Reducing energy costs

using
power factor correction and
energy control systems

Energy management
with a system

Planning guidelines

One System. Best Solutions.

KBR Energy Management

KBR services:

- System planning and on-site consulting
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KBR production facilities in Schwabach, Germany

Your personal contact:

The red KBR booklet - the original

This little booklet has been making work easier for us and you every day since 1976. The content of this booklet is intended to assist the user in the operation of reactive current compensation and energy control systems.

The issues of lowering energy costs and network quality are always current. The increased use of compensation and energy control systems does not only reduce costs but also the load on a company‘s own lines and distributions, as well as on electricity producers and distribution networks.

This booklet includes the most important information on various topics from the planning to the connection of our systems. In this context, particular attention is given to the topic of harmonics.

If you have any questions not answered by this booklet, feel free to contact us at any time.

Our sales team will be pleased to assist you in case of questions or problems.

Your KBR TEAM

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1 Terminology (in alphabetical order)

Absorption circuit, tuned

Series resonant circuit consisting of a reactor and a capacitor, tuned specially to create only minor impedances for harmonic currents. Tuned resonant circuits, in particular, are used to conduct a network cleanup of a network harmonic.

Absorption circuit, untuned

Series resonant circuit consisting of a reactor and a capacitor, tuned to a frequency below the lowest harmonic to prevent resonances.

Audio frequency

Signal with a higher frequency, superimposed on the line voltage and used to control street lights, HT/LT switching and storage heaters.

Audio frequency blocking circuit

Element consisting of a primary reactor and a parallel resonant circuit (secondary reactor and capacitor) connected in parallel to the coil. The audio frequency blocking device is used to block the energy supplier's audio frequency signal.

Combination filter

Parallel connection of two different detuning factors to block ripple-control signals and for cost-effective network cleanup.

Cos-phi φ

The displacement factor represents the phase shift between current and voltage (only fundamental component of 50/60Hz). Distinction is made between inductive and capacitive cos-phi. With cos-phi, the percentage of reactive power in the network can be calculated.

Detuning

Series connection of reactors and capacitors.

Detuning factor

Percentage ratio (p) of reactor reactance X_L to capacitor reactance X_C. Standard detuning factors are, for example, 5.5%, 7% and 14%.

Fourier analysis

By conducting a Fourier analysis, a non-sinusoidal function can be broken down into its harmonic components. Oscillation with an angular frequency of ω_0 is referred to as the fundamental component. Oscillations with angular frequencies of $n \times \omega_0$ are referred to as harmonics.

Harmonic currents

Harmonic currents are created by non-sinusoidal current consumption of devices and systems. Harmonic currents are imposed on the power supply system.

Harmonic voltages

Harmonic voltages are created by a voltage dip at the network impedances caused by the harmonic currents in the network.

Harmonics

Sinusoidal oscillation whose a frequency is an integer multiple of the line frequency. An ordinal n (3rd, 5th, 7th etc.) is assigned to every harmonic.

Impedance

The resulting impedance (resistance) at a certain point of the distribution network at a defined frequency. Impedance depends on the consumers connected to the network, the existing distribution transformers, line cross-sections and line lengths.

Impedance factor

The impedance factor α is the ratio of the audio frequency impedance and to the 50 Hz impedance.

Interharmonics

Sinusoidal oscillation whose frequency is not an integer multiple of the fundamental frequency.

λ **Power factor**

Lambda - The power factor represents the phase shift between current and voltage. This includes not only the fundamental components but also the harmonics.

Parallel resonant frequency

Frequency at which the modulus of impedance of a network is at its maximum. In the parallel resonant circuit, the partial currents IL and IC exceed the total current I.

Reactive power compensation

To avoid uneconomical power transmission, energy suppliers stipulate a minimum power factor. If a company's power factor is smaller than that minimum value, the respective part of the reactive power has to be paid for. Instead of making this payment, it is more economical to improve the power factor by using a capacitor. For this purpose, capacitors are connected parallel to other consumers.

Reactor frequency

Series resonant frequency to which the series connection of reactor and capacitor is tuned.

Reactive power

Reactive power Q is needed, for example, for magnetization of motors and transformers or for the commutation of converters. In contrast to active power, reactive power does not perform any effective work. The unit for reactive power is var or kvar.

Reactive power compensation

To avoid uneconomical power transmission, energy suppliers stipulate a minimum power factor. If a company's power factor is smaller than that minimum value, the respective part of the reactive power has to be paid for. Instead of making this payment, it is more economical to improve the power factor by using a capacitor. For this purpose, capacitors are connected parallel to other consumers.

Resonant frequency

Each connection of inductances and capacitances creates a resonant circuit with a certain resonant frequency. In a network with several inductances and capacitances, different resonant frequencies occur.

Resonances

The equipment used in the network creates resonant circuits due to their capacitances (cables, compensation capacitors, etc.) and inductances (transformers, reactors, etc.). These can be triggered to resonate by network harmonics. One reason for network harmonics is the non-linear magnetization characteristics of transformer magnetic circuits. The dominant component here is the 3rd harmonic, which has the same phase angle in all lines and is consequently not nullified in the neutral point.

Series resonant frequency

Frequency at which the modulus of impedance of a network is at its minimum. In the series resonant circuit, the partial voltages U_L and U_C are greater than the total voltage U.

Series resonant circuit

Series connection of inductance (inductor) and capacitance (capacitor).

THD-F

The harmonic distortion in percent in relation to the RMS value of the fundamental component. F = fundamental. Since the distortion applies only to the fundamental component, values larger than 100% are possible.

THD-R

The harmonic distortion in percent in relation to the RMS value of the entire waveform (fundamental component and harmonics). The total harmonic distortion cannot be greater than 100%.

2 Network quality

Network quality refers to the consumer's security of supply of an undistorted sinusoidal line voltage with a constant amplitude and frequency. Network quality can be affected by malfunctions in the supply network (automatic reclosing, voltage dips, overvoltage) or by disturbances caused by loads (flickers, harmonics, asymmetries, voltage fluctuations).

2.1 EN 50160 – European standard on power quality

The EN 50160 standard defines, among other things, parameters such as network frequency, voltage variations, voltage dips, supply voltage interruptions, flickers, etc. Some of the requirements are described in more detail below.

Low voltage level for network harmonics

for odd-numbered harmonics not divisible by 3		for odd-numbered harmonics divisible by 3		for even harmonics	
n	%	n	%	n	%
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6	0.5
13	3	21	0.5	8	
17	2	>21	0.5	10	0.5
19	1.5			12	
23	1.5			14	0.5
25	1.5			16	
29	1.05			>18	0.5
31	0.92				
35	0.76				
37	0.7				

Network frequency

The network frequency of 50Hz must not vary by more than ±1%.

Slow voltage variations

Over a measurement duration of a week 95% of the measured 10-minute voltage mean values have to be in the range of ±10% of the supply voltage.

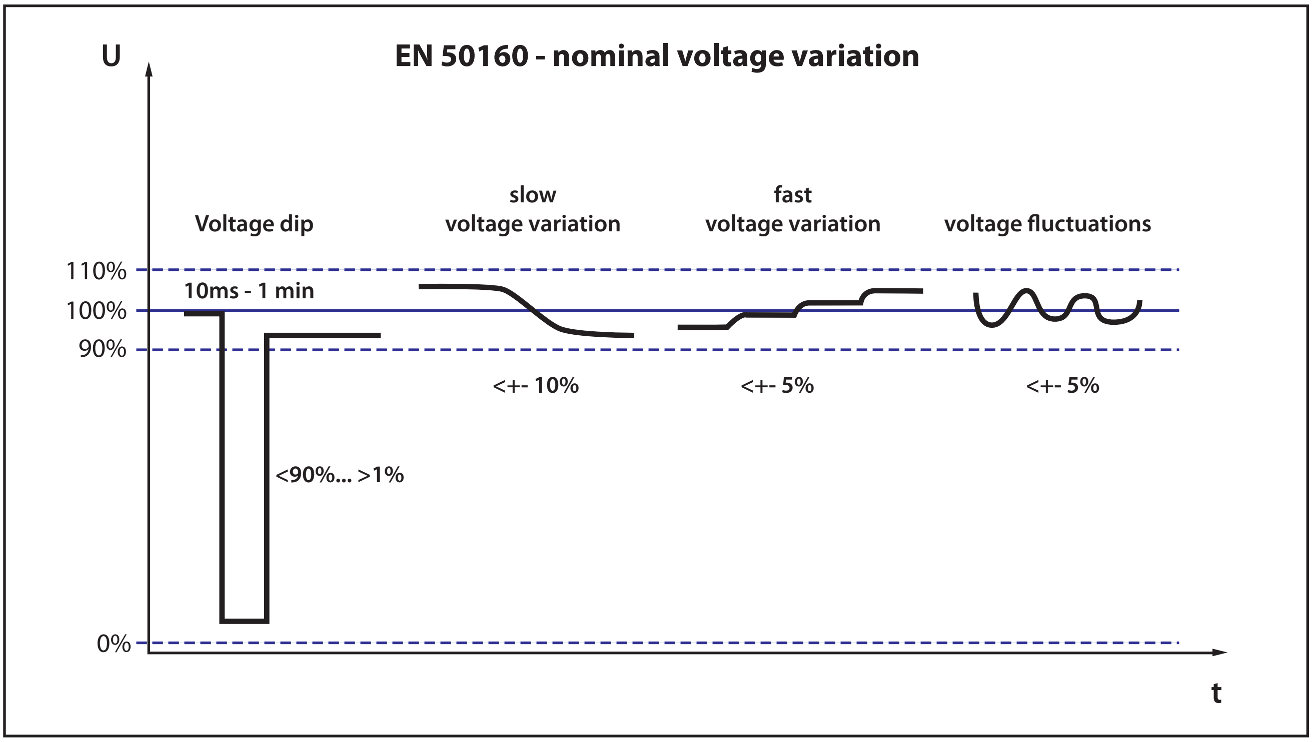
Voltage dips

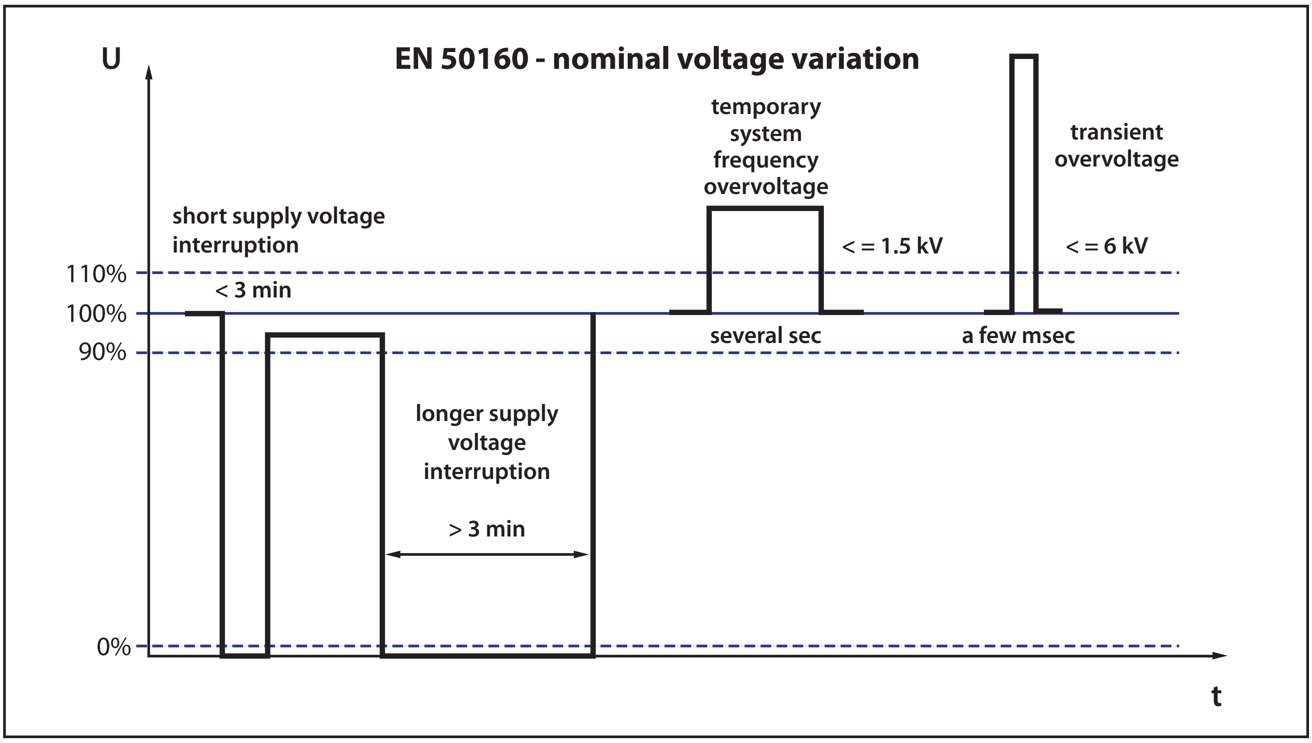
If the 10ms RMS value of the voltage exceeds or falls below a band of ±10% of the nominal voltage, then this is referred to as a voltage dip or overvoltage.

Supply voltage interruption

Up to 50 supply voltage interruptions are permissible per year. A voltage dip below 1% of the supply voltage is referred to as an interruption.

2.2 Graphical representation of the standard EN 50160





2.3 Malfunction - cause - effect - remedy

Malfunction	Cause	Effect	Remedy
Voltage fluctuations	Voltage variation dip at network impedance Switching big loads on or off Start-up of large motors Welding machines Furnaces	Variation in the supply voltage RMS value	Reduction of network impedance Reduction of power connected Voltage stabilizer Dynamic compensation
Voltage dips **Voltage interruptions**	High start-up currents Ground faults Short-circuits	Failure of electronic equipment	Limiting start-up currents Reducing network impedance
Voltage interruptions	High start-up currents Ground faults Short-circuits	Failure of device, system or production	Limiting start-up currents Reducing network impedance
Flicker	Copy machines Burst firing controls Electric arc furnaces Presses Welding devices	Luminance changes in bulbs Eye fatigue Dizziness Weakening of components	Reduction of network impedance Reduction of load Change in operating behavior
Harmonics	Power converters Rectifiers Frequency converters Switched-mode power supplies Iron saturation	Thermal overload of transformers Damage to electronic devices Malfunctions, production loss	Detuned compensation systems Absorption circuit systems Combination filter
Asymmetry	Asymmetric load distribution Monophase or dual phase load Induction furnaces Resistance welding machines Smelting furnaces	Uneven transformer load Transformer loss, transformer buzzing Motors running unevenly Bearings worn out	Even load distribution Converters or motor generator sets Symmetry installations Active power filters
Transients	Lightning strikes Switching operations of capacitors or inductors Triggering protective devices (fuses, switches...)	Control malfunctions Device malfunction, device destruction Destruction of motor windings	Overvoltage protection devices

2.4 Technical data – network configurations

1st letter transformer earthing type
- T direct earthing of the neutral point
- I insulation of the neutral point

2nd letter consumer earthing type
- T direct earthing of the consumer
- I insulation of the consumer

Three variants of TN-systems are distinguished:

TN-S	PE and N are separate conductors
TN-C	A combined PEN conductor fulfills the function of PE and N conductor
TN-C-S	Part oft he system uses combined PEN conductor, which is at some point split up to PE and N lines

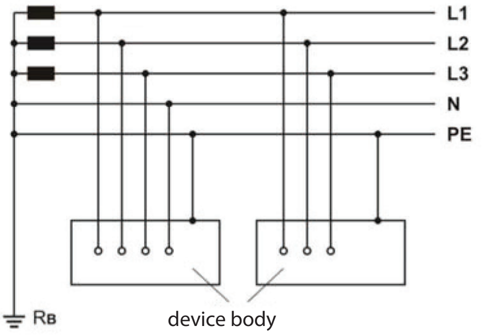


Image 1, TN-S system

- Direct earthing of transformer neutral point through network operation earthing RB
- Device body connected to the network operation earthing through earth conductor
- Earth conductor and neutral conductor designed as two separate wires throughout the entire system

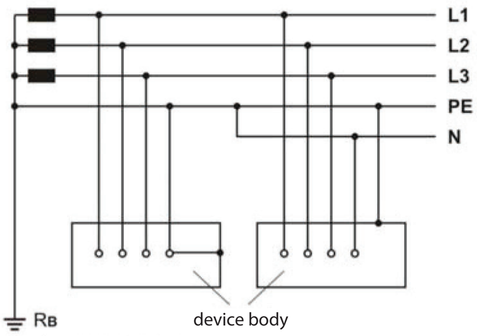


Image 2, TN-C-S system

- Direct earthing of transformer neutral point through network operation earthing RB
- Device body connected to the network operation earthing through PEN or earth conductor
- Earth conductor and neutral conductor partly combined with PEN conductor, partly designed as two separate wires

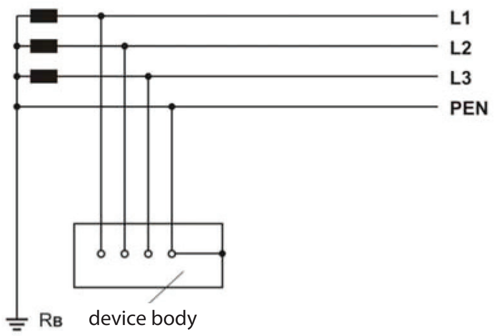


Image 3, TN-C system

- Direct earthing of transformer neutral point through network operation earthing RB
- Device body connected to the network operation earthing through earth conductor
- Earth conductor and neutral conductor combined with PEN conductor throughout the entire system

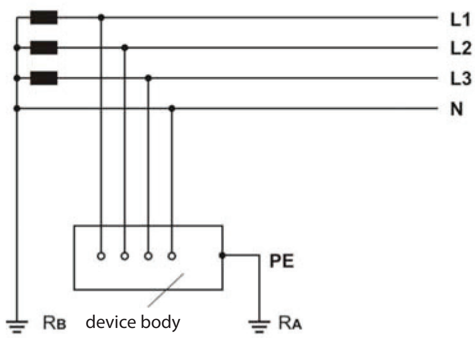


Image 4, TT system

- Direct earthing of transformer neutral point through network operation earthing RB
- Device body connected to the ground through network operation earthing RA

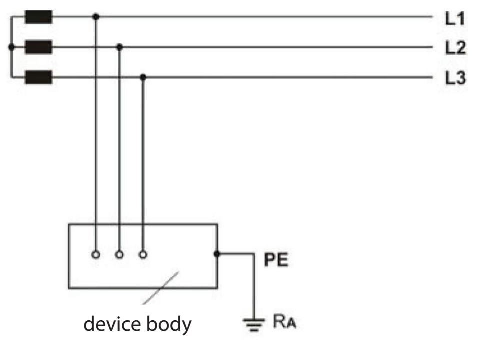


Image 5, IT system

- Insulation against earth of all active parts
- Device body connected to the device earthing RA

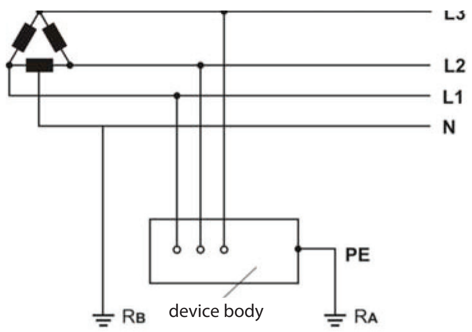


Image 6, asymmetrical system

- Earthing of one phase through device earthing RA
- Device body directly connected to the ground through device earthing RA

The network configuration is important for the design of the compensation system. For this reason, the network configuration must always be stated in the project planning. Compensation systems are usually configured for TN-C systems, that means, there is a common PEN rail. If the compensation system is used in a TN-S system, one connecting bar each has to be installed for the N and PE conductor.

3 Reactive power, reactive current - basics

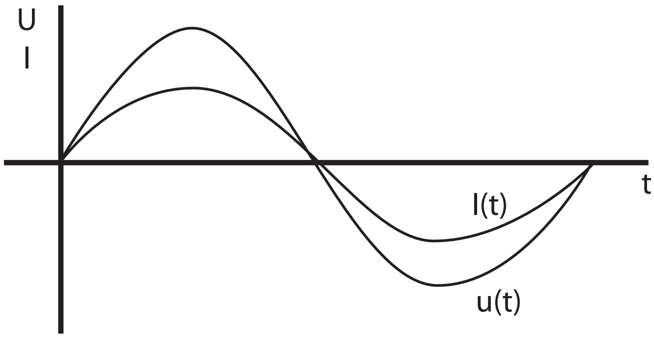
3.1 What is reactive current?

Reactive current is the current required to create a magnetic field in inductive consumers like motors, transformers, ballasts, induction furnaces, etc, that is, coils of any design. Reactive current is also referred to as magnetization current. The reactive current or reactive power oscillates between the consumer and the energy supplier at the clock cycle of the network frequency and thus loads cables, fuses and transformers.

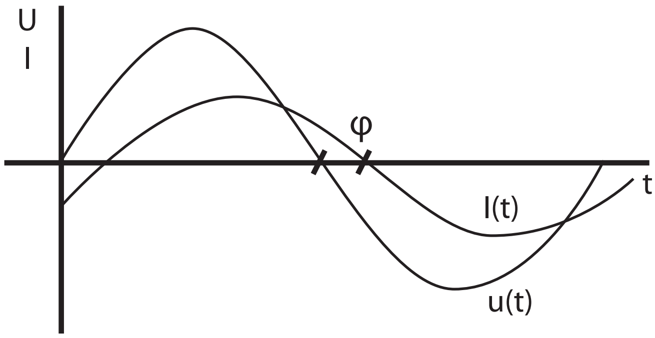
Phase shift

In an AC network with purely ohmic consumers (e. g. bulbs, flat irons, heating resistors), current and voltage are in phase.

cos-phi = 1



However, if inductive consumers (e.g. transformers, motors, ballasts) are connected, a phase shift between the current and voltage is created, with the current lagging behind the voltage at angle φ.



cos-phi is inductive

3.2 Which consumers require reactive current?

Inductive consumers such as

- Asynchronous motors
- Converters
- Transformers
- Welding devices
- Fluorescent lamps
- Fluorescent tubes
- Systems with other discharge devices
- Power supply lines

that is, coils of any design.

3.3 Power factors in different industries

Type of system or unit	**Medium power factor cos-phi medium (uncompensated)**
Food industry	
Butcher shops	0.6 … 0.7
Dairy	0.6 … 0.7
Mills	0.6 … 0.8
Breweries	0.6 … 0.7
Tobacco mills	0.6 … 0.7
Sugar production	0.6 … 0.7
Cold storage	0.8 … 0.85
	0.6 … 0.7
Timber industry	
Saw mills	0.6 … 0.7
Drying systems	0.8 … 0.9
Plywood mills	0.6 … 0.7
Carpentries and joineries	0.6 … 0.7
Metal processing	
Machine tools for small series production	0.4 … 0.5
Machine tools for large series production	0.5 … 0.6
Welding machines	0.5 … 0.7
Welding transformers	0.4 … 0.5
Crane assemblies	0.5 … 0.6
Larger machine tools including presses	0.65 … 0.7
Water pumps	0.8 … 0.85
Mechanical workshops	0.5 … 0.6
Fans	0.7 … 0.8
Compressors	0.7 … 0.8
Foundries	0.6 … 0.7
Garages	0.7 … 0.8

3.4 Why compensate?

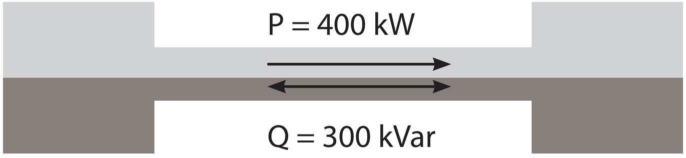
- In order to save on the reactive current costs that most energy suppliers charge.
- To take the reactive current load from electric components like lines, switches, transformers, generators and thus reduce transmission losses.
- In the best case, to save on the costs of a new line or the purchase of a new transformer.
- To be able to use one’s own generator more efficiently, that is, to source as little external energy as possible.

The energy supplier's tariff contracts define the required power factor cos φ that the consumer has to adhere to.

3.5 Effects of a compensation system

transformer
or generator

consumer



cos phi 0.8

System without compensation

The power connection and transformer are loaded with a reactive power of 300 kVar.

cos phi 1.0

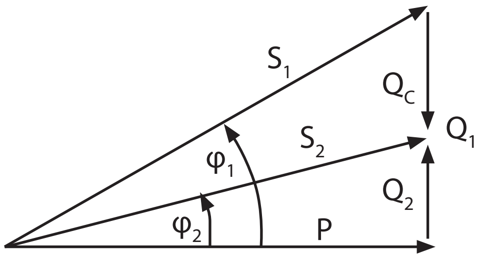
System with compensation

The load on the power connection and transformer is reduced, creating a power reserve in the transformer.

cos phi 1.0

Full transformer and power utilization through compensation power increase.

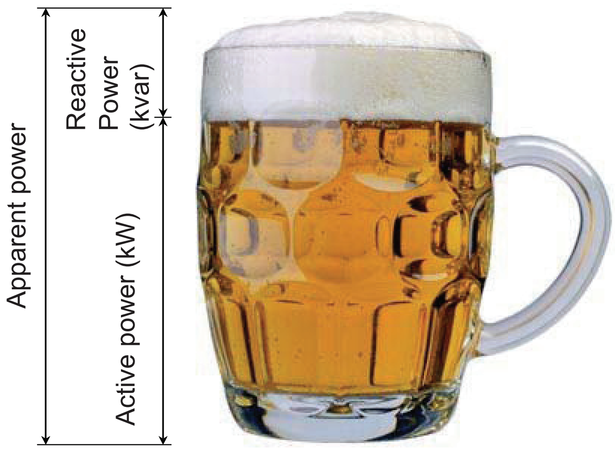
3.6 Power triangle



S_1 Apparent power without PFC
S_2 Apparent power with PFC
Q_1 Reactive power without PFC
Q_2 Reactive power with PFC
Q_C Capacitive reactive Power
P Active Power
φ_1 Power Factor without PFC
φ_2 Power Factor with PFC

As can be seen from the power triangle, using a compensation system reduces the reactive current consumption (reactive current costs) and thus the apparent power.

In practice, this may look as follows:



3.7 Calculation examples to illustrate cost savings

Annual reactive energy cost savings in an industrial enterprise
Average power consumption of 400 kW
Shift factor cos-phi 0.7
Annual working hours 2,500 h
Costs for reactive energy per year € 5,800.-

To achieve a target cos-phi of 0.9, 216 kvar are required.
The choice is a detuned system with 250 kvar.
The total investment amounts to € 8,000.- including installation.
The amortization period is 1 year 5 months.

Annual active energy cost savings for conduction losses.

A reduction of apparent current or apparent power also reduces active energy costs.
In the example above, this leads to the following reduction: Transformer power 630 kVA.
In uncompensated operation, conduction losses of 10 kW occur at full transformer load.
This corresponds to a power triangle with an angle of 89.09°.
$\cos \alpha = P/S = 10\text{ kW} / 630\text{ kVA} = 89.09°$

After installation of the compensation system, reactive power is reduced to 236 kvar.
This leads to the apparent power consumed of
$S^2 = P^2 + Q^2 = 400\text{ kW}^2 + 236\text{ kvar}^2$ to 464 kVA.

The conduction losses with compensation thus amount to:
$P = S \times \cos \alpha = 464\text{ kVA} \times \cos 89{,}09 = 7.37\text{ kW}$

Of course, there are also losses in a compensation system. In this example they amount to 1,250W.
Thus, the following power loss reduction is achieved:
$P = 10\text{ kW} - 7.37\text{ kW} - 1.25\text{ kW} = 1.38\text{ kW}$

Given 2,500 annual working hours, this amounts to an active energy reduction of 3,450 kWh.
Assuming the energy tariff is € 0.08 / kWh, this equals annual savings of € 276.-.

Saving investment costs

In this example, the transformer load falls from 630 kVA (100%) to 464 kVA (74%). This way, it is possible to install several consumers without having to replace the transformer. Including installation, a new transformer with 800kVA costs approximately € 30,000.-. Compensation usually has to be extended during the installation of new consumers, but all the same, the costs of a reactive current compensation system are 2 to 3 times lower than the costs of a new transformer.

3.8 Where is compensation used?

- Directly on the motor in case of good motor utilization, i.e. the motor has a long on-transition time.
- On the transformer, if a high-voltage measurement is performed.
- In ballasts for fluorescent lamps if the load on lines and ballasts is to be reduced.
- At the main distribution plant, if several consumers with different operating times and a low simultaneity factor have to be operated in the system.

3.9 Which equipment is used for compensation?

- Fixed capacitors without additional switching elements for the direct compensation of transformers and motors.
- Parallel or series capacitors in ballasts for fluorescent lamps.
- Capacitor with apparent current relay and switchgear at subdistributors for cable relief or for compensation in smaller operations.
- Automatically operating compensation systems adapted to the respective stage power conditions.

3.10 How is a compensation system planned?

The exact size of the compensation system is determined using an electricity bill of the energy supplier. This bill includes information on the type of tariff agreed on by the energy supplier and end customer.

kW tariff: The energy supplier e.g. requests a minimum cos φ of 0.9. The reactive kvarh to be paid is indicated. The reactive energy measured has to be incorporated into the calculation of tan φ_1.

tan φ1 = reactive energy in kvarh / active energy in kWh

Take the multiplier from the table and multiply with the power peak (kW peak).

Example: Power peak in kW = 62 kW
Reactive consumption = 15,600 kvarh
Active consumption = 13,000 kWh
Desired target cos φ_2 = 0.92
tan φ_1 = 15,600 / 13,000 = 1.2 -> refer to page 18
From table multiplier = 0.77 -> refer to page 18

Dimension of facility: 62 x 0.77 = 47.7 kvar

Facility selected from the standard portfolio:
untuned: **multicab-R 050/05-1220-00-SWSH** (observe harmonic contents)
tuned: **multicab-R 050/05-1220-07-SWSH**

The use of a tuned or untuned system can be verified with a network analysis.

Amortization time:

Costs for the compensation system / monthly savings = approx. months

Definition of $\tan \varphi_1$	$\cos \varphi_1$	$\cos \varphi_2$ = 0.90	$\cos \varphi_2$ = 0.92	$\cos \varphi_2$ = 0.95	$\cos \varphi_2$ = 0.97	$\cos \varphi_2$ =1.00
4.90	0.20	4.41	4.57	4.57	4.65	4.90
3.87	0.25	3.39	3.45	3.54	3.62	3.87
3.18	0.30	2.70	2.75	2.85	2.93	3.18
2.68	0.35	2.19	2.25	2.35	2.43	2.68
2.29	0.40	1.81	1.87	1.96	2.04	2.29
2.16	0.42	1.68	1.74	1.83	1.91	2.16
2.04	0.44	1.56	1.62	1.71	1.79	2.04
1.93	0.46	1.45	1.50	1.60	1.68	1.93
1.83	0.48	1.34	1.40	1.50	1.58	1.83
1.73	0.50	1.25	1.31	1.40	1.48	1.73
1.64	0.52	1.16	1.22	1.31	1.39	1.64
1.56	0.54	1.07	1.13	1.23	1.31	1.56
1.48	0.56	1.00	1.05	1.15	1.23	1.48
1.40	0.58	0.92	0.98	1.08	1.15	1.40
1.33	0.60	0.85	0.91	1.00	1.08	1.33
1.27	0.62	0.78	0.84	0.94	1.01	1.27
1.20	0.64	0.72	0.77	0.87	0.95	1.20
1.14	0.66	0.65	0.71	0.81	0.89	1.14
1.08	0.68	0.59	0.65	0.75	0.83	1.08
1.02	0.70	0.54	0.59	0.69	0.77	1.02
0.96	0.72	0.48	0.54	0.63	0.71	0.96
0.91	0.74	0.42	0.48	0.58	0.66	0.91
0.86	0.76	0.37	0.43	0.53	0.60	0.86
0.80	0.78	0.32	0.38	0.47	0.55	0.80
0.75	0.80	0.27	0.32	0.42	0.50	0.75
0.70	0.82	0.21	0.27	0.37	0.45	0.70
0.65	0.84	0.16	0.22	0.32	0.40	0.65
0.59	0.86	0.11	0.17	0.26	0.34	0.59
0.54	0.88	0.06	0.11	0.21	0.29	0.54
0.48	0.90		0.06	0.16	0.23	0.48
0.43	0.92			0.10	0.18	0.43
0.36	0.94			0.03	0.11	0.36
0.29	0.96				0.04	0.29
0.20	0.98					0.20

Additional possibilities for determining system size

Reactive power measuring device, KBR technical consultant,
Measurement with KBR-multilog 2 network measuring device and computer evaluation.

4 Types of compensation

4.1 Individual compensations

In general, application for consumers with constant power, preferably in continuous operation. Typical consumers are fluorescent lamps, asynchronous motors, transformers and welding rectifiers.

Advantages:

- Reactive current compensation on site,
- Reduction of losses and voltage dips,
- No need for switchgear.

Disadvantages:

- Several small capacitors are more expensive than one larger capacitor of the same total power.
- Short operating time of the capacitor for devices which are rarely switched on.

4.1.1 Individual and group compensation of fluorescent lamps

4.1.1.1 Parallel compensation 230 V

Light (W)	Capacitor (µF)
20	4.5
22	4.5
30	4.5
32	4.5
36	4.5
38	4.5
40	4.5
42	6
58	7
65	7
100	16

4.1.1.2 Series compensation (lead-lag circuit, 420 V)

Light (W)	Capacitor (µF)
20	2.9
22	3.2
30	3
32	3.6
36	3.6
38	3.6
40	3.6
42	4.4
58	5.7
65	5.7

4.1.1.3 Mercury vapor High pressure lamps 230 V

Light (W)	Capacitor (µF)
50	7
80	8
125	10
250	18
400	25
700	40
1000	60

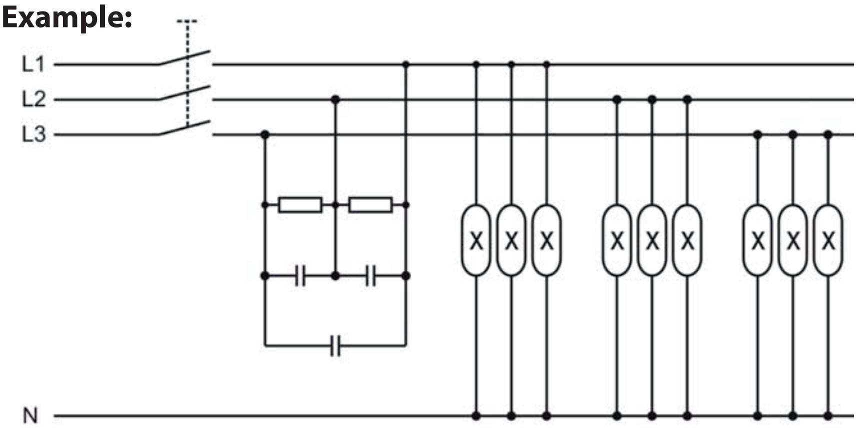
4.1.1.4 Sodium steam lamps

Light (W)	Capacitor (µF)
50	8
80	8
100	12
150	20
250	32
400	50
1000	100

Group compensation of fluorescent lamps

If a larger group of fluorescent lamps is switched at once, it is possible to establish group compensation with a 3-phase power capacitor.

Example:



9 lamps with 58W
capacitor 7 µF per lamp

Group capacitor in kvar (at 400 V) = 0.015 - total capacitance (µF)

Example: 9 lamps - 7 µF = 63 µF (total capacitance)
Group capacitor: 63 - 0.015 = 0.945 kvar
selected capacitor: 1 **kvar**, type GF-H 1
KBR power capacitors multicab-F…

IMPORTANT: Only capacitors with discharge resistors can be used. In case of the individual compensation of fluorescent lamps, series connection (lead-lag circuit) is recommended. This way, audio frequency disturbances and network feedback are avoided.

If capacitors containing PCB are removed from fluorescent lamps, it is recommended to use group capacitors with an integrated type multicab-F…-LS air-break contactor or, for automatic operation, an additional apparent current relay of the
multicab-F…-LSR type.

4.1.2 Individual compensation of three-phase asynchronous motors

To establish its magnetic field, the asynchronous motor requires reactive power. The reactive power demand of motors depends on their speed and rated power. In this context, cos φ gets less favorable if the load is decreased.

Some energy suppliers define requirements for the compensation of three-phase asynchronous motors. This value can e.g. be at 35 ... 40 % of the rated motor power.

If the energy supplier does not define any requirements, the choice of capacitor can be made according to the following table:

Rated motor power kW (400 V, 3 ~)	Capacitor power kvar (400 V, 3 ~)
1 ... 3	50 %
4 ... 10	45 %
11 ... 29	40 %
from 30	35 %

With these given values, the motor achieves a cos φ of 0.92 at full-load operation. In idle mode, the cos φ value approaches 1.

Motor self-excitation with star-delta connection

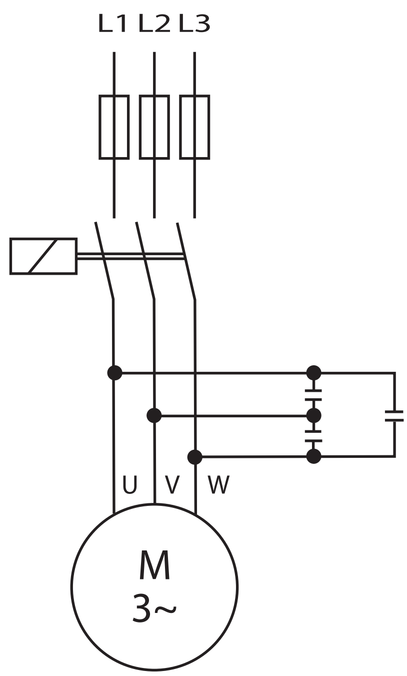
In case of a star-delta connection, disconnection from the network can lead to an overvoltage if the capacitor is hooked up to a winding of the star connection. Together with the capacitor, the rotating machine represents a group capable of self-oscillation. If this group is separated from the grid (during operation), the voltage created by the self-excitation of the motor remains present at the terminals. The energy to maintain this oscillation level is taken from the kinetic energy of the rotor. The motor thus acts as a generator with the excitation current powering the capacitor. As a consequence of this self-excitation, an overvoltage is created (2 to 3 times U_{RATED}) at the terminals of the rotating machine.

To avoid self-excitation, the capacitor should always be equipped with a separate air-break contactor. Type multicab-F…-LS.

Important:
Direct compensation may reduce current consumption considerably. Upstream motor protection (bimetallic relay) has to be set lower, adapted to the new current measurement.

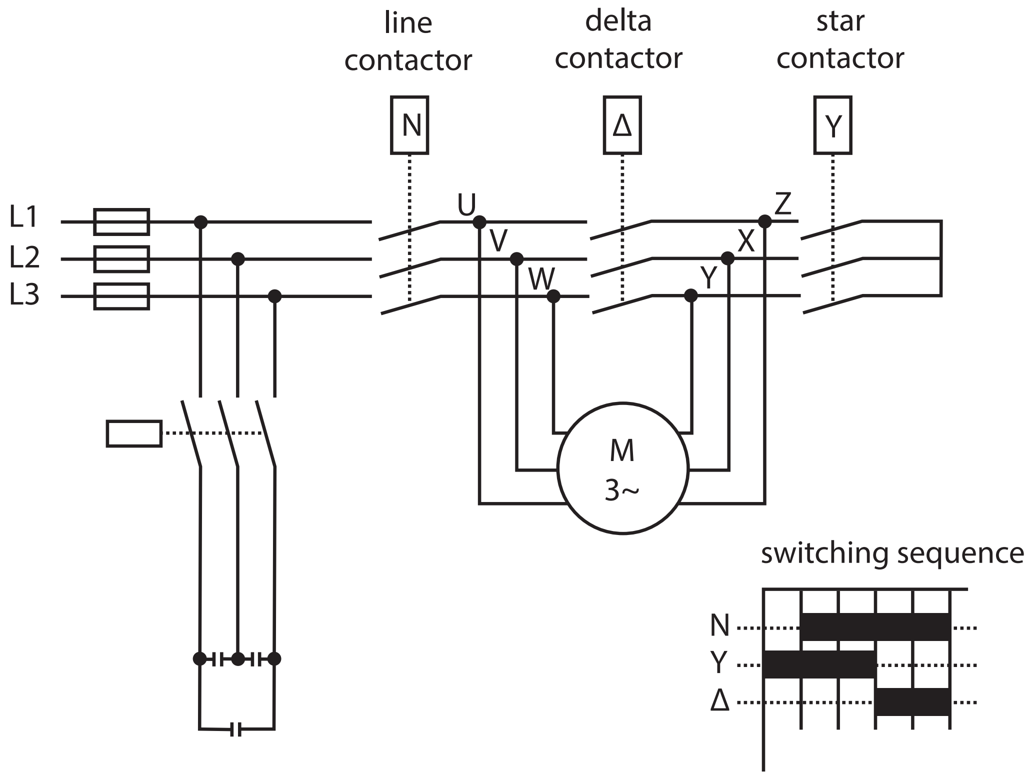
4.1.2.1 Connection diagrams for individual compensation of motors

The capacitor connection can be selected according to the following connection diagrams:



motor

To avoid self-excitation, always assemble a separate contactor to the capacitor.



motor with automatic star-delta switch

4.1.3 Individual compensation of elevator and crane motors

Due to the short switch-on times, elevator and crane motors should always be compensated directly. Switch-on times as short as this cannot be evaluated by a central compensation system.

The capacitor has to be switched within the tenth of a second, using a thyristor. The thyristor is controlled in parallel to the contactor of the motor.

Independent of the charge status of the capacitors, the thyristor module switches capacitors to the network any inrush current.

4.1.4 Individual compensation of three-phase asynchronous generators

Asynchronous generators are to be treated like motors, observing the following aspects. During load control, speed will increase temporarily until the output controller has tuned down the engine. During this period, over-excitation is possible due to the increase in frequency. For this reason, only switchable fixed capacitors for asynchronous generators must be installed, enabling them to be switched on or off via voltage relay or a section switch contact. Furthermore, observe that an asynchronous generator can only be hooked up to the network in its de-energized state (i.e. without excitation) since, otherwise, dangerous overvoltage states could be created. When using control technology, make sure to only use a reactive power controller with 4-quadrant measuring option.

4.1.5 Individual compensation of transformers

When loaded, transformers consume transformer reactive power, which consists of the idle power and the stray field reactive power at the short-circuit reactance.

For low-voltage measurements, the compensation of station transformers is often performed by the energy supplier, in order to achieve a favorable cos phi? Particularly profitable for a energy supplier is transformer compensation, since it keeps power losses on the lines at a minimum.

For medium-voltage measurements, direct compensation is recommended, since the reactive power demand of the transformer is not completely met by a compensation system.
Since the transformer load can vary, the capacitor size must not be chosen according to the maximum reactive current demand. This prevents an overcompensation (increase in voltage) during low-load periods. Furthermore, the current consumption of the capacitor could increase if the network has a higher harmonic content.
For these reasons, most energy suppliers only authorize a maximum load-independent transformer compensation of 3 to 5% of the transformer output. Connection should only be established with fuses.

Rated transformer power kVA	Oil transformers kvar	Cast-resin transformers kvar	Transformers with reduced stand-by losses kvar
2	5	3	2
2	5	3	2
3	8	4	2
4	8	5	2
5	12.5	5	3
6	15	5	3
8	15	8	5
1	20	8	5
1	20	10	5
1	25	10	5
2	30	-	8
5	80	-	15

Example: Oil transformer with an output of 630 kVA
Capacitor = 15 kvar
KBR power capacitors, 14% tuned with NH isolator
type multicab-F 015/01-14-SWGB-N

Also observe that, in combination with the leakage reactance of the transformer, the secondary capacitor creates a series resonant circuit. If the individual frequency of the resonant circuit equals a network harmonic (resonance), the latter can be considerably amplified in low-load periods. In a network with audio frequencies, the natural frequency has to correspond to the control frequency. Otherwise, this configuration has the same effect on the ripple control voltage as a short-circuit.

Calculation of the individual frequency:

$$f_e = f_o \times \sqrt{\frac{100 \times S_n}{U_k\% \times Q_c}}$$

f_e = individual frequency
f_o = network frequency
S_n = rated transformer power
$u_k\%$ = relative short-circuit voltage
Q_c = capacitor power

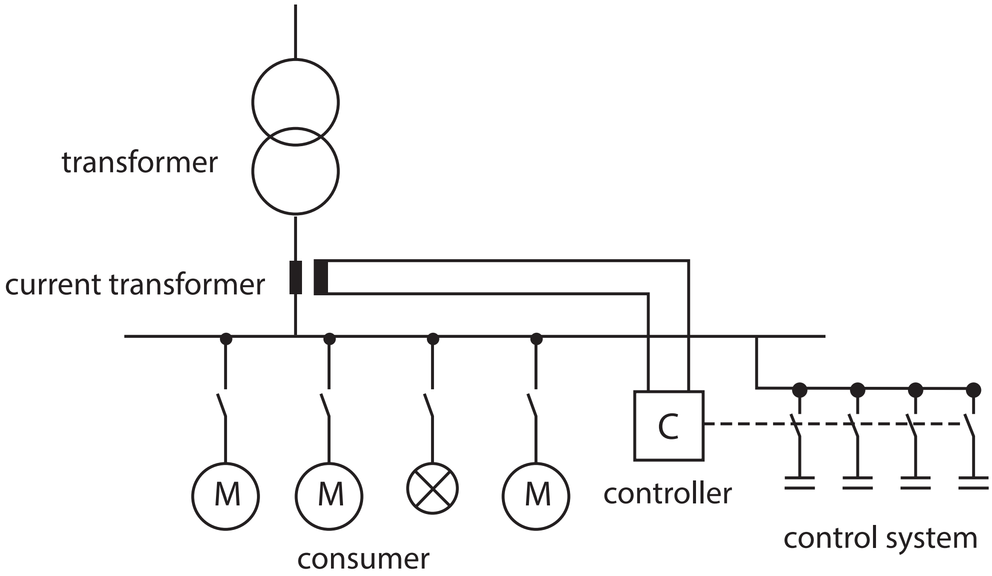
4.2 Central compensation systems with automatic operation

With this type of compensation, the capacitive reactive power is created at one single point of the distribution.

Advantages:

- Improved utilization of the capacitor power,
- easier monitoring,
- automatic control possible,
- improved adaptation to the reactive power demand,
- subsequent installation and expansion is relatively easy.

Disadvantage:
No relief of distribution and supply lines.



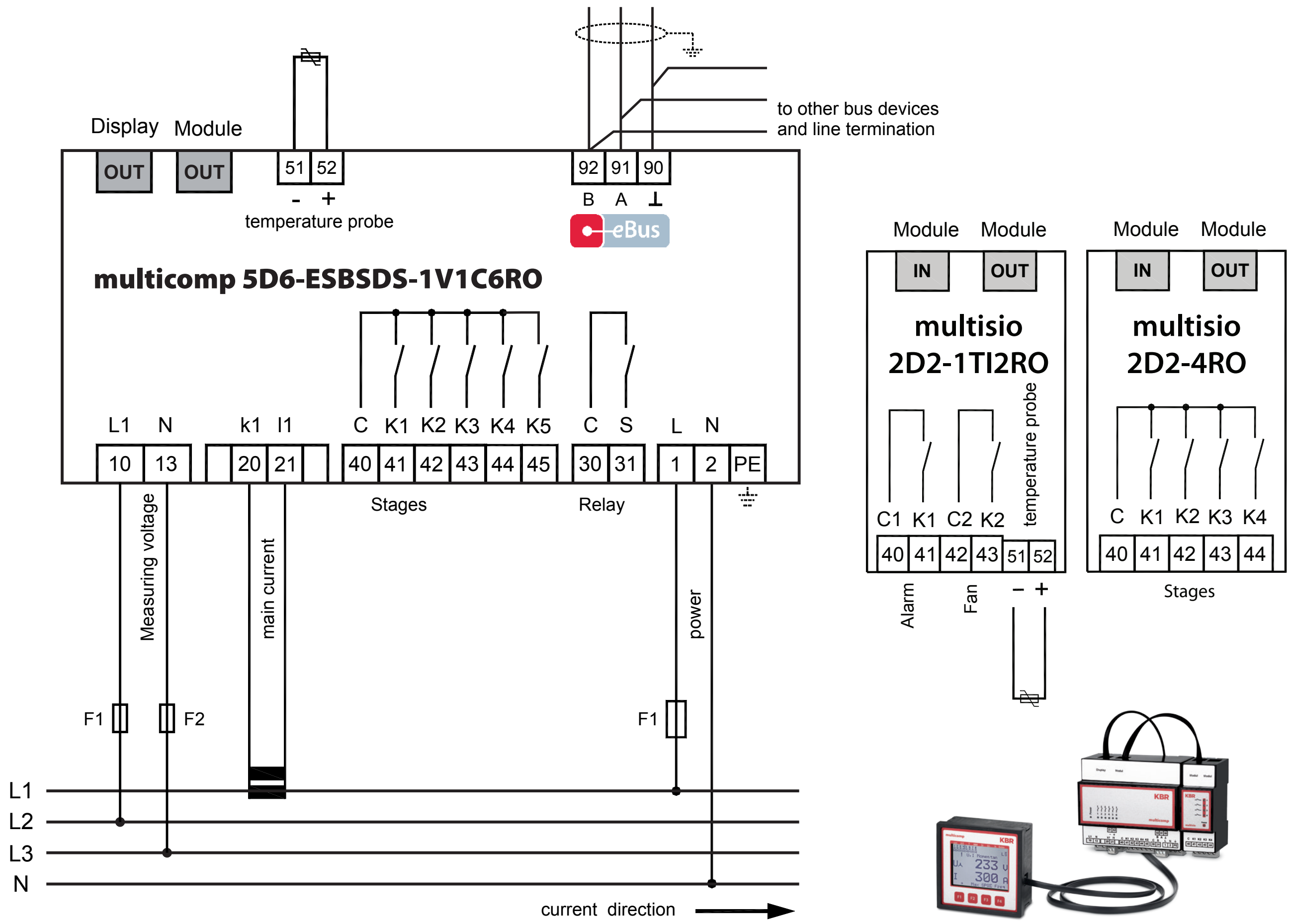
After the required capacitor size has been determined, the automatically operated compensation system is defined.

In general, 5 capacitor stages are defined. For connection of the facility, a x/5 A or x/1 A converter, as well as an outgoing fuse at the main distribution with a supply line to the compensation system, are required. In case of a large distance between the converter and the compensation system, using a x/1 A converter is recommended, as this keeps conduction losses down.

The connection and switch-off of capacitor stages takes place automatically via a reactive power controller.

4.3 Reactive power controller

Reactive power controller
(system connection diagram, changes reserved - observe operating instructions):



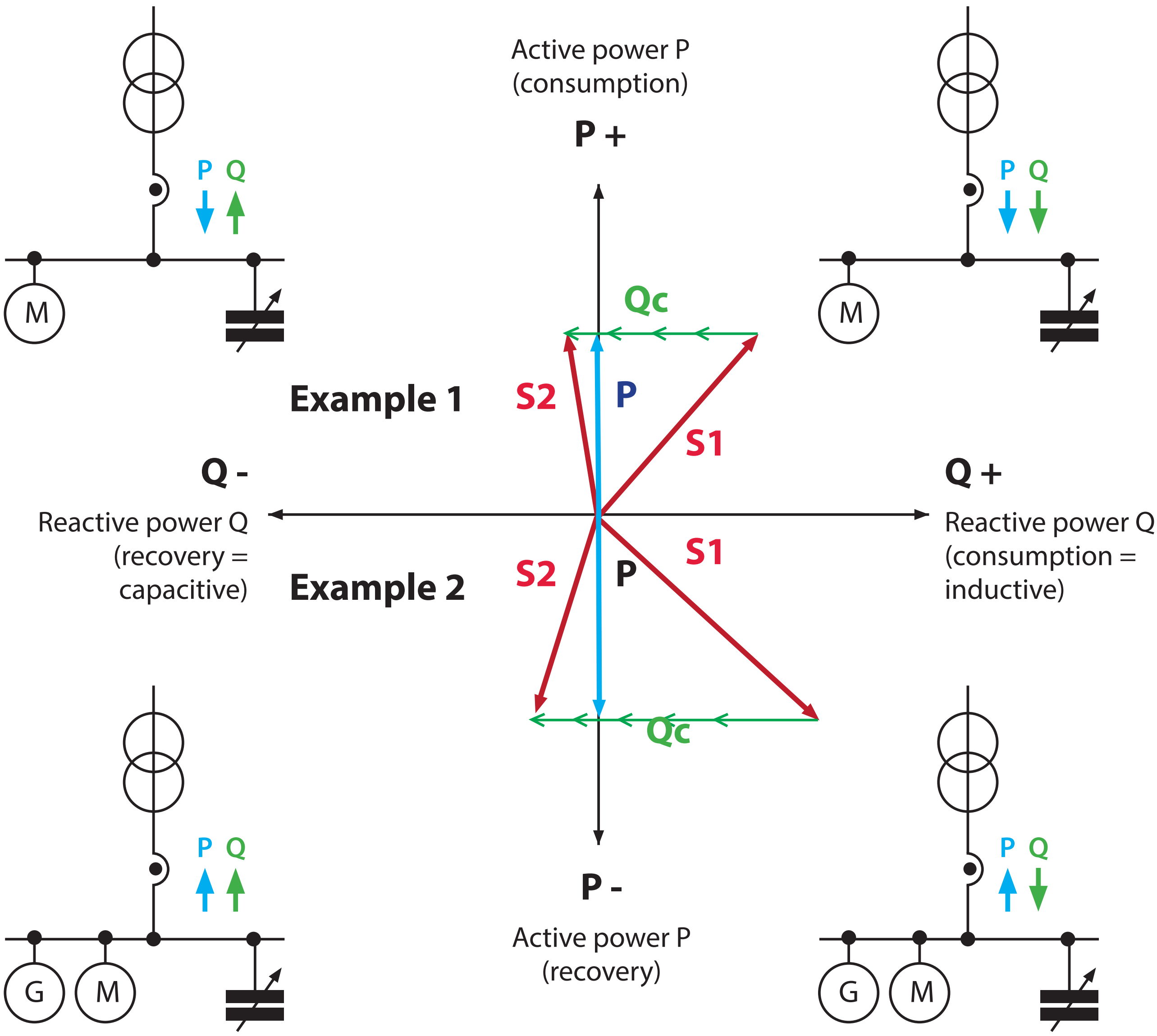
Advantages of KBR reactive power controllers of the multicomp-basic type

- Easy installation and expansion thanks to modular concept
- Real reactive power measurement and calculation of the necessary compensation power in 4-quadrant operation
- Optimized system for quick compensation with only a few switching operations
- Temperature measurement with automatic fan start-up and capacitor switch-off when the set temperature limits are exceeded (also applies for expansion cabinets)
- Harmonic measurement with stage switch-off if limits are exceeded
- extensive displays with large LCD display (cos-phi, missing kvar, current, voltage, active power and network harmonic)
- Manual 0 automatic switching selectable for each stage
- Connection terminals for 5 A and 1 A converter
- Up to 24 stages through expansion with multi-ro modules.
- Programmable error message contact
- Connection of **KBR eBus**

■ Optional: Gateways for MOD Bus or Profibus

■ All KBR controllers are suitable for 4 quadrant operation. In the following illustration, the direction of power flow is shown. In general, the systems only operate in quadrants I and IV, with quadrant IV only valid for generator operation. Quadrants II and III can mostly be accessed for a short time only, namely in case of an overcompensation reversed by the controller.

4.3.1 4 quadrant operation



5 Compensation systems in networks with harmonics

5.1 What is a harmonic?

Harmonics are a result of modern electronics. Harmonics are sinusoidal interferences of the voltage or current fundamental with a frequency that is an integer multiple of the standard line frequency. The 50/60Hz frequency is referred to as the fundamental component. All other integer multiples are referred to as n th harmonics.

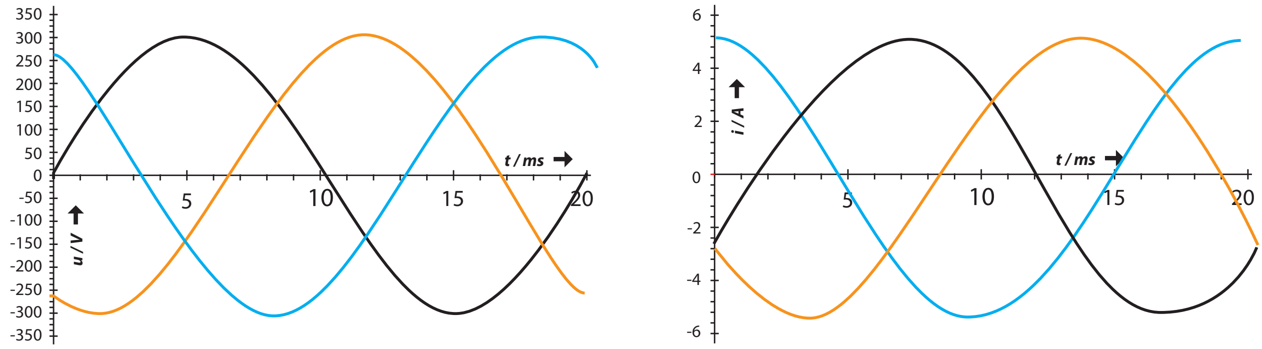
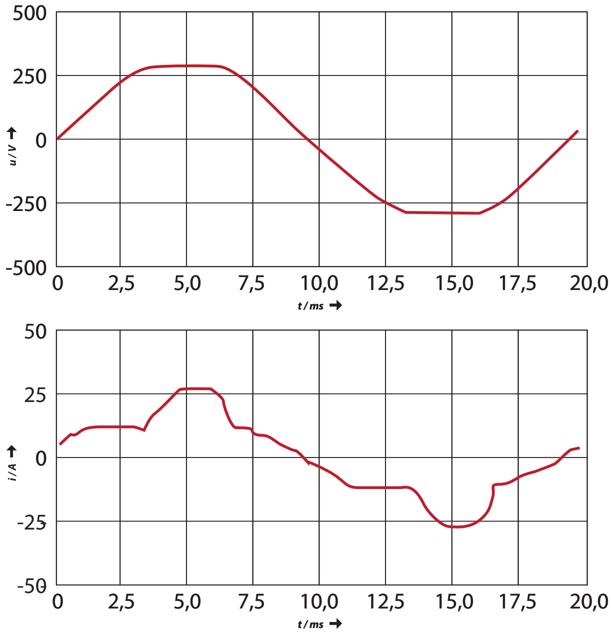
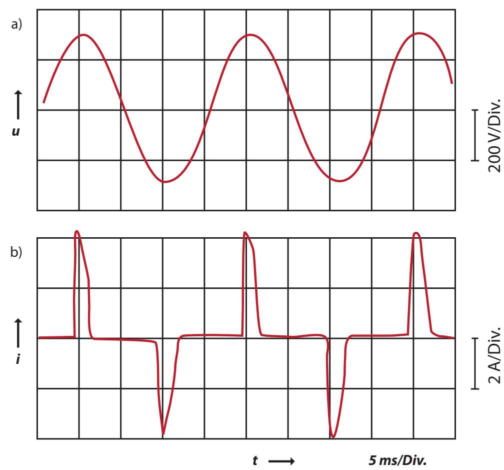


Illustration of the ideal voltage and current waveform (sine curve).



Existing voltage and current curves recorded in large storage, distribution and management buildings.

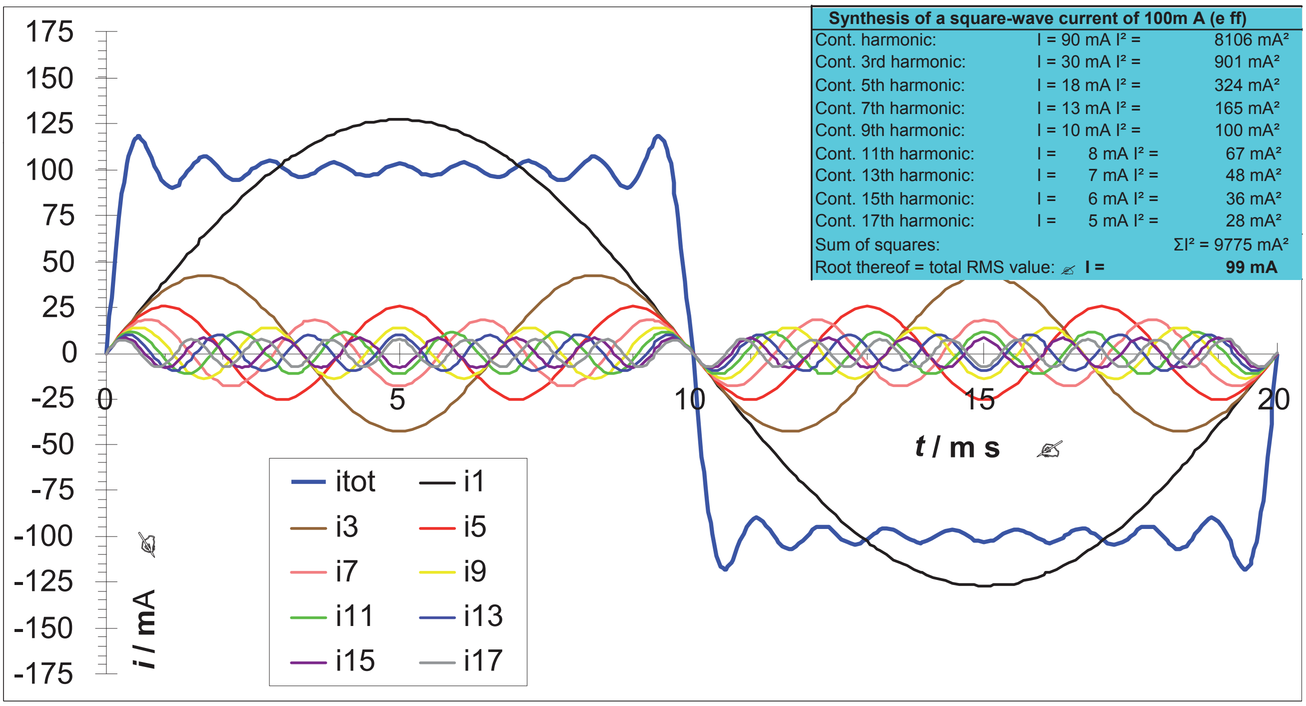


Voltage and current of a TV.

INFORMATION:
All pictures and calculations are related to a fundamental frequency of 50Hz.
In case of 60Hz the drawings and results of calculation are different.

Division of the converter current in fundamental components and harmonics

Each curve can be divided into individual harmonics with a Fourier analysis. Measuring equipment calculate the individual segments and yields results for each existing harmonic. In order to design a compensation system, it is important to know the orders of magnitude and ordinal number of the harmonics. This way, the detuning factor can be determined precisely.



The waveform can be changed by adding the fundamental component and the different network harmonics. In this example, a square function is created.

5.2 Where do harmonics come from?

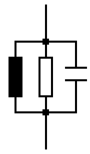
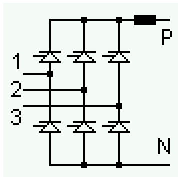
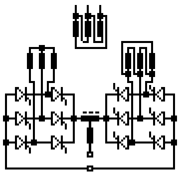
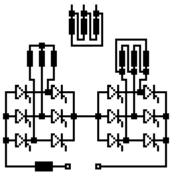
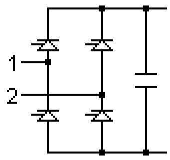
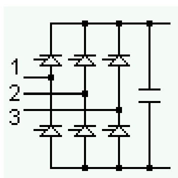
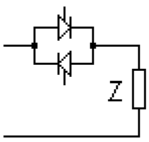
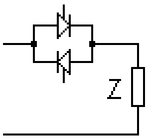
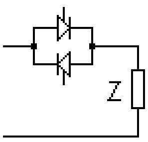
In case of linear loads, a pure sinusoidal current flows though the network in stationary state, causing the voltage drop at network impedances to have a sine waveform as well. The network terminal voltage is only influenced in its amplitude and phase, not in its shape. For this reason, the waveform is not distorted.

In case of non-linear loads like iron reactors, electric arcs, frequency converters, clocked power supplies or fluorescent lamps, a non-sinusoidal current flows through the network, causing a non-sinusoidal voltage drop at the impedances, which leads to a distortion of the network terminal voltage.

5.3 Which consumers create harmonics?

Lighting regulation (brightness control), clocked power supplies (TV sets, computers), speed control of motors, saturated iron cores with inductors, UPS unit (uninterrupted power supply), rectifiers (post), welding machines, electric arc furnaces, machine tools (CNC), ballasts, spark erosion machine tools.

Information see page 27.

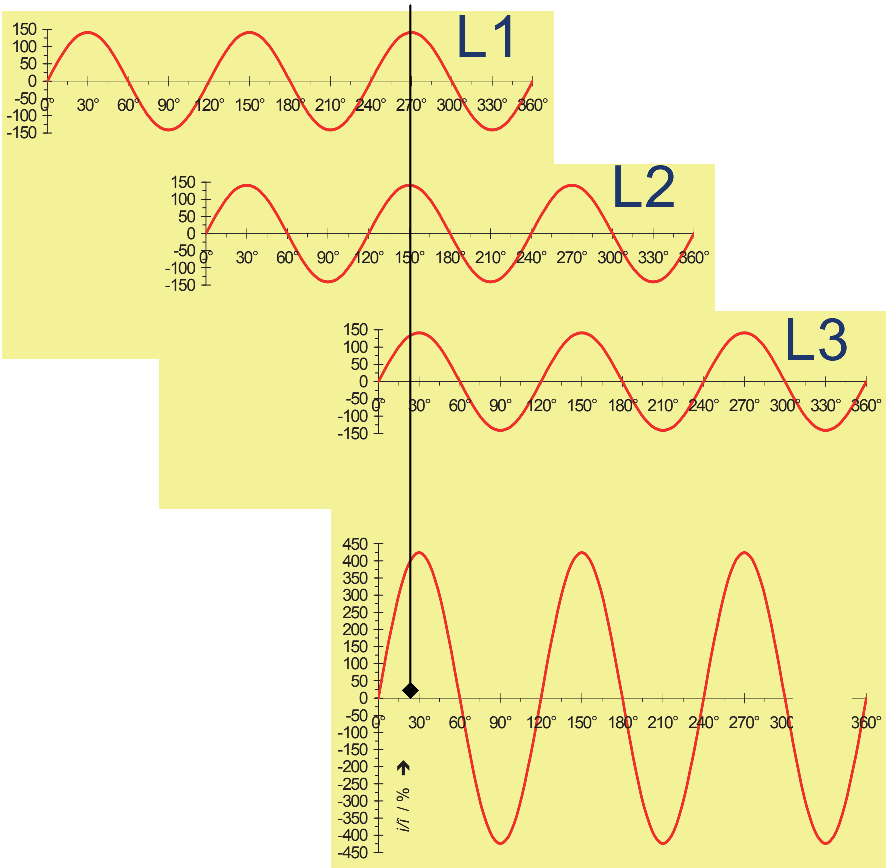
Switching diagram	Description	Harmonic current in relation to In in % for reference number ν											
		3	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**23**	**25**
	Load without harmonics	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Converter, ind. smoothing, B6	0.0	27.0	11.0	0.0	9.0	6.0	0.0	5.0	4.0	0.0	3.0	3.0
	Converter, ind. smoothing, B6.2/15	0.0	4.0	3.0	0.0	9.0	6.0	0.0	0.0	0.0	0.0	3.0	3.0
	Converter, ind. smoothing, B6.2S15	0.0	4.0	3.0	0.0	13.0	6.0	0.0	0.0	0.0	0.0	5.0	3.0
	Converter, untuned, cap. smoothing, alternating current	95.0	80.0	70.0	65.0	62.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0
	Converter, tuned, cap. smoothing, three-phase current	0.0	86.0	70.0	0.0	36.0	22.0	0.0	0.0	0.0	0.0	0.0	0.0
	Actuator, cos-phi = 1.0	33.0	14.0	10.0	8.0	6.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
	Actuator, cos-phi = 0.8	23.0	8.0	3.0	2.0	2.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	Actuator, cos-phi = 0.6	17.0	6.0	3.0	2.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0

5.4 The effects of harmonics

- Harmonic currents (high frequencies) cause eddy currents. Eddy currents circulate in mechanic components and are caused by the magnetic field of the energized conductor.
- Harmonic currents create the skin effect. Due to the skin effect, the impedance of the conductor is increased by shifting the current flow to the outer layer of the cable. The skin effect increases with the frequency.
- Distortion of the network voltage
- Low network quality
- Overload / failure / malfunction of consumers
- Heating of motors, transformers, capacitors, fuses etc.
- Early triggering of power switches
- Violation of requirements by the energy supplier
- Ripple control receivers are disturbed
- Shorter lifespan of illuminants and other equipment

5.4.1 Why are harmonics dangerous to neutral conductors?

Consumers influence the load on conductors in the network
In the past, mostly linear consumers with a sinusoidal current shape distributed evenly on three phases were used, creating a symmetrical network. In three-phase operation, the three currents add up to zero at the neutral conductor. Today, the ever increasing percentage of electric devices, particularly with mass-produced products like lamps with electronic ballasts, TV sets and computers, leads to an increasing use of capacitively smoothed power supplies.



In the neutral conductor, the 150 Hz currents in the three phases add up to

$3 \times I_{\text{external conductor}}$

Information see page 27.

How do power supply units work?

Power supply units generate direct voltage for electronic devices. Today, they are constructed without an input transformer or ballast inductor. Charging the storage capacitor is done quickly and with a high current pulse. The current shape created is non-sinusoidal and generates harmonics.

What effects does this have on our network?

Harmonics superimpose the fundamental (network frequency e.g. 50 Hz) as its integer multiples. In particular, the 3rd and 15th harmonic create string currents per phase and do not reverse themselves, not even in case of a symmetrical load distribution, but add up in the neutral conductor. The result: Measurements have shown that the neutral conductor current can rise above 100% of the phase current.

In conclusion: More attention needs to be paid to the dimensions of the neutral conductor.

Definitions in technical guidelines
„VDE standards" DIN VDE 0100/520 / IEC 364-5-5: 1993 section 524.2:
The neutral conductor, if existing, may not have a smaller diameter than the external conductor,

- in alternating current circuits with two conductors with a random external conductor diameter,
- in alternating current circuits with three conductors and in multi-phase alternating current circuits, if the external conductor diameter is smaller or equal to 16 mm² for copper and 25 mm² for aluminum.
- Section 524.3: For multi-phase alternating current circuits with an external conductor diameter larger than 16 mm² for copper and 25 mm² for aluminum, the neutral conductor may only have a smaller diameter than the external conductor if the following requirements are met:
- The maximum current to be expected, including harmonics in the neutral conductor, is never larger than the current-carrying capacity of the reduced neutral conductor diameter in uninterrupted operation.

Note: This observation is made assuming a symmetrical load on the external conductor in uninterrupted operation.

- The neutral conductor is insulated against overcurrent in accordance with section 473.3.2 (DIN VDE 0100-470).
- The neutral conductor diameter is larger than or equal to 16 mm²

Effects
Due to a possible overload of the neutral conductor resulting from asymmetric currents and additional harmonic currents, the following risks for electric equipment arise.

Cables and conductors

- Overheating of the neutral conductor
- Fire hazard
- Risk of disruption of the neutral conductor with strongly decreasing or increasing phase voltage. This way, connected devices are at risk.
- Higher conduction losses
- Creation of strong magnetic fields, which can cause malfunctions.

Information see page 27.

Transformers

- Higher power losses
- Overload of the neutral point
- Resonance risk
- Higher noise level

Capacitors (especially sensitive to harmonics)

- Higher power losses
- Resonance risk
- Shorter operating time

Additionally, the following issues have to be considered in planning the low-voltage switchgear combination:

- Where is the neutral conductor installed to minimize the electromagnetic fields?
- How can stray currents in the earth conductor or constructive switchgear elements be avoided?
- How can the TN network of the switchgear be planned in an EMC compliant way?

Identifying risks

In case of new switchgear combinations, the right dimensions or filtering can avoid risks in connection with the power supply.

In an existing switchgear combination, there's the possibility of early risk detection in the power supply by measuring the neutral conductor currents.

Recommendation

For **existing** switchgear combinations:

- Measurement and monitoring of the neutral conductor (reduced operation possible).
- Integration of an active power filter for reducing the neutral conductor current.
- Restructuring and upgrade of the facility by enlarging the neutral conductor diameter.
  For **new** switchgear combinations:
- Dimensioning the neutral conductor to a value corresponding to 100% of the external conductor capacity according to DIN VDE 0100-520.
- Analysis of intended consumers and their effects on the neutral conductor load in case of usage of
  - clocked power supplies
  - electronically controlled drive controls
  - uncompensated illumination.
- Monitoring of output circuits in the neutral conductor via 4-pole protection devices.
- Dimensioning of cables, lines and busbar systems, taking the neutral conductor loads into consideration.

5.4.2 Why are harmonics dangerous for power cables?

Current harmonics increase the flow of current through the conductor. Due to the skin effect, conductors are additionally heated, speeding up their deterioration (of the insulation) and possibly even cause burn-off. In case of the neutral conductor, the lack of protective equipment which could limit the current in an emergency needs to be considered. Furthermore, overvoltage may occur between the neutral and earth conductor.

5.4.3 Why are harmonics dangerous for circuit breakers?

In electronic peak fuses, current harmonics cause incorrect or early triggering. Eddy currents and the skin effect can lead to additional heat formation.

5.4.4 Why are harmonics dangerous to motors?

Current harmonics lead to additional heat formation in motor loads. The torque of voltage harmonics can be in the same or opposite direction, depending on their reference number, which leads to the machine running nonuniformly, creating a reduction of the motor power and lifespan.

5.4.5 Why are harmonics dangerous to transformers?

Current harmonics lead to a higher thermal load. Furthermore, they can lead to vibrations and humming noises.

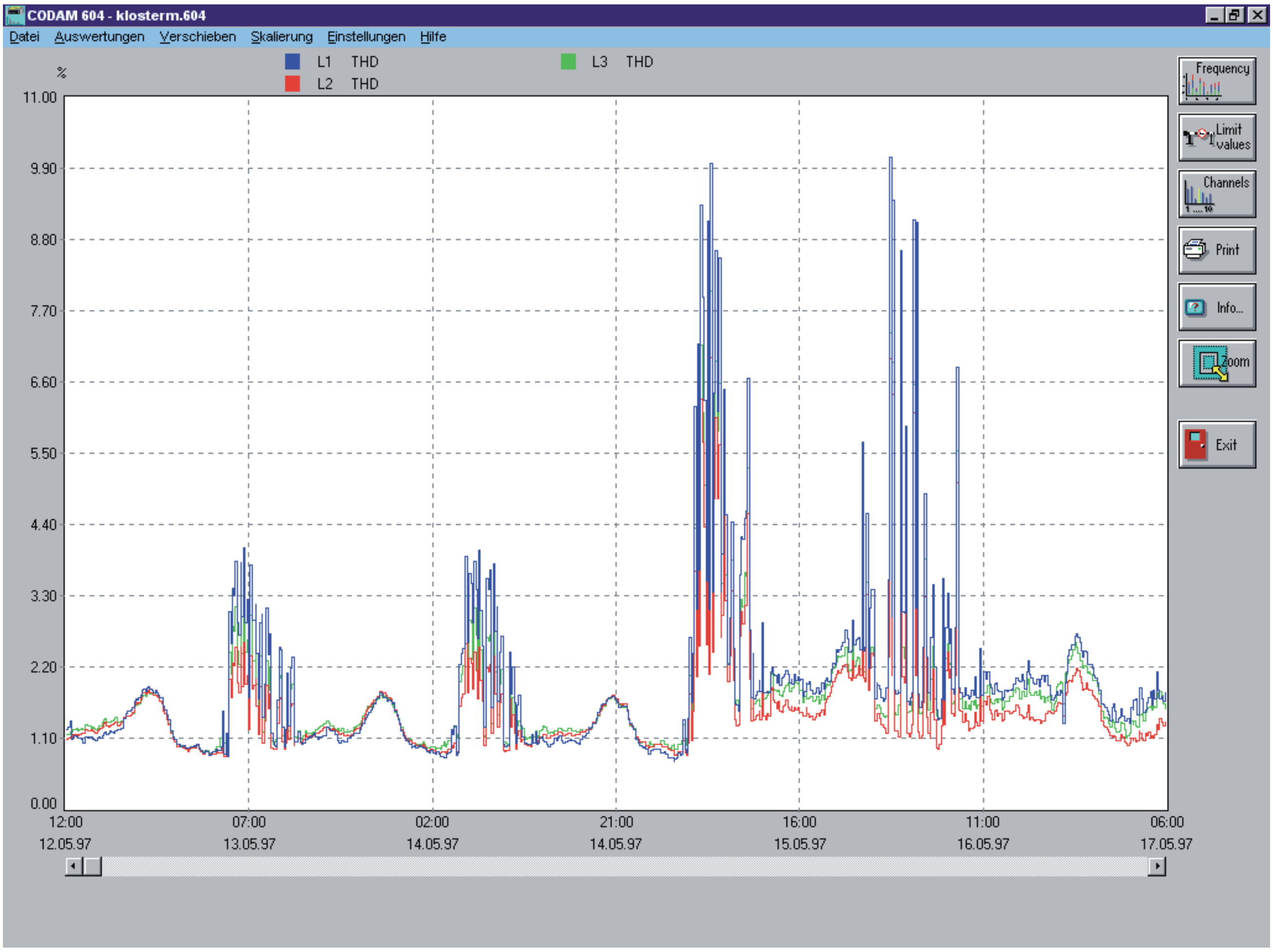
Third-order harmonics circulate within a star-delta connection and also lead to heat formation.

5.4.6 Why are harmonics dangerous to electronic devices?

In networks with an increased harmonic content, device malfunctions can occur. The distorted wave shape can lead to incorrect measurements and instrument displays.

5.4.7 Why are harmonics dangerous to capacitors?

Capacitances (capacitors) in networks with converters cause oscillations that additionally distort the network voltage. The frequency of these oscillations depends on the network parameters. Untuned network capacitors may thus cause the quality of the voltage shape to deteriorate. At the same time, they are also additionally loaded by the harmonics they create. This particularly applies to capacitors for reactive current compensation.



In the measuring diagram above, the voltage harmonics are illustrated. The values on the left side are the values without the use of a compensation system, the values on the right side have been measured with an **un**tuned compensation system in use.

This leads to an increased current consumption of the capacitors, which shortens the lifespan considerably.

5.5 Resonances

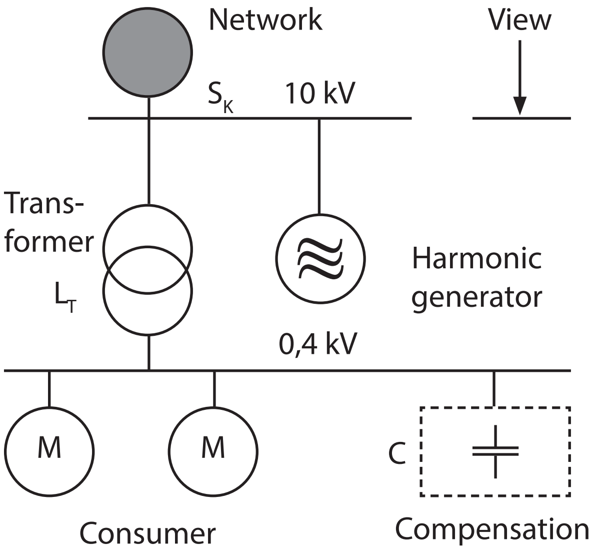
Another important aspect to be considered are possible resonances which can occur if the capacitor forms a series or parallel resonant circuit with existing network inductors. Distinction is made between two types of resonances. Independent of the type of resonance, the damage to the entire switchgear is considerable.

Real networks always consist of inductors, capacitors and ohmic resistors. Network capacitors consist of system capacitors of cables and lines as well as the power capacitors installed. This way, the network turns into a oscillatory system. The most simple form of a resonant circuit consists of an inductor L and capacitor C, either switched in series or in parallel.

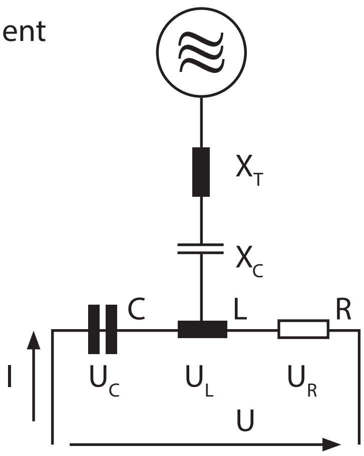
A series resonance is created if inductor and capacitor are arranged in series (seen from the harmonic generator). A series resonance is created if inductor and capacitor are arranged in parallel (seen from the harmonic generator).

Series resonance
L and C in series

A capacitor overload can occur if the resonant circuit consisting of capacitor capacitance and transformer inductance draws harmonic current from the network. The smallest resistance of the series resonant circuit is achieved at resonant frequency. The current flowing through the resonant circuit causes an increase in voltage in the capacitor and inductor. If the resonant circuit is periodically excited, the resonant amplitudes increase. In this context, amplitudes can become considerably larger than the network voltage and even voltage flashovers are possible.



Replacement switching diagram

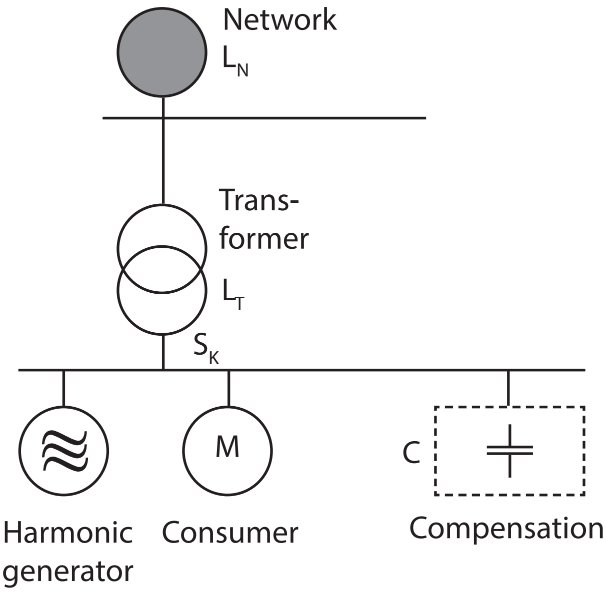


$$f\ res = \frac{1}{2\pi\sqrt{L \times C}}$$

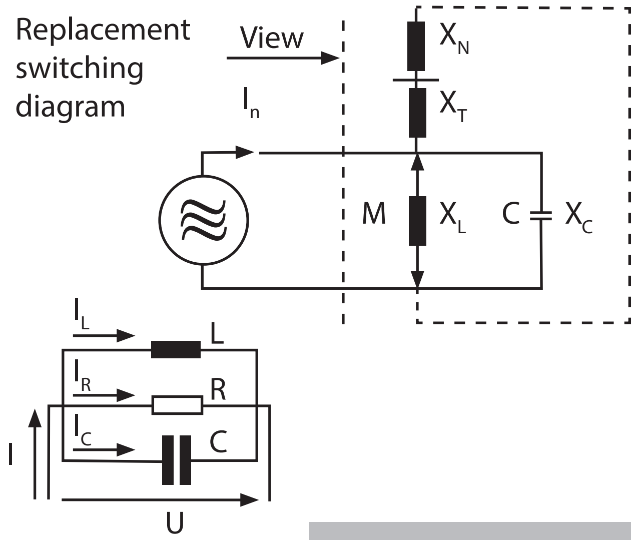
Parallel resonance
L and C in parallel

In a parallel resonant circuit excited by a power source, the resonant circuit current oscillates with a multiple of the current flowing from the harmonic generator to the network. If the resonant circuit is periodically excited, the resonant amplitudes increase. In this context, amplitudes can become considerably larger than the normal harmonic current.

The high network impedance also leads to high voltage harmonics.



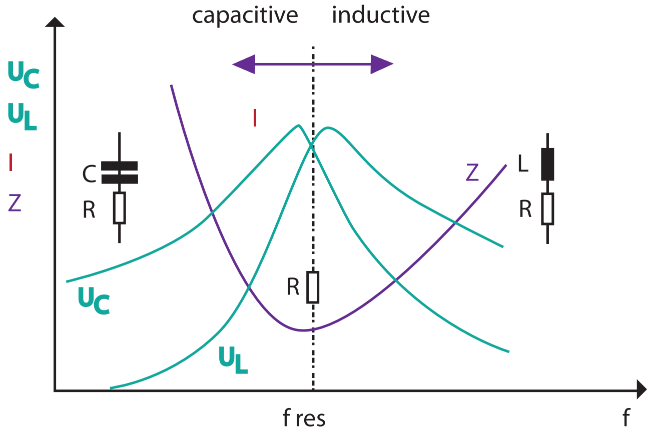
Replacement switching diagram

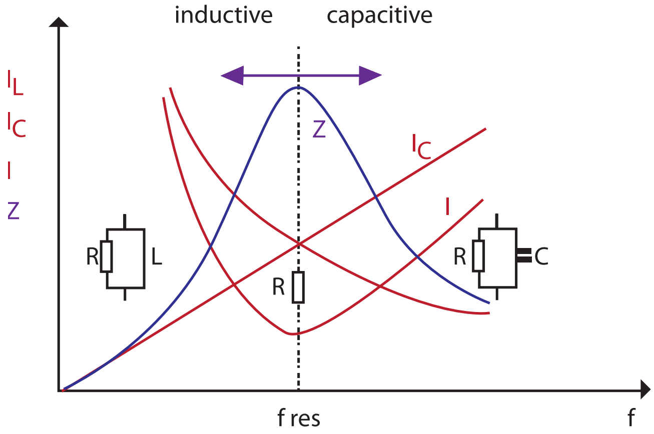


$$f\ res = \frac{1}{2\pi\sqrt{L \times C}}$$

Series resonance L and C in series
Z minimum at fr I maximum at fr Increase in voltage at L and C (voltage resonance)

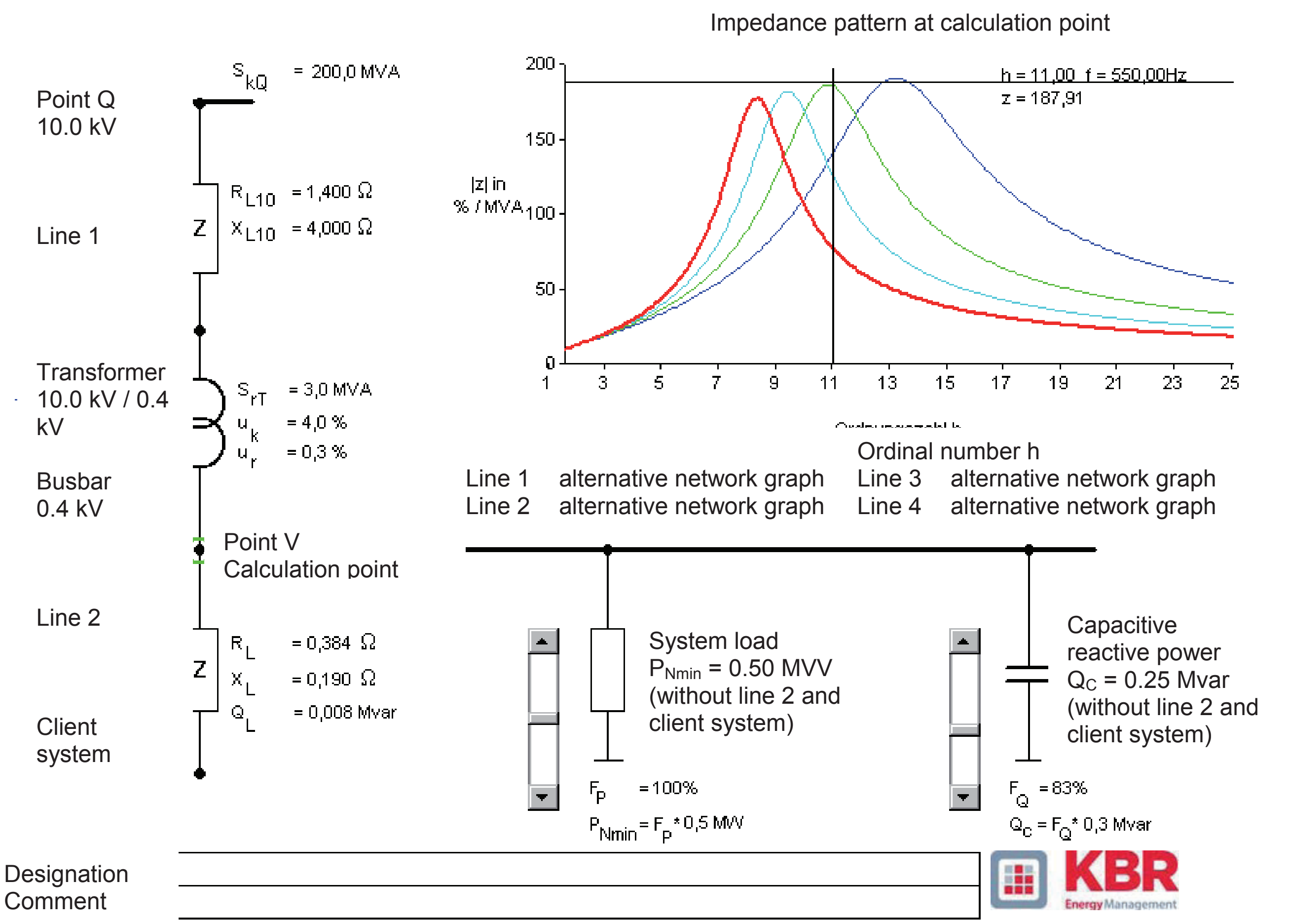
Parallel resonance L and C parallel
Z maximum at fr
Iadm minimum at fr Overcurrent at L and C (current resonance)





Both parallel and series resonant circuits can be found in real current distribution networks. Since converters act as a source for harmonic current as well as for voltage generation, both resonance types need to be considered.

In the following illustration, the resonance point shift is shown for different load states. Resonance points can be calculated. However, since the load is currently changing, avoiding resonances is impossible.

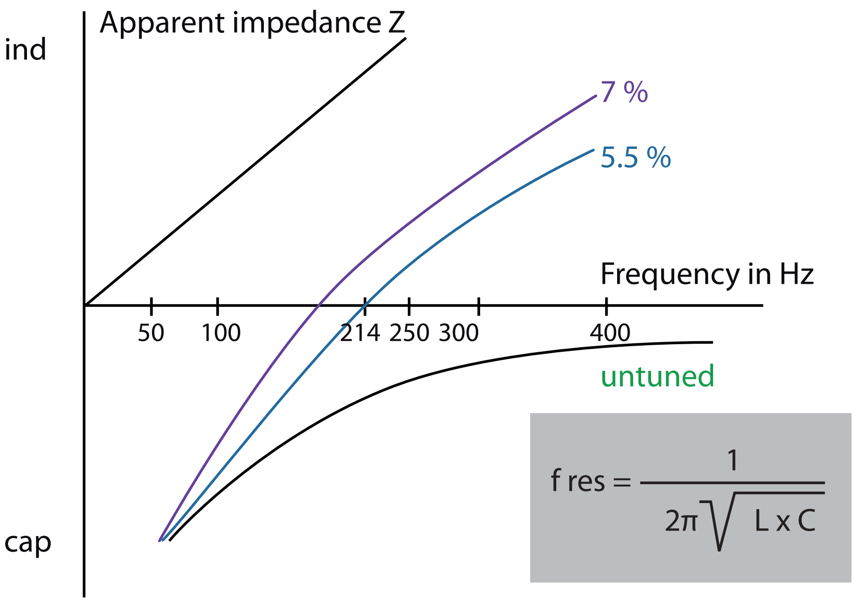


Information see page 27.

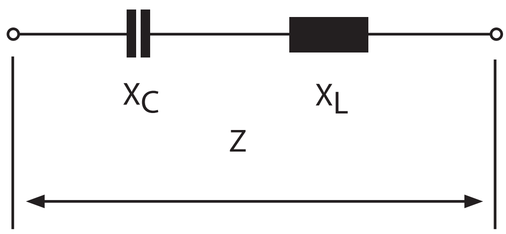
Remedy:
To avoid the problems mentioned, it is crucial to use a detuned compensation system. Detuned compensation systems are the state of the art!

5.6 What is „detuning" of a compensation system?

An inductor is connected in series to the capacitor. The series resonant circuit created this way acts inductively starting from a certain frequency (resonant frequency), and cannot create a resonant circuit together with other network inductances for signals with higher frequencies.



The impedance of an untuned capacitor is always capacitive. The impedance of a detuned capacitor is capacitive below the resonant frequency and inductive above it.



5.7 When is it recommended to use a detuned facility?

When planning a compensation system, it is always important to investigate the composition of the consumer.

The percentage in KW of the total facility power accounted for by devices generating harmonics should not exceed 15 %.

Example: If, from a total power of 100 KW, 20 KW are from a converter, a detuned compensation system should be used.

This ratio is also to be monitored in low load periods, since the frequency of shifts that can contribute to a fast creation of resonances is particularly increased here. The creation of resonances can lead to damage of electrical equipment. A network analysis should always be performed before planning a detuned facility. After evaluation of the network analysis, the detuning factor of the compensation system needs to be determined. Furthermore, the ripple-control signal needs to be determined by the energy supplier before utilization of a detuned facility.

Information see page 27.

As an additional guideline for the use of a detuned compensation system, a voltage of 2% for one of the existing harmonics (in relation to the rated voltage) can be assumed.

Example: For a rated voltage of 400 V, this corresponds to a limit value of 8 V.

For the determination of these values, you can use KBR measuring equipment. For group compensation of machines or subdistributions, only detuned capacitors with an integrated air-break contactor must be used, since the integrated temperature monitoring is only effective in this case. KBR type multicab F...-SWSH or SWSB. Detuned compensation systems of the standard KBR series, type multicab R...-SSGH or SSGB.

Important:
Detuned and untuned capacitors may never be operated with the same network. The reason for this is the fact that parallel switching of detuned and untuned capacitors creates a new resonant circuit. In the worst case, the resonant frequency of this newly created resonant circuit can coincide with one of the existing harmonics. The absorption circuit created this way would completely draw off the respective harmonic and overload the capacitors. Additionally, parallel resonances could be created.

6 Audio frequency blocking devices

Energy suppliers control the audio frequency (ripple control signal), storage heaters, meters, illumination, etc. The pulses superimposed on the network have a frequency of between 155 and 2,000 Hz, depending on the energy supplier. The pulses are absorbed by audio frequency control ripple receivers, which then trigger the corresponding switching operation. In this context, it is crucial that the signals are transmitted with sufficiently high voltage.

Since the reactance of the capacitor acts inversely proportional to the frequency, the ripple-control signal is more or less shorted out.

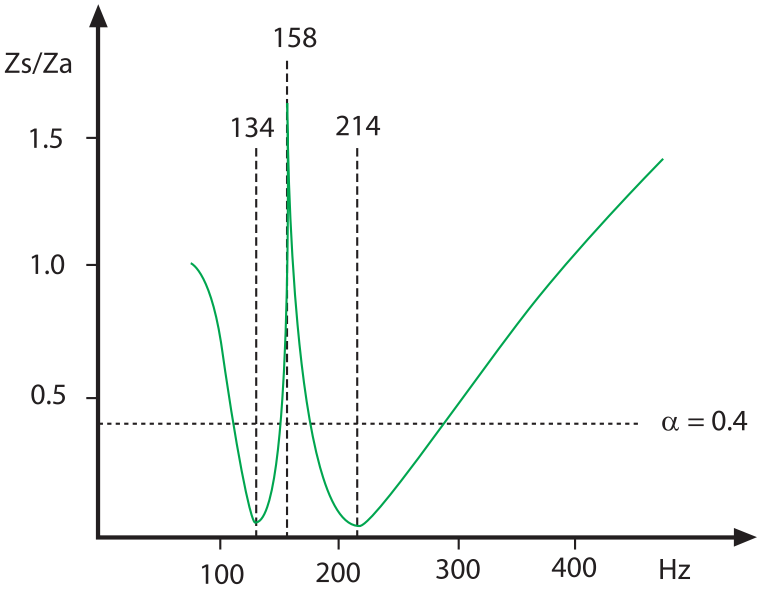
$$Xc = \frac{1}{2 \times 3.14 \times f \times C}$$

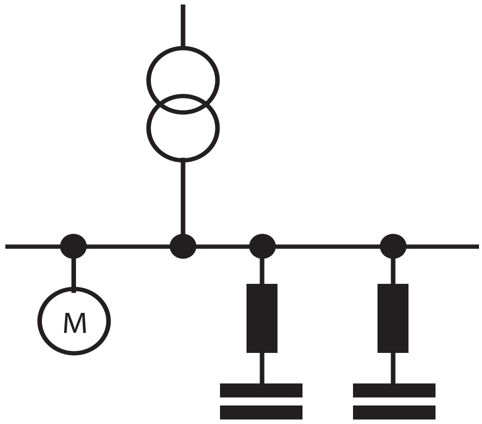
In order to prevent this, an audio frequency blocking device needs to be connected upstream of the capacitors. The frequency transmitted can be requested from the respective energy supplier. The audio frequency blocking device must be connected in series to the compensation system.

For detuned systems and higher frequencies, the audio frequency blocking device may be omitted depending on the detuning factor. Energy suppliers request an impedance factor of a > 0.4 or a more easily determinable impedance factor of a* > 0.5. By using customer data like transformer power, relative short-circuit voltage, capacitor voltage and detuning factor, a compensation system can be tested on its suitability for use or, conversely, the necessary detuning factor needed to be able to omit an audio frequency blocking device can be determined.

7 Combination filter

Another alternative is using a combination filter. In a combination filter, stages with different detuning factors are used. The combination of two different detuning factors leads to an impedance pattern with a strong blocking effect of the ripple-control signal transmitted.





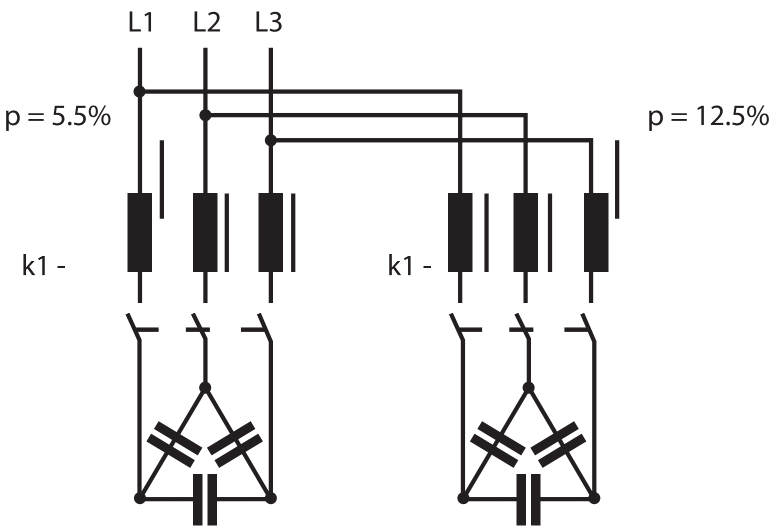
5.5 and 14% detuned compensation stages, connected in parallel

For a combination filter, distinction is made between two construction types:

a) A capacitor stage consists of two modules with different detuning factors which can be switched at once. This layout is quite complicated mechanically and thus expensive.

b) A second option is to alternate the switching of the stages with different detuning factors. Make sure here that the stages with a high detuning factor are switched on first and switched off last. This option is considerably less expensive and accepted by many energy suppliers.

Due to the parallel connection, a special frequency range is created, in which the existing audio frequencies are blocked. In this system one resonant frequency needs to be above, the other below the frequency to be blocked. One possible combination is the detuning factors 5.5/14% or 5.5/12.5%.



Circuit of a combined filter version a

Information see page 27.

The advantage of this technique is the ripple-control signal blocking effect as well as the concurrent network cleanup.

For existing systems, the conversion to a combination filter is complicated but an audio frequency blocking device can be retrofitted easily.

8 Use of a non-detuned compensation system

If no harmonic content was determined or it is really low, there's the possibility of using an untuned compensation system.
In case of untuned systems, however, resonance can also occur with a low harmonic content. Through the creation of a resonant circuit between capacitors and transformers or network inductances, the harmonic content close to the resonant frequency of the resonant circuit can be considerably increased (also refer to measurement on page 27).
A resonance can damage electronic consumers and, in case of overvoltage, lead to operation interruptions.

9 What do you need to observe when operating compensation systems?

- When installing modules into cabinets of other manufacturers, make sure the heat dissipation is good. For power greater than 100 kvar, we recommend the installation of a fan with thermostat control.
- For existing systems, clean the filter mats in regular intervals.
- Detuned facilities may not be operated with untuned capacitors on the same busbar, since there is a danger of parallel resonance.
- The ripple-control signal must be taken into account when planning a compensation system.
- Detuned facilities need to be inspected regularly, since changes to the capacitance can lead to an overload.
- Power capacitors are manufactured and tested in accordance with VDE 0560 part 46. For use of the T40 temperature class (temperature of the ambient air):
  maximum 40°C, briefly,
  highest average over 24 hours = 30°C,
  highest average over 1 year = 20°C.

Reactive current compensation for all requirements

KBR offers solutions for all requirements

Fixed compensations
Modules for all cabinet systems
Automatically controlled systems in ISO or sheet steel cabinets
Filter circuits
Combination filters
Audio frequency blocking devices
Reactive power controllers
Custom versions on request

Type tested versions according to:

DIN VDE 0660 part 500	short-circuit resistance
DIN VDE 0670 part 601	insulation resistance
DIN VDE 0470 part 1	efficiency of the PE connection
EN 60439-1	clearance and creepage distances
IEC 61921	IP protection type fault arc testing
	CE certification

10 Functionality of a compensation

The functionality of a compensation system includes

Saving reactive current costs

The reactive current costs billed by the energy suppliers can be saved completely. The amortization time is between 2 and 3 years.

Lowering apparent current levels

By lowering the apparent current level, the load on lines, transformers, fuses etc. is reduced. Losses are decreased and the modules heated up less. In case of sufficient dimensions, new consumers may even be installed without the need for new investments in lines and transformers.

Contribution to environment protection

By using a compensation system, the required reactive energy is stored in the on-site network and recovered when needed. This way, this type of energy does not have to be generated in power plants.

In addition to the functions of untuned systems, detuned systems have the following advantages

Avoiding resonances

By using detuned compensation systems, the excitation of existing resonant circuits through harmonics is prevented.

Drawing off harmonics

Depending on the detuning factor, the existing harmonic content can be drawn off the low-voltage network.

11 Power capacitors

The power capacitors of the UHPC type, installed by KBR, have been specifically developed for use in networks with a high harmonic content. Frequent checks and steady development provide for the continuous improvement of technical properties. All the important properties of a power capacitor are combined in the UHPC series. In addition to the long lifespan, the high current and voltage load capacity, and safety in case of overload are other key advantages of this series.

Safety in case of overload

Capacitors contain a self-healing dielectric. In case of overload in the capacitor (overtemperature, overvoltage), the foil used "heals" itself after a breakdown, recreating the capacitor function.

Furthermore, the capacitor is equipped with an overpressure disconnector. In order for the overpressure disconnector to function properly, a sufficient pressure level needs to be created inside the cup for the aluminum lid (flanged diaphragm) to bulge outwards and thereby cause the connection wires inside to tear. Special mechanical parts separate all three connection wires, ensuring the highest level of safety possible. Due to the pressure created, the connection between the lid and the cup may not be damaged since, otherwise, the pressure would escape. For this reason, this connection is established with a special adhesive.

Long lifespan

For the use of a compensation system to pay off, it is recommended to only use high-quality materials for the construction of UHPC power capacitors. Thanks to proper processing, the capacitors have a longer lifespan, leading to a reduction in costs for the user.

High resistance

In their standard configuration, the capacitors are designed for twice the rated current. This is necessary since the harmonic load on networks increases and thus puts an additional load on the capacitors. The capacitor can also be loaded with current peaks of up to 400 times the rated current for a short period.

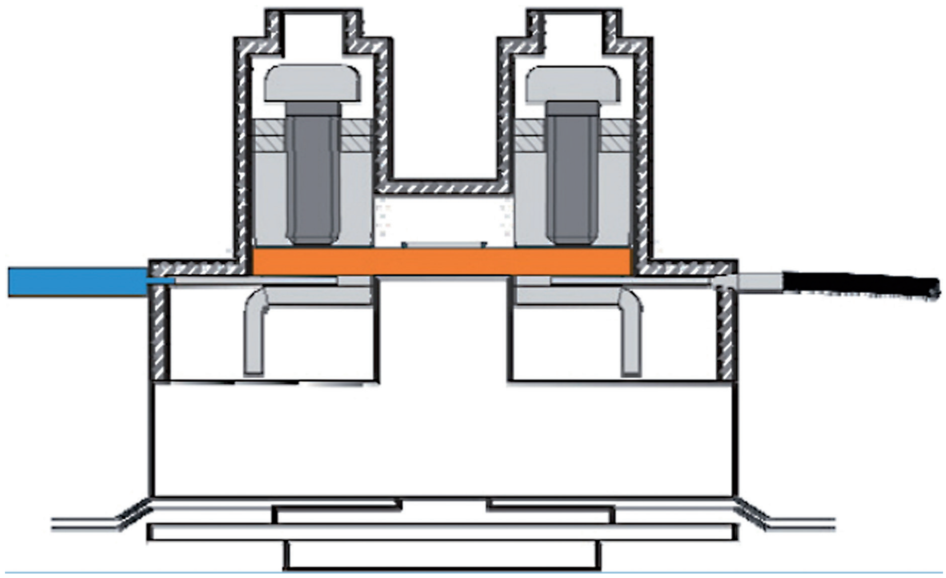
According to VDE 0560, part 41, EN 60831-1 and -2, the capacitors are designed for the following voltage load capacity:

Rated voltage	**440 V**	**480 V**	**525 V**	**690 V**
8 h per day	484 V	528 V	578 V	759 V
30 min per day	506 V	552 V	604 V	793 V
5 min	528 V	576 V	630 V	828 V
1 min	572 V	624 V	683 V	897 V

Assembly of power capacitors

The capacitors are filled with gas and can thus be used in any position. They are free of PCB. Each capacitor is equipped with an encapsulated discharge resistor at the connection terminals.

Connection terminal with discharge resistors assembled.



12 Formulas in connection with the capacitor

$\cos \varphi = P / S$	$Q = S \times \sin \varphi$	$\tan \varphi = Q / P$
S = apparent current	P = active power	Q = reactive power

Meter stop:
(determination of instantaneous active power)
Count the number of rotations n* during 1 minute and enter into the following formula.

Instantaneous active power = n* x 60 / c = kW
c = meter constant U/kWh
Conversion of PS in kW: PS x 0.736 = kW

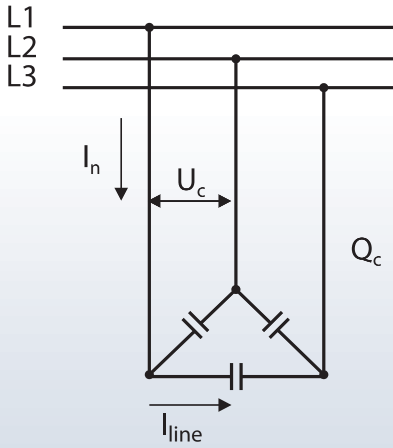
Line diameters: up to 50 kvar: kvar x 0.7 = mm^2
from 75 kvar: kvar x 1 ... 1.2 = mm^2

Back-up fuse dimensions: capacitor power (kvar) x 2 = fuse (A)

Current consumption of capacitors:
kvar x 1.4 = current per phase (A)
(also for capacitor check)

Increase in voltage in case of overcompensation:
ΔU = Increase in voltage in %
u_k = relative short-circuit voltage of the transformer in %
S_N = Transformer rated power
Q = Capacitor power
$\Delta U = u_k \times Q / S_N$

Delta connected capacitor:



U_n = line-to-line voltage
f_n = network frequency

Total rated current

$$I_n = \frac{Q_c}{U_c \times \sqrt{3}} = \frac{50000 \text{ var}}{400 \text{ V} \times \sqrt{3}} = 72 \text{ A}$$

Capacitor voltage

$$U_c = U_n$$

Capacitor line current

$$I_{line} = \frac{I_n}{\sqrt{3}} = \frac{72 \text{ A}}{\sqrt{3}} = 41{,}6 \text{ A}$$

Capacitive reactance

$$X_c = \frac{U_n^2}{Q_c} = \frac{(400 \text{ V})^2}{50000 \text{ var}} = 3{,}2 \ \Omega$$

Total capacity

$$C = \frac{1}{2 \times \pi \times f_n \times X_c} = \frac{1}{2 \times \pi \times 50 \text{ Hz} \times 3{,}2 \ \Omega} = 994{,}5 \ \mu\text{F}$$

Line capacity

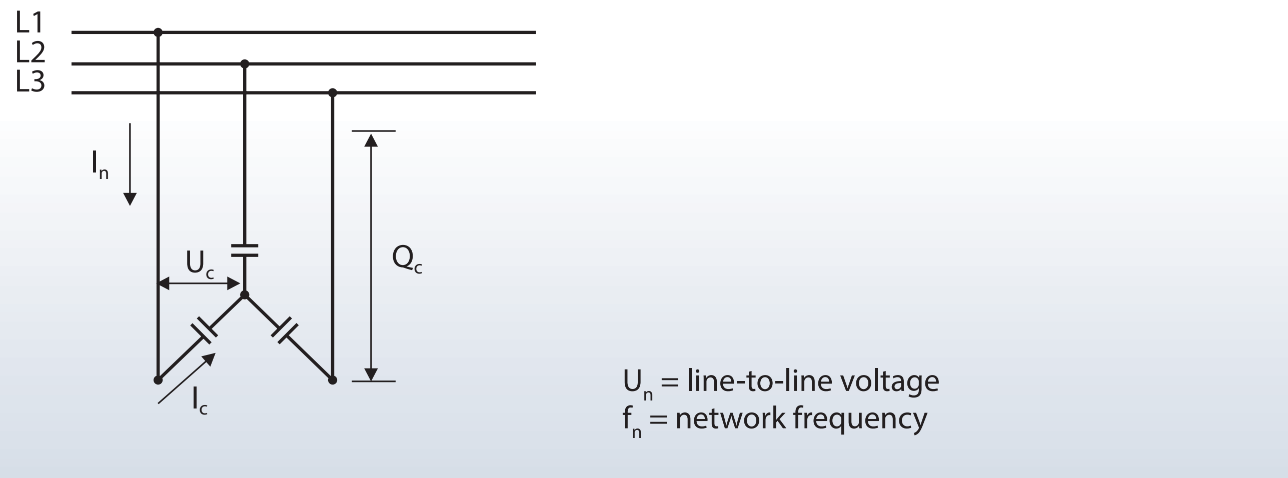
$$C_{ph} = \frac{C}{3} = \frac{994{,}5 \ \mu\text{F}}{3} = 331{,}5 \ \mu\text{F}$$

Reactive power

$$Q_c = U_c^2 \times 2 \times \pi \times f_n \times C = (400 \text{ V})^2 \times 2 \times \pi \times 50 \text{ Hz} \times 994{,}5 \ \mu\text{F} = 50000 \text{ var}$$

Information see page 27.

Star connected capacitor:



Capacitor voltage

$$U_c = \frac{U_n}{\sqrt{3}} = \frac{400\ V}{\sqrt{3}} = 230\ V$$

Capacitor line-to-line current

$$I_c = I_n$$

Reactive power

$$Q_c = U_c^2 \times 2 \times \pi \times f_n \times C = (230\ V)^2 \times 2 \times \pi \times 50\ Hz \times 994{,}5\ \mu F = 16{,}5\ kvar$$

Total rated current

$$I_n = \frac{Q_c}{U_n \times \sqrt{3}} = \frac{16500\ var}{400\ V \times \sqrt{3}} = 24\ A$$

Capacitive reactance

$$Xc = \frac{U_n^2}{Q_c} = \frac{(400\ V)^2}{16500\ var} = 9{,}6\ \Omega$$

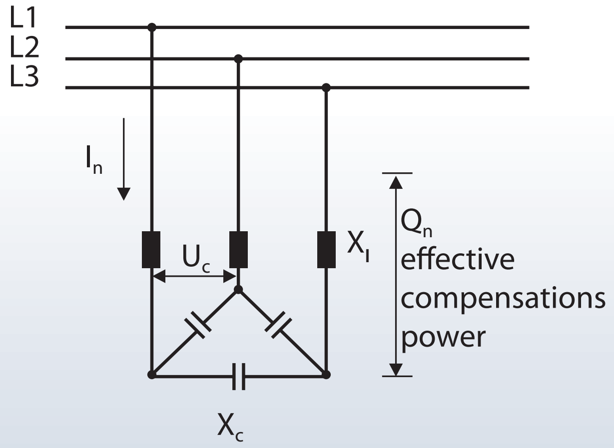
Effective Capacity

$$C = \frac{1}{2 \times \pi \times f_n \times X_c} = \frac{1}{2 \times \pi \times 50\ Hz \times 9{,}6\ \Omega} = 331{,}5\ \mu F$$

Caution:
Capacitor reactive power in case of star connection = 1/3 of capacitor reactive power in case of delta connection

Information see page 27.

3 phase delta connected capacitors:



U_n = line-to-line voltage
f_n = network frequency

Increase in voltage at capacitor	$U_c = \dfrac{U_n}{1-p}$	$= \dfrac{400\ V}{1-0.07} = 430\ V$
Reactive power	$Q_c = U_c^2 \times 2 \times \pi \times f_n \times C$	$= (430\ V)^2 \times 2 \times \pi \times 50\ Hz \times 924\ \mu F = 53{,}6\ kvar$
Total rated current	$I_n = \dfrac{Q_c}{U_c \times \sqrt{3}}$	$= \dfrac{53600\ var}{430\ V \times \sqrt{3}} = 72\ A$
Total capacitive reactance	$X_c = \dfrac{U_c^2}{Q_c}$	$= \dfrac{(430\ V)^2}{53600\ var} = 3{,}44\ \Omega$
Detuning factor	$p = \left(\dfrac{10 \times f_n}{f_{res}}\right)^2$	$= \left(\dfrac{10 \times 50\ Hz}{189\ Hz}\right)^2 = 7 \quad \widehat{=}\ 7\ \%$
Series resonant frequency	$f_{res} = \left(\dfrac{10 \times f_n}{\sqrt{p}}\right)$	$= \left(\dfrac{10 \times 50\ Hz}{\sqrt{7}}\right) = 189\ Hz$
Total inductance	$L_{tot} = \dfrac{1}{(2 \times \pi \times f_{res})^2 \times C}$	$= \dfrac{1}{(2 \times \pi \times 189\ Hz)^2 \times 924\ \mu F} = 0{,}76\ mH$
Inductive reactance	$X_L = 2 \times \pi \times f_n \times L_{tot}$	$= 2 \times \pi \times 50\ Hz \times 0{,}76\ mH = 0{,}238\ \Omega$

Information see page 27.

13 Selection of current transformer

When designing the converter transmission ratio, the total current of the system is crucial. If this value is not known, only the assumed total system current, the converter can be dimensioned according to the following rule of thumb:

Total power (kW) x 2 = converter dimension

Example: Facility 180 kW x 2 = 360 converter chosen: **400/5 A**.

In any case, a converter of class 1 accuracy is sufficient. In general, a class 3 converter is sufficient. For short distances between the converter and the controller (e.g. inside of switchgear), converters with a power of 5 VA are sufficient for a line diameter of 1.5 mm².

Converter line in mm²	Consumption per m double line, in VA
2.5	0.36
4.0	0.22
6.0	0.15
10.0	0.09

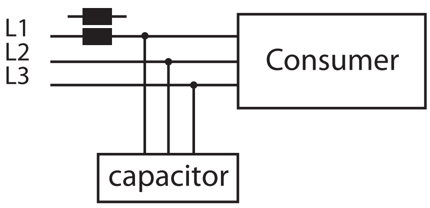
Consumption of converter lines made of copper at a secondary current of 5A

For larger distances between the converter and controllers or when using totalizing transformers, the line diameters and the converter power need to be increased accordingly, or converters with 1A secondary current are to be used instead of 5A secondary current. In this case, the current path needs to be connected to the 1A input at the controller. In case of existing systems with integrated measuring equipment from the energy supplier, the same transmission ratio as for the meter transformers can be set for the transformer of the compensation system.

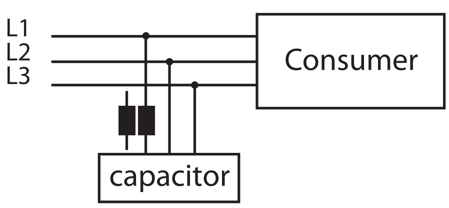
When feeding in with two or more transformers, the individual transformers can be combined using a totalizing current transformer. Observe that the primary currents are added and programmed at the reactive power controller. The primary current transformers should have the same transmission ratio.

14 Mounting of current transformer

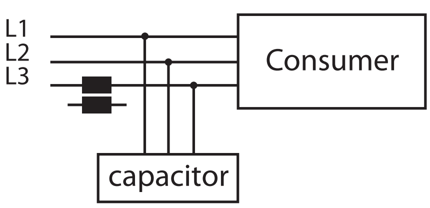
Correct! transformer in line 1 records line current



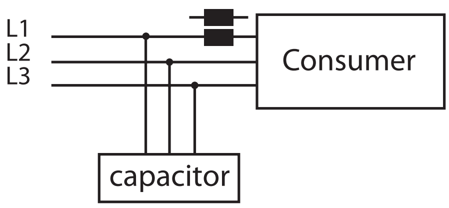
Incorrect! transformer only records The capacitor current controller does not switch



Incorrect! transformer connected to the wrong phase



Incorrect! transformer only records the capacitor current controller hooks up everything



15 Recommendations for selection of lines and fuses

The recommendations for the supply lines (NYY; four-core; Cu) was in accordance with DIN VDE 0298-4 (Table 3, laying type C, without bundling). Ambient temperature +35°C.

The recommendation of the fuse strengths was for short-circuit protection.

If conditions are different (including harmonics), appropriate reduction factors must be taken into account.

The system installer is responsible for measuring and selecting cables and fuses.

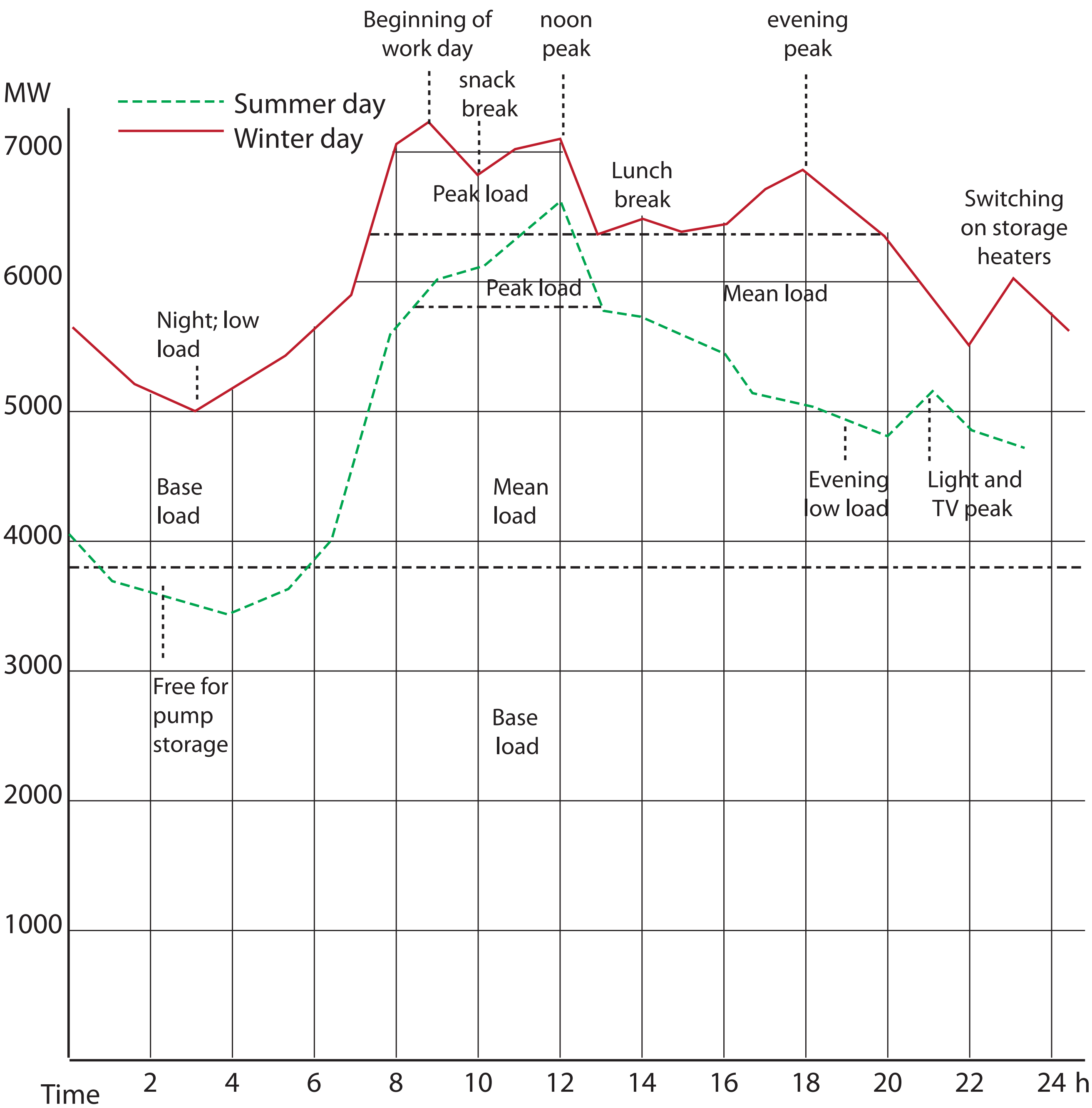
Capacitor power (400 V / 50/60Hz) kvar	Current input I (A) per phase	Supply line Cu mm²	Fuse protection NH system gL / gG per phase
1	1.44	4x 1.5	10
1.5	2.16	4x 1.5	10
2	2.88	4x 1.5	10
2.5	3.60	4x 1.5	10
3	4.32	4x 1.5	10
4	5.76	4x 1.5	10
5	7.20	4x 2.5	16
6	8.64	4x 2.5	16
7.5	10.80	4x 2.5	20
10	14.40	4x 4	25
12.5	18.00	4x 6	35
15	21.60	4x 6	35
17.5	25.20	4x 10	35
20	28.80	4x 10	50
25	36.00	4x 16	63
30	43.20	4x 25	80
35	50.40	4x 25	80
40	57.60	3x 35/ 16	100
50	72.00	3x 35/ 16	125
60	86.40	3x 50/ 25	125
70	100.80	3x 70/ 35	160
75	108.00	3x 70/ 35	160
80	115.20	3x 95/ 50	200
90	129.60	3x 95/ 50	200
100	144.00	3x 120/ 70	250
120	172.80	3x 120/ 70	250
125	180.00	3x 150/ 70	315
150	216.00	3x 185/ 95	315
175	252.00	3x 240/120	400
200	288.00	3x 240/120	400
250	360.00	2 x 3x 150/ 70	500
300	432.00	2 x 3x 185/ 95	630
350	504.00	2 x 3x 240/120	2 x 400
400	576.00	2 x 3x 240/120	2 x 400
450	648.00	4 x 3x 120/ 70	2 x 500
500	720.00	4 x 3x 150/ 70	2 x 500

Information see page 27.

16 Why energy optimization?

Next to the special energy supplier tariffs, the price for electric energy in kWh is given, as well as the average power in kW.

All energy suppliers are interested in supplying as much power (kWh) as possible and as evenly distributed over time as possible. However, this is impossible in practice, as the following diagram illustrates:



Thus, the energy supplier needs to provide all energy generators and distribution options to match the highest possible kW peak.

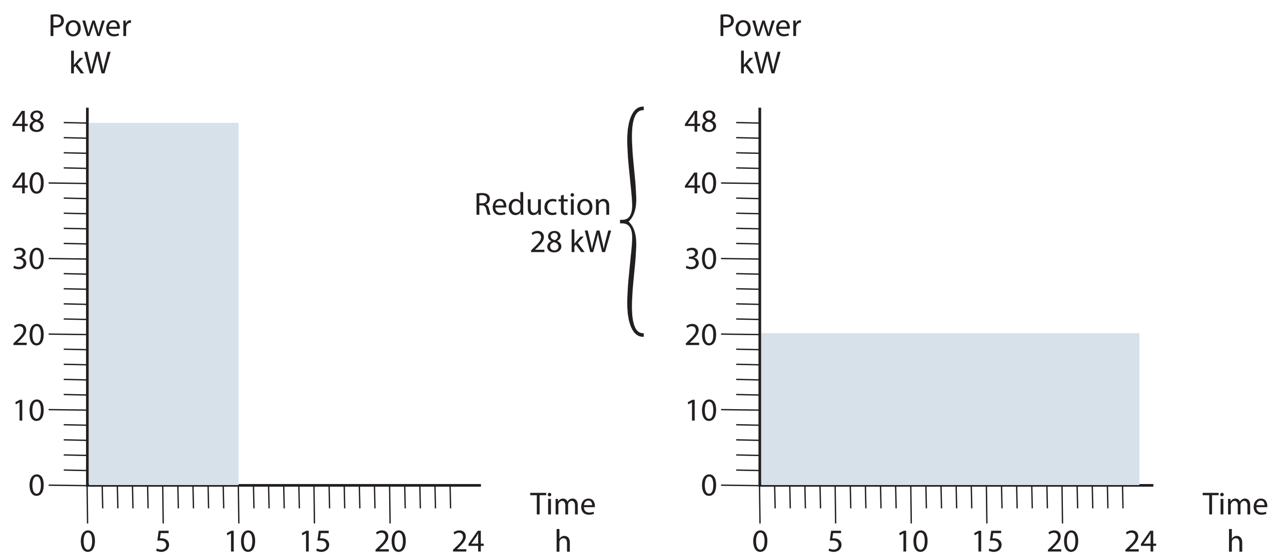
Since the distribution of energy creates vast costs, the kW peak created by the consumer if calculated by the energy supplier.

For this reason, it is also in the interest of the consumer to distribute the energy consumed over the day as evenly as possible.

Example:	Operating efficiency:	48 kW (peak)
	On-time:	10 hours
	equals a consumption of **480 kWh**	

However, the required energy of 480 kWh can also be distributed over 24 hours. This way, the only kW peak calculated is 480 : 24 = 20 kW.

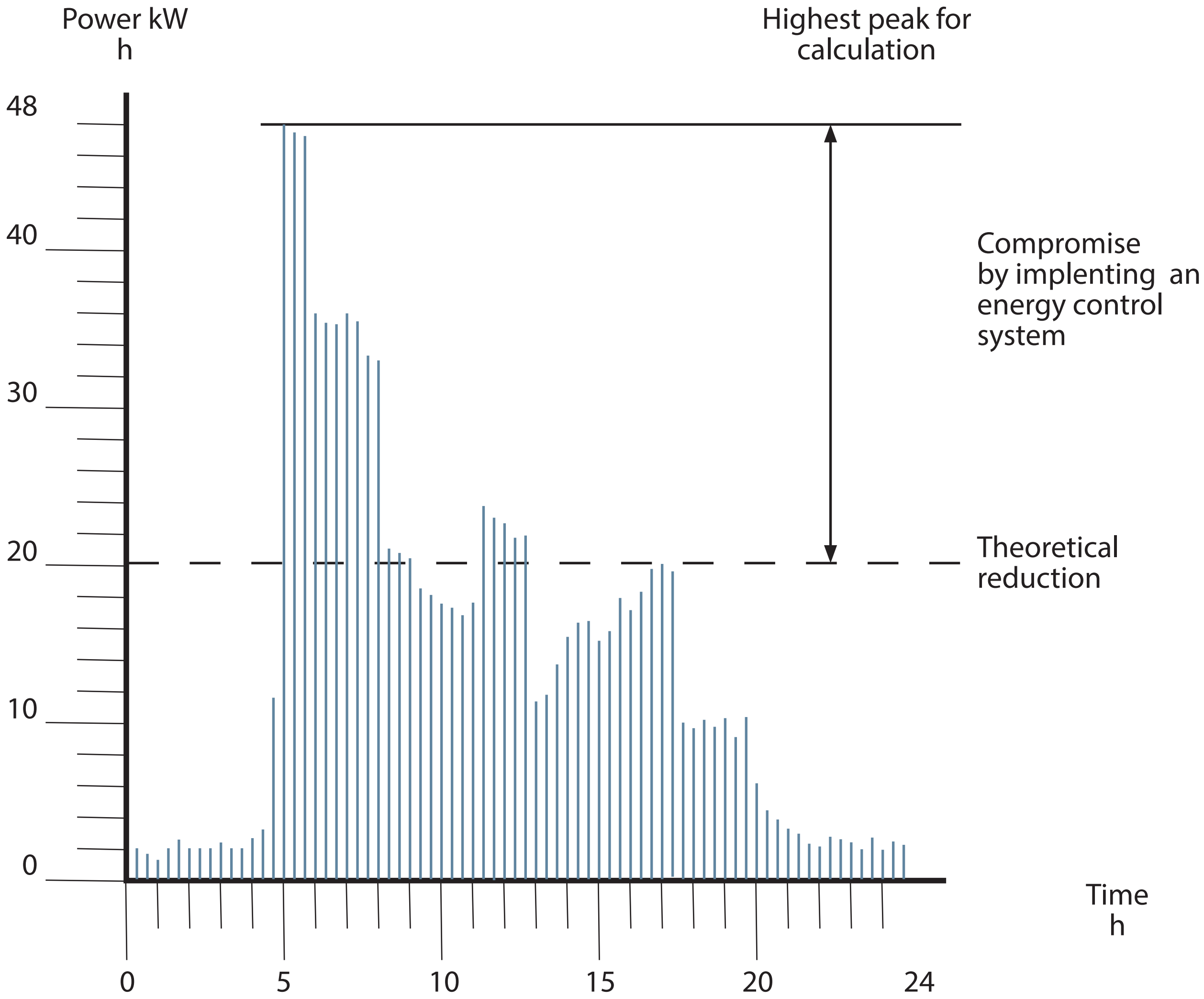
In this theoretical example, the kW peak was lowered to 20 kW.



If the energy supplier bills € 14.00 per kW, the monthly savings in this example would be 28 x 14 = € 392.00.
For a year, this corresponds to € 392.00 x 12 months = € 4,704.00.

In the example above, the theoretical possibility of reducing the costs of energy consumption is explained. In practice, however, there are most probably more values where considerable savings are possible.

Example: Average energy consumption of a bakery



The example above clearly shows that the average energy consumption registered by the meter is only measured for a very short time.

An automatic energy monitoring system now makes it possible to optimally lower the performance peak by switching off adequate consumers at an early stage.

17 Does it pay off to use an energy control system?

17.1 Checking energy bills

Values registered	200 kW peak 25,000 kWh
Operating hours:	170 hours / month
Calculation:	Monthly kWh / operating hours = 25000 / 170 = 147 kW
Conclusion:	In case of an even energy distribution of 25,000 kWh in 170 hours, this corresponds to 147 kW. However, 200 kW are invoiced on the electricity bill.

With commercial considerations, the consumers causing the high load peak of 200 kW can be identified.

17.2 Operation of a KBR-multilog2 measuring device

Via current transformers and voltage connections, the KBR multilog2 device records the energy consumption of a company and saves the corresponding data for subsequent evaluation on a computer.

With the computer, a comfortable evaluation of the energy consumption is performed. For documentation purposes, the energy consumption patterns can be printed.

18 Which consumers can be switched off?

Cooling systems
Compressors working with storage tanks
Hardening and annealing furnaces
Extractor and venting fans
Heatings
Illumination — partially
Kitchen devices
Miscellaneous not work-related machines

A switch-off by the energy monitoring system means a temporary shutdown of consumers during the measuring period.

19 How does an energy control system work?

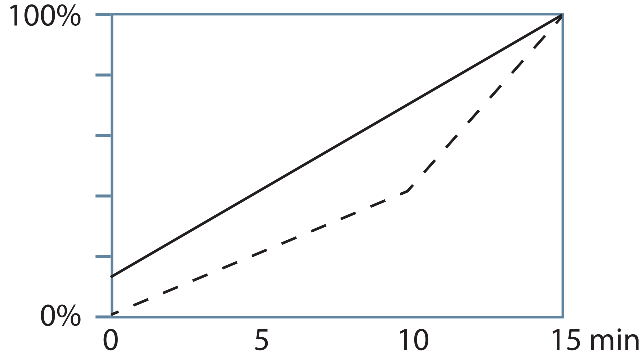
In the easiest setup, multiplication of current x voltage x cos φ determines the instantaneous power in kW

kW peak = U x · I x · cos φ

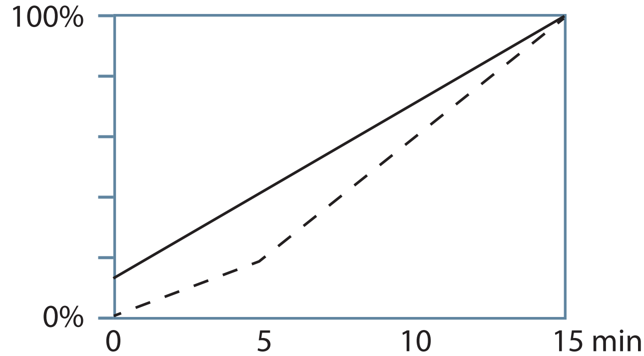
A setpoint adjuster defines the desired power peak that should not be exceeded. If it is exceeded, an output contact is triggered. This contact can also be used to switch off consumers. If the value falls below the defined setpoint, this contact releases the consumers that have been switched off. The most simple devices can only be used with small power levels of up to around 30 kW.

For larger power levels, the energy monitoring systems must run in parallel to the meter and take over several calculation functions. Apart from the instantaneous power determined, the measuring period of the meter is now also taken into account. In a trend calculation, the power that needs to be switched off is continuously monitored to avoid any exceedances after the measuring period is over.

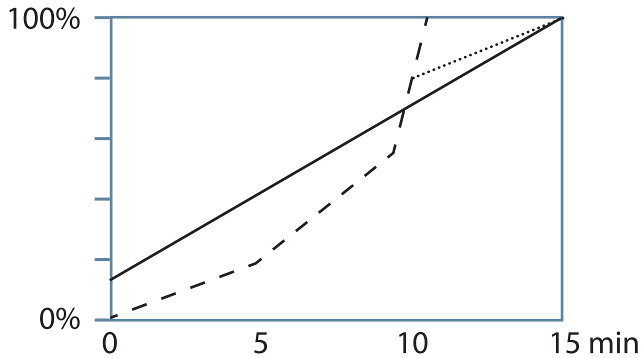
Examples for power periods:



The maximum is not used.
No warning is issued.



No risk of exceedance.
No warning is issued.



The maximum is exceeded.
A warning is issued in time and a switch-off takes place.
The maximum limit is adhered to through a reduction of the load.

Rated power
Actual power
Compensated power

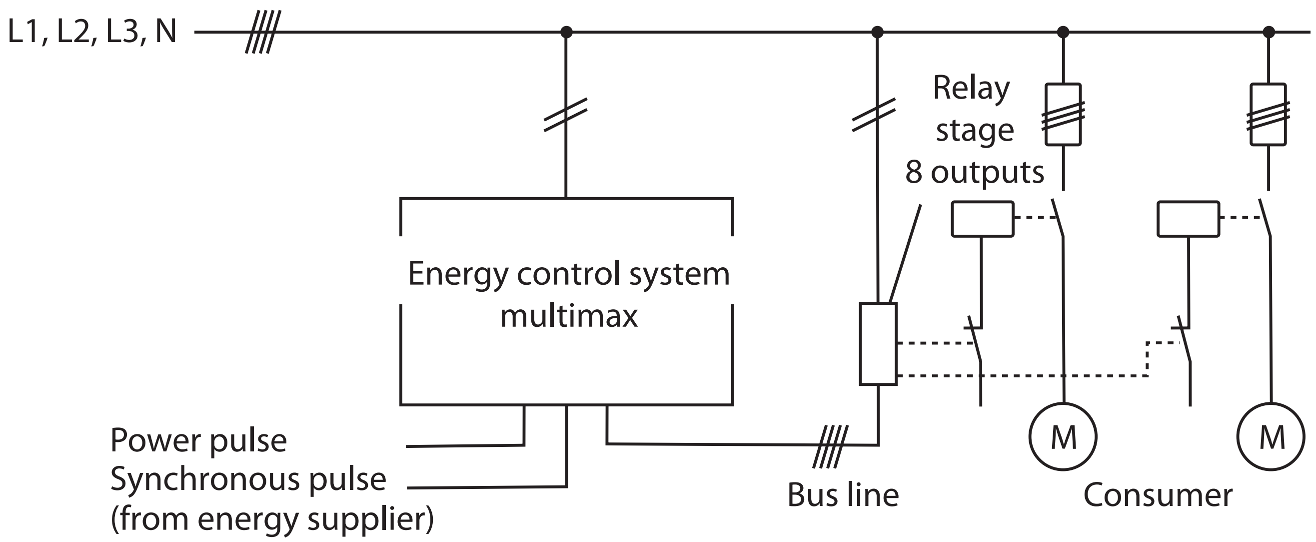
20 Which energy optimization system is used?

All KBR energy monitoring and management systems are microprocessor controlled units with trend calculation function (optimization calculator). The devices can be adapted to any energy supplier requirements.

The integrated synchronization equipment can compensate missing synchronous pulses from the energy supplier. To achieve savings when laying lines, the relay stage can be assembled where the switch-off takes place. Program and data storage with included batteries.

For the selection of the right device, we are at your service on site or via telephone.

Schematic circuit diagram



Our portfolio:

Reactive current compensation

- Power capacitors
- Filter circuit inductors
- Reactive power controller
- Fixed capacitors
- Modules and elements for switchgear cabinet assembly
- Customized modules
- Compensation controllers
- Customized assemblies
- Thyristor-switched compensation facilities
- Audio frequency blocking devices
- Discharge inductors

Active power filters

Energy management systems

- Consumption recording
- Energy optimization

Energy measurement technology

- Universal network measuring devices
- Mobile network analysis systems

Visualization software

What sets us apart:

Short delivery times
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One System. Best Solutions.

KBR Energy Management

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