currents flow in the PE conductor. Since the N and PE conductors are effectively arranged in parallel, the currents are distributed between the two in inverse proportion to their relative resistances.

This connection between the N and PE conductors means that voltages and consequently electromagnetic fields are developed in cable shielding, conduits and the piping for water, central heating and gas. All metal components in the building can thus become sources of interference. The earth conductor is now burdened with load currents and its potential relative to earth is raised. Depending on the magnitudes of the current and the resistance, voltages up to the order of 100 V can occur. When harmonic currents also flow in the earth conductor, the amperage can rise to levels considerably higher than the actual rated current of the load. Apart from causing the system to malfunction, this can also result in an impermissible temperature rise in the PE/N conductors. In the worst case, this can even cause a fire. The voltage in the PE conductor naturally increases in proportion to the current, thus developing a high potential relative to earth. As the PE conductor is no longer at earth potential, it cannot fulfil the task for which it was provided in the first place.

Summary

An effective measure to reduce harmonics and their undesirable effects on the power distribution system is to install active harmonic filters. It is just as important, however, to have an electrical system that has been installed correctly and is as transparent as possible. In practice it is therefore imperative to measure currents in the earth conductor. This means that impermissible currents can be detected immediately. Far more effort is involved, however, in locating the superfluous connections between the N and PE conductors. This requires accurate knowledge of the cable layouts and the construction of the building. Only by following the above mentioned guidelines systematically is it possible to 'clean up' the power distribution system and improve the quality of the supply voltage.

13.2: Featured topic: Active filters (voltage-controlled) 'Also for standby generator power'

Nowadays, nearly all the consumers connected to the electricity supply network constitute non-linear loads. Their non-sinusoidal current draw distorts the supply network voltage and thus generates harmonics. This results in overloading of the connected devices and installations, which can disrupt the infrastructure of a company even to the point of jeopardizing operational reliability. Passive or active filter systems provide a remedy for this situation.

High-speed active filter in enclosure system

Difficulties arise with vital infrastructure systems in which network stability must always be ensured, not only when running on the normal power supply but also when powered by standby generators. Such critical infrastructure facilities have a high societal relevance and merit special safeguards. Examples include IT and telecommunications systems, electrical distribution networks and water supplies, medical and emergency services, and financial systems, to name but a few.

A public service broadcaster installed new transmitters when upgrading from the DVB-T to the DVB-T2 HD standard, which promised to provide more programmes with a much improved picture quality. As public service broadcasting is also considered a vital infrastructure, the transmission equipment must be able to broadcast at all times without interruption. In addition to working from the normal power supply, the system must also function correctly when an emergency generator is providing the power. FRAKO was entrusted with the analysis of power quality measurements made during operation with both external utility power and the standby generator, in order to identify any problems with harmonics or resonant ranges.

Results: The new transmitter system with a total rating of 150 kW is not a particularly powerful consumer. Its power factor (cos phi, inductive) is better than 0.95 and therefore no power factor correction is needed. All harmonic voltages up to the 50th, and their vector sum THDv, were within the limits called for by Class 2 of the standard EN 61000-2-4 when the installation was running on external utility power. However, when it operated with power from the standby generator, high harmonic levels above the 25th, i.e. well above 1 kHz, were identified. These resulted from points of resonance around the 29th harmonic, the measurements revealing an abrupt rise in higher-order harmonics.

Problems with harmonics when a standby generator is used

The points of resonance are caused by the capacitances in the transmitter systems that are not detuned. They give rise to system resonance at about 1450 Hz, and should therefore be mitigated with a filter. However, the resonant frequency varies greatly, being dependent on the short-circuit power of the complete installation. When operating with power from the external utility, its short-circuit power is high, the resonant frequency being over 3 kHz, but when powered by a standby generator the short-circuit power is much lower, the resonant frequency falling to only 1.5 kHz.

When the filter system was selected, the primary objective was to obtain undisrupted operation when running either on external power or with the standby generator. In addition, the harmonics, which as a rule are audible, were not to be broadcast by the transmitter system!

Only voltage-controlled active filters are suitable

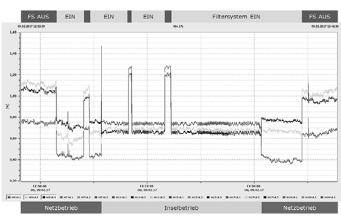
Passive filter systems act inductively at frequencies above their tuning frequency, displaying a low impedance to the harmonics and thus effectively extracting them selectively. Their disadvantage is that they are only designed for a certain frequency range, and they create an additional fundamental reactive power, which in this case would have resulted in a capacitive power factor. This, however, was not the only reason they were unsuitable for the application—the harmonics spectrum when operating on generator power is also vastly different.

Active filter systems provide a compensating current in phase opposition to neutralize the harmonics. They can automatically adapt to the frequencies to be neutralized. A distinction is made between current-controlled and voltage-controlled active filters. The former measure the load current and use Fourier analysis to compute the required compensating current in phase opposition. They can neutralize various orders of harmonics simultaneously while dynamically correcting reactive power. Voltage-controlled filters can be impedance-regulated, i.e. not only do they neutralize the harmonics, they also actively suppress resonance. As no current transformers are necessary, these systems work significantly faster than current-controlled filters. In the case of the transmitter application, a voltage-controlled active filter was the optimum solution. Had a current-controlled active filter been used, there could have been instability between the filter's current regulating function and the control of the standby generator when this was operating.

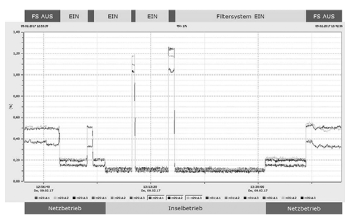
The solution: a high-speed active filter

The broadcaster was supplied with a voltage-controlled active filter by FRAKO. This 3-wire device with a nominal power rating of 70 kVA can mitigate harmonics up to the 100th, i.e. up to 5 kHz, either the entire spectrum being neutralized or only selected frequencies. In addition, resonance is extensively dampened. A response time of under 20 µs makes the filter especially suitable for rapid and substantial load changes. This active filter system does not require current transformers, which in this case simplified the electrical installation.

The voltage-controlled filter unit meets the specified requirements when the system is operating on external power or with the standby generator, now considerably reducing the impact on the power supply network. The levels of all the previously critical higher harmonics have been significantly reduced. This is particularly evident on standby power, since far less generator noise can be heard. Additionally, in both operating modes the typical 5th and 7th harmonics from the power converter have been reduced to uncritical levels below 1%.



5th voltage harmonic [250 Hz]



29th voltage harmonic [1450 Hz]

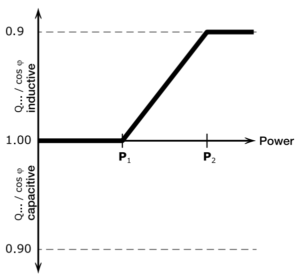
13.3: Featured topic: Inductive power factor correction for solar parks 'A special case'

In recent decades, the drive to reduce our dependence on fossil fuels for power generation has resulted in solar parks, otherwise known as photovoltaic power plants or simply PV systems, establishing themselves as a reliable source of electrical energy. In the case of the larger systems, maximization of their overall efficiency is an important aspect in ensuring that the power generated remains not only reliable but also affordable. In addition to the usual measures taken to enhance the performance of the solar modules themselves, there is further potential in optimizing the energy they produce.

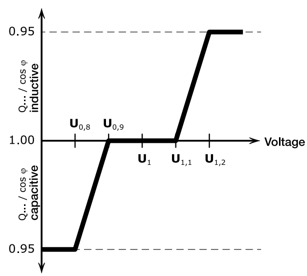
In Germany, most solar parks typically generate between 1 MW and 20 MW, and are thus governed by the technical regulations of the Federal Association of the German Energy and Water Industries (BDEW): 'Guideline for the connection and parallel operation of generation plants in the medium voltage network'. Since 2008, this guideline has set out the key points to be observed when a power generation system is connected up to a power distribution operator's medium voltage network.

These requirements include a network-compatible power factor at the feed-in point. This means that when delivering active power, the generation plant must be capable, under all load conditions, of operating with a reactive power corresponding to a power factor cos φ between 0.95 lagging and 0.95 leading at the network entry point. Overexcited operation (capacitive) would increase the voltage, while underexcited operation (inductive) would reduce it ➛ generation systems must therefore help in maintaining a steady network voltage.

Various network configurations and load conditions give rise to a variety of needs, which is why power distribution operators stipulate individual requirements for the network section concerned. These can vary greatly from one operator to the next, and are set out in the form of a characteristic curve where the power factor is stated either as a function of the active power (the cos φ (P) characteristic) or directly as a function of the voltage (the Q (V) characteristic). The BDEW guideline calls for the power factor to be regulated to the target value thus stipulated within 10 seconds.



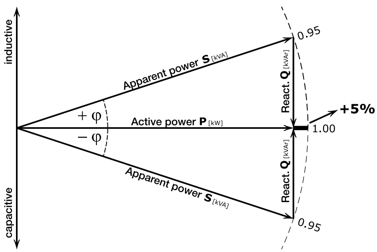
Typical cos cos φ (P) characteristic



Typical Q (V) characteristic

Optimization potential 1: Modern inverters are 'reactive power capable' and can convert the energy captured by solar modules and feed it into the utility network in compliance with the characteristic curves. However, there is a great disadvantage to this: inverters deliver apparent power, i.e. the Pythagorean sum of active and reactive power! The worse the required power factor specified, the less is the revenue-earning active power that an inverter can supply, regardless of whether this in the inductive or capacitive region.

Example: If a power factor of 0.95 is stipulated, the inverters must supply an amount of reactive power equivalent to 33% of the active power. However, if this required reactive power is supplied by a suitable power factor correction system, allowing the inverters to operate at a power factor of 1, this yields 5% more billable active power for the same inverter apparent power!



Power triangle, the relationship between active, reactive and apparent power

To make it at all possible for larger PV systems to feed into existing medium voltage networks, some present-day operators are even specifying power factors that can go as low as 0.90. In this case, the amount of reactive power required is equivalent to 48% of the active power. Supplying this reactive power from the PFC system can thus increase the billable active power exported by 11%!

It is therefore a worthwhile proposition to provide the reactive power separately, so that the inverters can deliver the maximum possible active power!

Optimization potential 2: When modern inverters operate under no-load conditions (particularly at night or if the solar panels are deprived of sunlight by clouds, fog, snow, etc.), the total no-load reactive power from all the inverters puts a heavy capacitive load on the network. To suppress this effect, inverters are often switched off during such periods, but this considerably reduces their service life. In this case as well, a separate power factor correction system offers significant potential for system optimization.

Optimization potential 3: The length of the cabling between a solar park and the medium voltage network entry point can easily amount to several kilometres. As the conductors are laid close together, long underground cables have a capacitive effect, whereas overhead lines have an inductive effect. One kilometre of underground cabling can therefore give rise to several kVAr of capacitive reactive power, which, since it develops on the way to the solar park and thus can neither be detected nor measured by the inverter control system, must be corrected separately.

The problem: The network operator's specifications relate to the PV system's entry point to the medium voltage network, which is frequently several kilometres away from the solar park itself. This means that these specifications and the BDEW guideline must be complied with not directly at the solar park, but at the feed-in connection!

The solution: Some time ago, FRAKO carried out an in-depth study of a medium-sized solar park, applying the three optimization approaches outlined above. An appropriate power factor correction system was then designed, installed and commissioned.

Solar park key data:

- System power rating: .... 3,122 kWp
- Annual output: .... 2,849,400 kWh
- Surface area:.. 4.7 ha
- Annual CO_2 savings:.. 1,710 t
- Distance of park from feed-in point: .... 5 km

The network operator's specifications:

- The target power factor must be 0.95 inductive during network feed-in operation.
- The power factor must never be capacitive when power is drawn from the network.
- The power factor must be adjusted to the target value within 10 seconds as per the BDEW guideline.

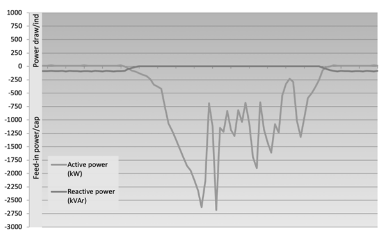
These specifications lead to the requirement that appropriate power factor correction is made - during the day for the necessary dynamic reactive power of the entire solar park plus the cabling capacitance, and at night for the no-load reactive power of the inverters plus the cabling capacitance.

Reactive power determined:

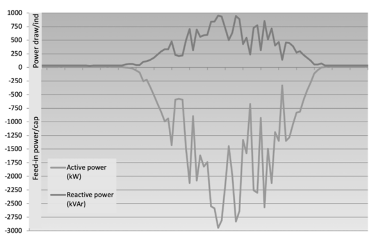
- The reactive power needed to correct cos φ at the inverters to 1.00 amounts to a total of 950 kVAr inductive (equivalent to about 1/3 of the active power).
- Total no-load reactive power of the 141 inverters: 98 kVAr capacitive.
- Cabling reactive power under partial load and no load conditions: 45 - 90 kVAr capacitive.

As all three of the above circumstances called for inductive reactive power to be provided, a power factor correction system with a total of 990 kVAr inductive reactive power was installed, distributed across seven bayed cabinets. The system was designed with differently sized stages, comprising low-loss inductors, switchgear and group overcurrent protection. It was essential to measure and evaluate the various requirements for reactive power. This was done by linking measurements at the remote feed-in point with those directly in the solar park and transmitting their readings to an intelligent reactive power control relay, which switched the stages of the power factor correction system in or out within the stipulated 10 seconds, thus ensuring ongoing compliance with the specifications.

The result: Thanks to the additional yield of billable active power achieved by the power factor correction system, the investment paid for itself completely within 22 months, and now continues to boost the revenue of the solar park by 5%.



*Reactive and active power **without** PFC*



*Reactive and active power **with** PFC*

Notes

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