REACTIVE POWER COMPENSATION

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A PRACTICAL GUIDE

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Contents

Foreword and Acknowledgements

The book gives a general overview and also specific deep knowledge about the segment "compensation of reactive power". Network quality, power losses, energy saving and reduction of CO_2 are discussed within 22 chapters forming a technical "dictionary". It is written to be accessible for all specialists; including engineers, electricians and students. The purpose of this book is to extend the knowledge in this specified field. This "technical guide" answers a lot of questions arising in controlling reactive power e.g. at parallel operation with generators.

This book is based on a book in German published by the VDE Verlag GmbH (Berlin and Offenbach) in the year 2003. Some chapters were revised and adapted or entirely rewritten to conform to new technological developments and changing standards. The chapters have been primarily revised by:

Jürgen Schlabbach – Chapters 1 incl. 4; 18 and 22

Wolfgang Hofmann – Chapters 5 incl. 16 and 21

Wolfgang Just – Chapters 17, 19 and 20

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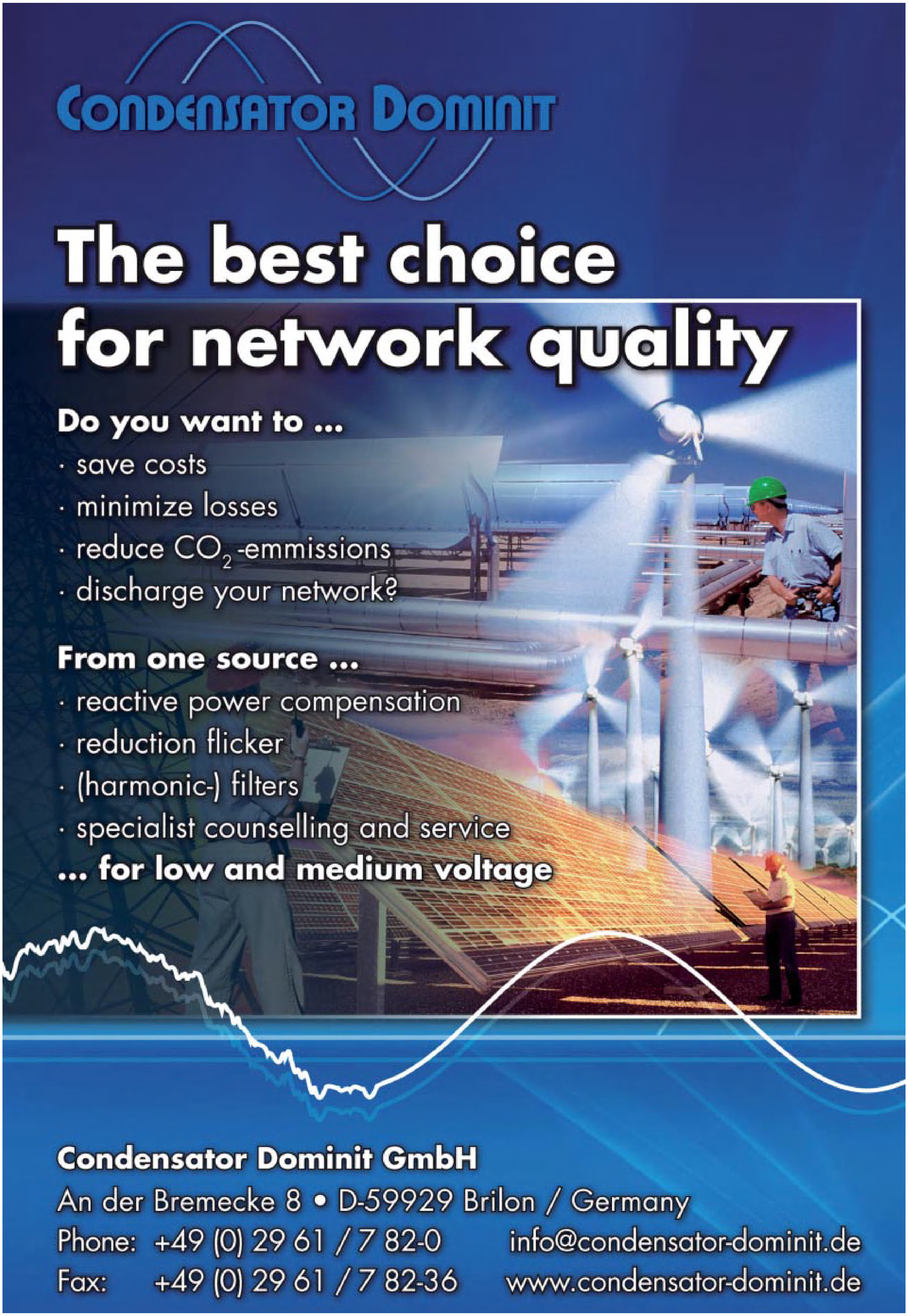
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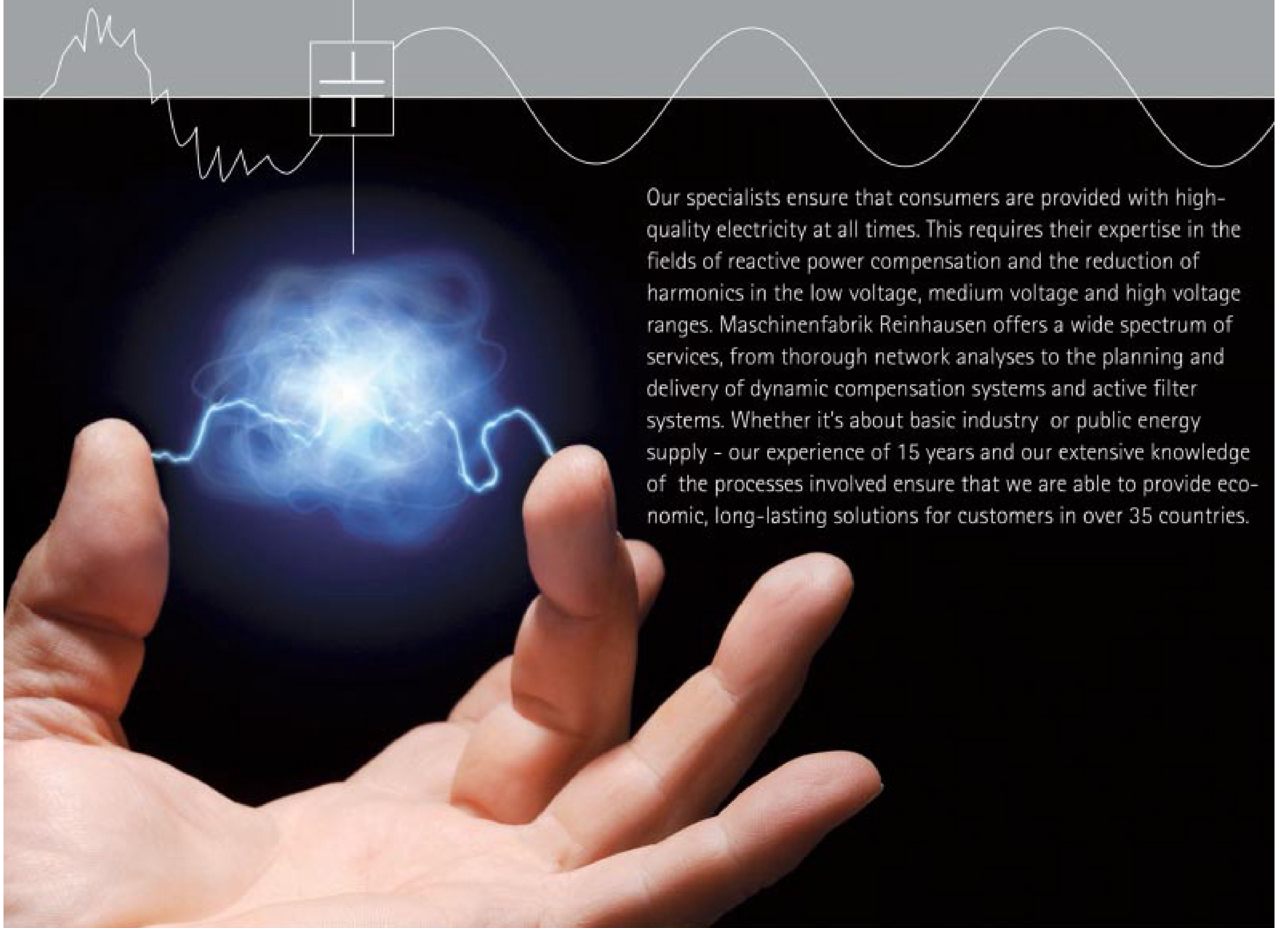

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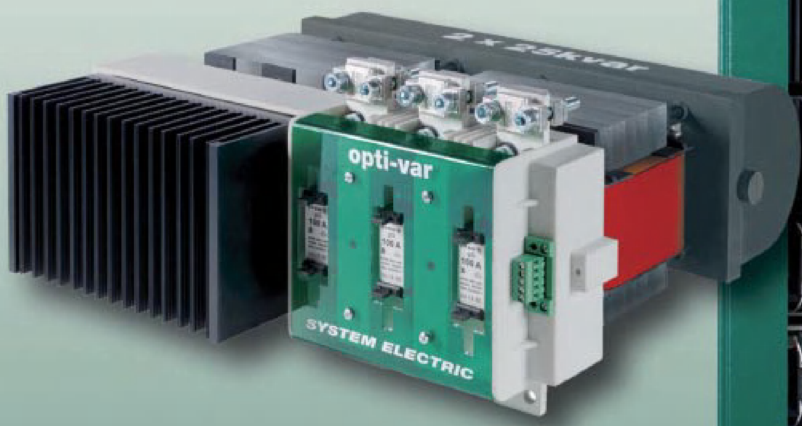

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1

Basics of Reactive Power

1.1 Chapter Overview

This chapter deals with the definitions and fundamentals of active, reactive and apparent power in the case of sinusoidal and non-sinusoidal current and voltage. The differences between power factor, taking account of only the fundamental frequency components, and distortion factor, taking account of higher frequency components as well, are explained. Equivalent mechanical models are presented to explain the behaviour of inductance and capacitance and the generation of reactive power.

1.2 Phasors and Vector Diagrams

Motors, discharge lamps, transformers, generators with lagging power factor, as well as cables and overhead lines with high current loading, need reactive power to build up the magnetic field, sometimes called the consumption of reactive or inductive power. Other equipment and consumers, such as rectifiers with capacitive smoothing, compact fluorescent lamps, capacitors, generators with leading power factor and overhead transmission lines and cables in no-load or low-load operation, need reactive power to build up the electric field, an effect called the generation of reactive or capacitive power. In contrast to active power, reactive power is not converted into heat, light or torque, but fluctuates between the source (e.g. capacitor) and the drain (e.g. motor). Compared with pure active power, the current is increased as the active current and the reactive current are added to the apparent current according to their amount and phase angle.

When dealing with AC and three-phase systems, it should be noted that currents and voltages are generally not in phase. The phase position depends on the amount of inductance, capacitance and ohmic resistance at the impedance.

The time course, for example of a current or voltage, varies in accordance with

$$u(t) = \hat{u}\cos(\omega t + \varphi_U) \tag{1.1a}$$

$$i(t) = \hat{i}\cos(\omega t + \varphi_I) \tag{1.1b}$$

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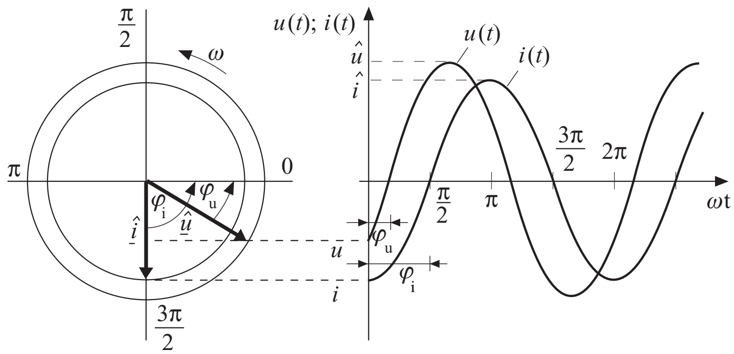

Figure 1.1 Vector diagram and time course of AC voltage [1].

as can be shown in a line diagram, see Figure 1.1. In the case of sinusoidal variables, these can be shown at the complex numerical level by rotating pointers, which rotate in a mathematically positive sense (counter-clockwise) with angular velocity ω as follows:

$$\underline{U} = \sqrt{2}U \cdot e^{(j\omega t + \varphi_U)} \tag{1.2a}$$

$$\underline{I} = \sqrt{2}I \cdot e^{(j\omega t + \varphi_I)} \tag{1.2b}$$

The time course in this case is obtained as a projection onto the real axis, as in Figure 1.1.

The terms for the designation of resistances and admittances are stipulated in DIN 40110 [2] and in IEC 60027-7 [3]. These specify the following:

Resistance	R	Active resistance
Reactance	X	Reactance
Conductance	G	Active conductance
Susceptance	B	Susceptance

The generic term for resistances is given as impedance or apparent impedance

$$\underline{Z} = R + jX \tag{1.3a}$$

The generic term for conductance is admittance or apparent admittance

$$\underline{Y} = G + jB \tag{1.3b}$$

The reactance depends on the particular frequency under consideration and can be calculated for capacitances or inductances from

$$X_C = \frac{1}{\omega C} \tag{1.4a}$$

$$X_L = \omega L \tag{1.4b}$$

For sinusoidal variables, the current through a capacitor, or the voltage at an inductance, can be calculated as follows:

$$i(t) = C \cdot \frac{du(t)}{dt} \tag{1.5a}$$

$$u(t) = L \cdot \frac{di(t)}{dt} \tag{1.5b}$$

The derivation for sinusoidal variables establishes that the current achieves, by an inductance, its maximum value a quarter period after the voltage. When considering the process at the complex level, the pointer for the voltage precedes the pointer for the current by 90°. This corresponds to multiplication by $+j$.

For capacitance, on the other hand, the voltage does not reach its maximum value until a quarter period after the current, the voltage pointer lagging behind the current by 90°, which corresponds to multiplication by $-j$. This enables the relationship between current and voltage for inductances and capacitances to be expressed in a complex notation. Thus

$$\underline{U} = j\omega L \cdot \underline{I} \tag{1.6a}$$

$$\underline{I} = \frac{1}{j\omega C} \cdot \underline{U} \tag{1.6b}$$

Vectors are used to describe electrical processes. They are therefore used in DC, AC and three-phase systems. Vector systems can, by definition, be chosen as required, but must not be changed during an analysis or calculation. It should also be noted that the appropriate choice of the vector system is of substantial assistance in describing and calculating special tasks. The need for vector systems is clear if one considers Kirchhoff's law, for which the positive direction of currents and voltages must be specified. In this way, the positive directions of the active and reactive powers are then also stipulated.

For reasons of comparability and transferability, the vector system for the three-phase network (L1,L2,L3 components or RYB) should also be used for other component systems (e.g. symmetrical components), which describe the three-phase network.

If vectors are drawn as shown in Figure 1.2, the active and reactive powers, for instance output by a generator in overexcited operation, are positive. This vector system is designated as a generator vector system (GVS). Accordingly, the active and reactive powers consumed by

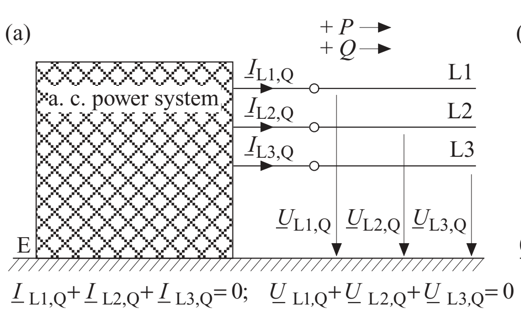

Figure 1.2 Definition of vectors for current, voltage and power in three-phase AC systems [1]: (a) power system diagram; (b) electrical diagram for symmetrical conditions (positive sequence system).

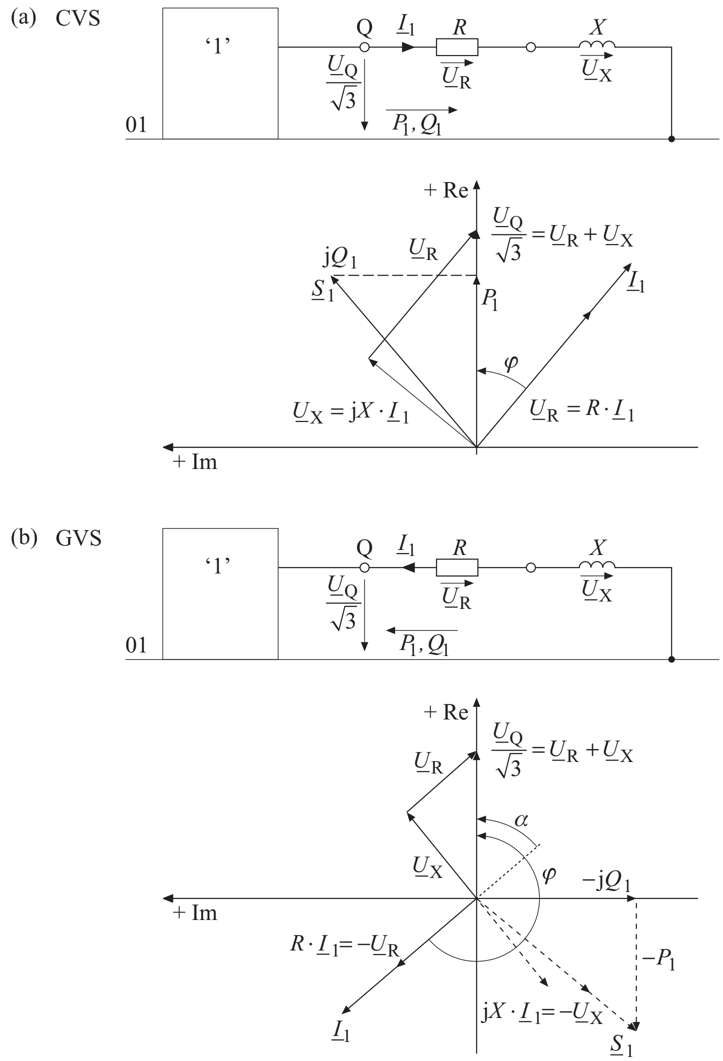

Figure 1.3 Vector diagram of current, voltage and power [1]: (a) related to consumers (consumer vector system – CVS); (b) related to power generation (generation vector system – GVS).

the load (e.g. motor) are positive when choosing the consumer vector system (CVS). Figure 1.3 shows the phasor diagram of an ohmic–inductive load in the generator and in the consumer vector system.

1.3 Definition of Different Types of Power

The definitions and explanantions are given in accordance with DIN 40110 [2]. The instantaneous value of the power $p(t)$ in an AC system is calculated as follows:

$$p(t) = u(t) \cdot i(t) \tag{1.7}$$

with $i(t)$ and $u(t)$ as the instantaneous values of current and voltage. Generally the product of current and voltage is oscillating and shows positive and negative values within one period. The mean value of the oscillating power is called active power $\overline{P}$:

$$\overline{P} = \frac{1}{T} \int_0^T u(t) \cdot i(t)\, dt \tag{1.8}$$

In the case of sinusoidal current and voltage

$$u(t) = \hat{u} \cos{(\omega t + \varphi_U)} \tag{1.9a}$$

$$i(t) = \hat{i} \cos{(\omega t + \varphi_I)} \tag{1.9b}$$

The instantaneous value of the power $p(t)$ as the product of the instantaneous values of current and voltage is

$$p(t) = \hat{u}\hat{i} \cos(\omega t + \varphi_U) \cos(\omega t + \varphi_I) \tag{1.10a}$$

After some numerical operations and with $\varphi = \varphi_U - \varphi_I$, the following equation is obtained:

$$p(t) = \frac{\hat{u}\hat{i}}{2} \cos\varphi + \frac{\hat{u}\hat{i}}{2} \cos(2\omega t + \varphi) \tag{1.10b}$$

Equation 1.10b indicates that the power $p(t)$ oscillates with twice the frequency of the current and voltage; its mean value is called active power P:

$$P = \frac{\hat{u}\hat{i}}{2} \cos\varphi \tag{1.11a}$$

The term $\hat{u}\hat{i}/2$ is called apparent power S:

$$S = \frac{\hat{u}\hat{i}}{2} \tag{1.11b}$$

If one eliminates φ_I in the above equations the following is obtained:

$$p(t) = \frac{\hat{u}\hat{i}}{2} \cos\varphi + \frac{\hat{u}\hat{i}}{2} \cos\varphi \cdot \cos{(2\omega t + 2\varphi_U)} + \frac{\hat{u}\hat{i}}{2} \sin\varphi \cdot \sin{(2\omega t + 2\varphi_U)} \tag{1.12}$$

The term $(\hat{u}\hat{i}/2) \sin\varphi$ is called reactive power Q. The reactive power oscillates with twice the frequency of the current and voltage; its mean value is zero:

$$Q = \frac{\hat{u}\hat{i}}{2} \sin\varphi \tag{1.11c}$$

The reactive power in the CVS is positive if the phase angle φ is between 0° and $+180^\circ$; that is, if the voltage pointer leads the current pointer. In this case the reactive power is called the inductive power, which is the power drawn from the system by a reactance. If the voltage pointer lags behind the current pointer, which is when the phase angle φ is between 0° and -180°, the reactive power becomes negative. This is called capacitive power, as it is the power supplied to the system by a capacitance.

In general, the following equation is valid

$$|Q| = \sqrt{S^2 - P^2} \tag{1.13}$$

for the amplitudes of the active power P, reactive power Q and apparent power S are defined as above. If rms values are used instead of peak values, as is common in calculating power systems, the active, reactive and apparent power become

$$\overline{P} = P = U \cdot I \cos(\varphi_U - \varphi_I) \tag{1.14a}$$

$$Q = U \cdot I \sin(\varphi_U - \varphi_I) \tag{1.14b}$$

$$S = U \cdot I \tag{1.14c}$$

The quotient from active power P and reactive power S is called the power factor λ. In the case of sinusoidal currents and voltages the power factor is identical to the distortion factor of the fundamental frequency $\cos \varphi_1$.

Figure 1.4 indicates the time course of current and voltage at an ohmic–inductive consumer load and the resulting active, reactive and apparent power.

1.4 Definition of Power for Non-Sinusoidal Currents and Voltages

Active power can only be converted if current and voltage have equal frequency, as the integral for current and voltage of unequal frequency in accordance with

$$\overline{P} = \frac{1}{T} \int_0^T u(t) \cdot i(t)\, dt \tag{1.8}$$

makes no contribution.

If current and voltage both have a non-sinusoidal waveform

$$u(t) = \sum_{k=1}^{N} \hat{u}_k \cos(k\omega_1 t + \varphi_{U,k}) \tag{1.15a}$$

$$i(t) = \sum_{l=1}^{N} \hat{i}_l \cos(l\omega_1 t + \varphi_{I,l}) \tag{1.15b}$$

the instantaneous value of the power is calculated as

$$\begin{aligned} p(t) = & \sum_{k=l=1}^{N} \frac{\hat{u}_k \hat{i}_l}{2} \cos(\varphi_{U,k} - \varphi_{I,l}) \\ & + \sum_{k=1}^{N} \sum_{l=1}^{N} \frac{\hat{u}_k \hat{i}_l}{2} \cos((k+l)\omega_1 t + \varphi_{U,k} + \varphi_{I,l}) \\ & + \sum_{\substack{k=1 \\ k \neq l}}^{N} \sum_{l=1}^{N} \frac{\hat{u}_k \hat{i}_l}{2} \cos((k-l)\omega_1 t + \varphi_{U,k} - \varphi_{I,l}) \end{aligned} \tag{1.16}$$

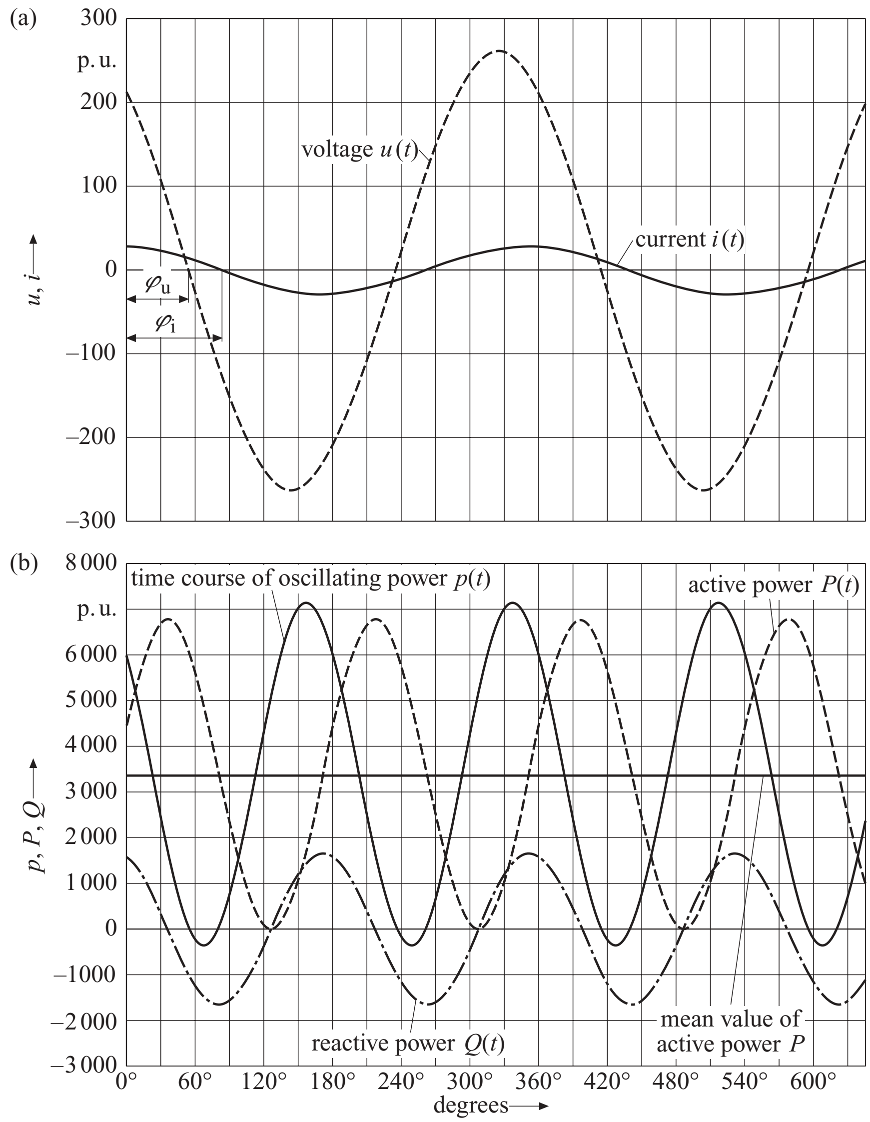

Figure 1.4 Current, voltage and powers at an ohmic–inductive consumer load: (a) current and voltage; (b) active, reactive and apparent power.

The first summand describes the active power, whereby the component with $k = l = 1$ represents the fundamental component active power and the summands where $k = l > 1$ render the harmonic active powers. The second summand renders the reactive power Q and the third summand the distortion power Q_d. The time course of these powers oscillates non-sinusoidally about the zero-frequency mean value. Note that the higher frequencies of voltage and current generate active power as well, if their frequencies are the same.

The correlation between the powers is as follows (active part of fundamental current I_{w1}; reactive part of fundamental current I_{b1}; harmonic part of current I_ν):

$$S^2 = P_1^2 + Q_1^2 + Q_d^2 \tag{1.17a}$$

$$S^2 = U^2\left(I_{w1}^2 + I_{b1}^2 + \sum_{\nu=2}^{H} I_\nu^2\right) \tag{1.17b}$$

The active power P_1 and the reactive power Q_1 are related to the fundamental frequency of current and voltage, and the distortion power Q_d is related to the harmonic currents and the fundamental frequency of the voltage:

$$P_1 = U \cdot I_1 \cdot \cos\varphi \tag{1.18a}$$

$$Q_1 = U \cdot I_1 \cdot \sin\varphi \tag{1.18b}$$

$$Q_d = U \cdot \sqrt{\sum_{\nu=2}^{H} I_\nu^2} \tag{1.18c}$$

The different terms are represented in a three-dimensional diagram as in Figure 1.5.

The power factor λ, which is defined as the quotient of active power and apparent power, is generally defined as follows:

$$\lambda = \frac{|P|}{\sqrt{\left(P^2 + Q_1^2 + Q_d^2\right)}} \tag{1.19}$$

The displacement factor $\cos\varphi_1$ is defined as the quotient of active power and apparent power with fundamental frequency (in the case of sinusoidal voltage and non-sinusoidal current):

$$\cos\varphi_1 = \frac{P_1}{\sqrt{P_1^2 + Q_1^2}} = \frac{P_1}{S_1} \tag{1.20}$$

The power factor λ and displacement factor $\cos\varphi_1$ are related to each other by the fundamental content g_i of the current:

$$\lambda = g_i * \cos\varphi_1 \tag{1.21}$$

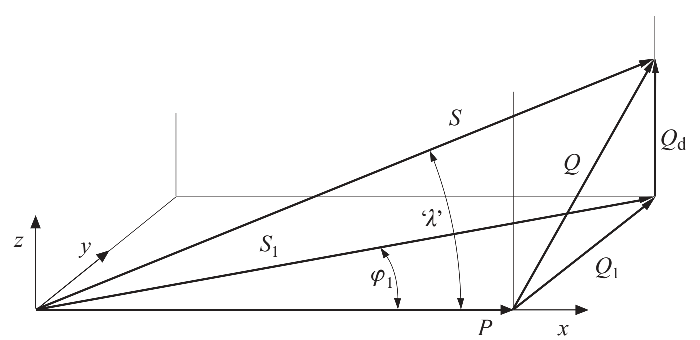

Figure 1.5 Active, reactive, apparent and distortion power, power factor and displacement factor.

The fundamental content g_i is defined as the quotient of the rms value of fundamental current to the total rms value:

$$g_i = \frac{I_1}{I} \tag{1.22}$$

The total rms value also includes the higher frequency components of the current as well:

$$I = \sqrt{\sum_{\nu=1}^{H} I_\nu^2} \tag{1.23}$$

1.5 Equivalent Mechanical Model for Inductance

An equivalent model from mechanics can illustrate, as in Figure 1.6, the phenomena of inductance, capacitance, active and reactive power. A train with mass m is accelerated by the locomotive to its final velocity v. The pointers of force and velocity are in the same direction, and the power and energy supplied are positive as well. When the force is increased or decreased in a stepwise fashion, the velocity of the train does not change stepwise, but increases or decreases by means of an exponential function. The energy supplied, in the case of increasing force, or not supplied, in the case of decreasing force, is stored in the movement of the train, which is identical to the phenomena of storage and discharge of electrical energy in an inductance. The mechanical energy W_{mec} is given by

$$W_{mec} = m \cdot \frac{v^2}{2} \tag{1.24a}$$

and the electrical energy W_{el} by

$$W_{el} = L \cdot \frac{I^2}{2} \tag{1.25a}$$

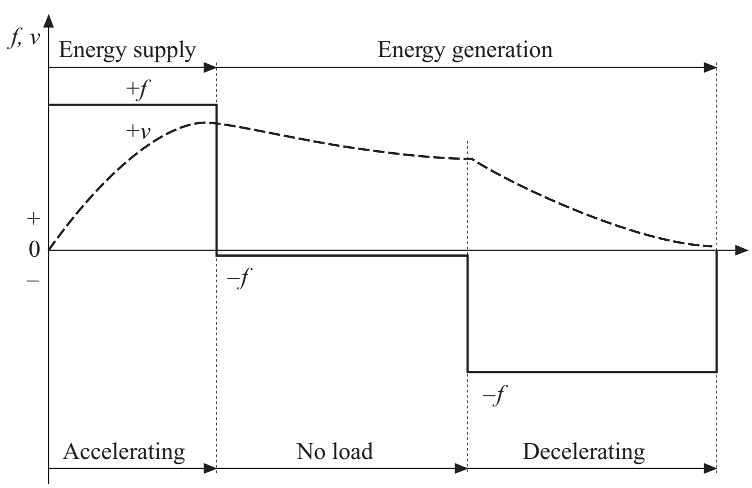

Figure 1.6 Force and velocity while accelerating and decelerating a train [4].

Comparing electrical and mechanical phenomena, the equivalents are:

Voltage	≡	Mechanical force
Current	≡	Velocity
Inductance	≡	Physical mass
Capacitance	≡	Spring constant
Electrical energy	≡	Mechanical energy
Electrical power	≡	Mechanical power

If the force to accelerate the train is a sinusoidal function it is obvious that the velocity of the train does not change synchronously (with the same frequency), but with a time delay, see Figure 1.7. The maximal values of velocity and mechanical force have a time delay or phase shift similar to the phase shift between voltage and current at an inductance, which is described by the term ‘reactive power’. Reactive power in this case is reactive power by an inductance. It is always present if the phasors of mechanical force (equivalent to the voltage) and velocity (equivalent to the current) have opposite directions and different signs. Reactive power W_{mag} in inductances stored in the magnetic field is

$$W_{mag} = L \cdot \frac{I^2}{2} \tag{1.25b}$$

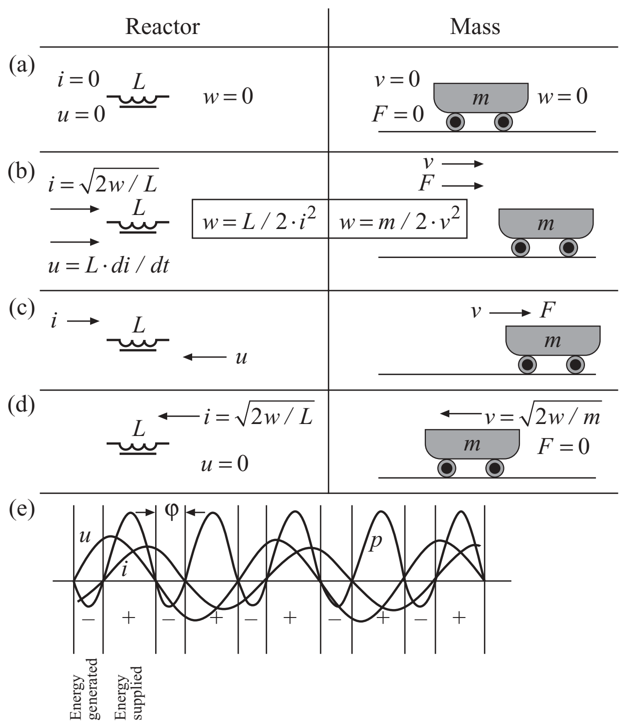

Figure 1.7 Equivalent electrical and mechanical model (inductance and mass): (a) starting point; (b) accelerating – energy supply (imported); (c) decelerating – energy generation (exported); (d) exported energy (voltage switched off); (e) time course of current, voltage and power.

In the mechanical model the equivalent of the magnetically stored energy is the kinetic energy of the moving mass:

$$W_{kin} = m \cdot \frac{v^2}{2} \tag{1.24b}$$

1.6 Equivalent Mechanical Model for Capacitance

Reactive power can be compensated by capacitors, which store energy in the electric field:

$$W_{cap} = C \cdot \frac{U^2}{2} \tag{1.26}$$

The equivalent of a capacitor in the mechanical model is a spring, which stores energy (potential energy)

$$W_{pot} = k \cdot \frac{F^2}{2} \tag{1.27}$$

with mechanical force F and spring constant k. If a laminated spring (leaf spring) is compressed and expanded with a sinusoidal force, the maximum mechanical force is supplied when the velocity is zero. In the case of maximal velocity the mechanical force is zero, see Figure 1.8.

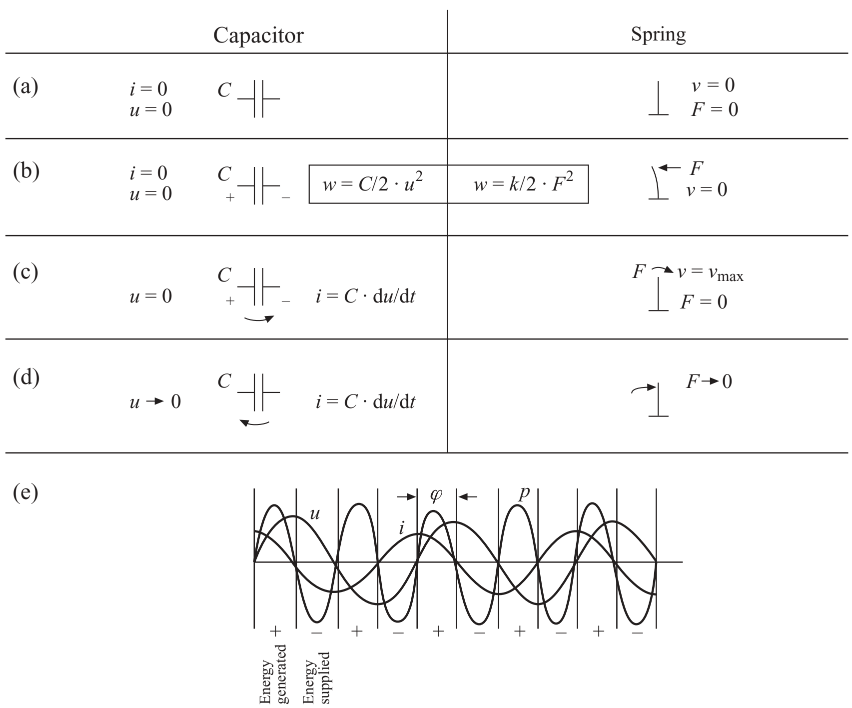

Figure 1.8 Equivalent electrical and mechanical model (capacitance and spring): (a) starting point; (b) compressed – energy supply (imported); (c) expanded – energy generation (exported); (d) discharging the capacitor, voltage switched off (exported); (e) time course of current, voltage and power.

Mechanical force and velocity are characterized by a time shift of 90°, similar to the time shift of current and voltage at a capacitor. The mechanical system 'mass ↔ spring' and the electrical system 'inductance ↔ capacitor' can both oscillate with a defined frequency, namely the resonance frequency.

1.7 Ohmic and Reactive Current

An ohmic–inductive load with a sinusoidal waveform of current and voltage, such as in AC motors, transformers and reactors, can be modelled as the equivalent circuit of an ohmic resistance R in parallel with an inductive resistance X_L as in Figure 1.9a. The current can be represented in this equivalent model as two orthogonal components, see Figure 1.9b, one in phase with the voltage U, called the active current I_w, and the other with a phase shift of 90° lagging, called the inductive or reactive current I_b. The apparent current I has a phase shift against the voltage of phase angle φ. The active component I_w of the current describes the ohmic component and active power, while the reactive component I_b describes the inductive component, representing the reactive power. A line diagram of current, voltage and power is outlined in Figure 1.9c.

Electrical parameters such as voltage, current and power can be described by pointers (vectors) with rms values represented by the length of the pointer. Figure 1.10 indicates the relationship of active, reactive and apparent current and power in the orthogonal system, representing the same quantities and relations as the line diagram in Figure 1.9c. The phase shift (phase angle φ) depends on the amount of the reactive component in relation to the active component. With constant reactive power and increasing active power, the power factor and

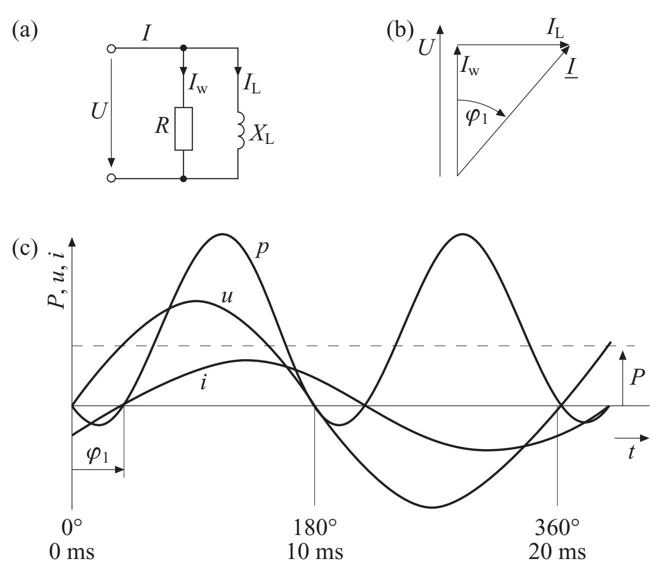

Figure 1.9 Phase shift of current and voltage in the case of ohmic–inductive load: (a) equivalent circuit diagram; (b) orthogonal components of current; (c) line diagram of current, voltage and power.

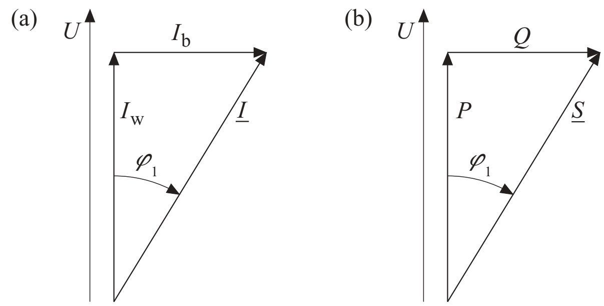

Figure 1.10 Orthogonal components of current and power: (a) current; (b) power.

the apparent power are both increasing; in the case of constant active power and increasing reactive power, the power factor is decreasing and the apparent power increasing. For details see also Figure 1.5 and Equation 1.20.

1.8 Summary

The power in AC systems has an oscillating time course; the mean value is called the active power. The reactive power has a mean value of zero and is determined by the phase angle between voltage and current. One has to distinguish between the fundamental power factor cos φ, sometimes called the displacement factor, which takes account of the active power and reactive power at the fundamental frequency, and the power factor λ, which takes the distortion power Q_d of the higher frequencies (harmonics and interharmonics) into account as well.

References

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[2] DIN 40110 (2002) *Wechselstromgrößen – Teil 2: Mehrleiter-Stromkreise* (Quantities used in alternating current theory – Part 2: Multi-line circuits), Beuth-Verlag, Berlin, November.
[3] Hofmann, W. (1995) Reactive power does not always mean reactive power. *etz*, **116** (22), 22–28.
[4] IEC 600027-7 (2008) *Quantities and units, and their letter symbols*.

2

Reactive Power Consumers

2.1 Chapter Overview

This chapter describes the characteristic of typical consumers with respect to reactive power. The general structure of consumers with series and parallel equivalent circuits is described. Typical values of reactive power for motors and transformers are also given.

2.2 Reactive Energy Demand

Reactive power is an oscillating power, as described in Chapter 1. Reactive power oscillates between reactive power generation, for example capacitances, and reactive power consumers, for example motors. Both parts of this oscillation must have the ability to store the reactive energy. Considering typical electrical consumers and equipment, storage is only possible through the magnetic field as magnetic energy or through the electric field in capacitances as electrical energy. Magnetic energy is stored by means of AC motors, transformers and inductive loads, for example gas discharge lamps, and in the magnetic field of overhead lines and cables. Electrical energy storage in electric fields is possible in all types of capacitances and in the electric field of overhead lines and cables. In the explanations below, reactive power consumption and reaction power generation are so named, despite the correct physical behaviour.

The energy W stored in a magnetic field, for example in the case of a simple coil having N windings, depends on the design of the current-carrying conductors, on the current in the conductor and on the relative permeability μ_r of the surrounding area

$$W = \frac{1}{2} \cdot L \cdot I_{\max}^2 \tag{2.1a}$$

The inductance L depends on the geometric design

$$L = A \cdot \mu_r \cdot \mu_0 \cdot \frac{N^2}{l} \tag{2.1b}$$

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

where
$A =$ cross-sectional area
$N =$ number of conductors (windings)
$l =$ length of conductor
$\mu_0 =$ permeability (magnetic field constant)

The reactive power is then given as

$$Q = 3 \cdot I^2 \cdot \omega L \tag{2.2}$$

in the case of three-phase AC systems.

2.3 Simplified Model: Series Reactive Power Consumer

Series reactive power consumers are consumers whose reactance is connected in series with the resistance as outlined in Figure 2.1, indicating the simplified equivalent circuit of a motor. Besides motors, overhead lines and air-core reactors (short-circuit limiting reactors) are series reactive power consumers. The reactive power and energy of series reactive consumers is the energy of the magnetic leakage field, stored in the area around the current-carrying conductor; that is, in the iron core in the case of a motor or transformer and in the air in the case of an overhead line.

2.4 Realistic Model: Mixed Parallel and Series Reactive Power

In practice, reactive power consumers cannot be represented by pure series equivalent circuits but as mixed circuits, composed of inductive and ohmic impedances connected in series and in parallel as outlined in Figure 2.2, indicating the equivalent circuit diagram of a transformer which is similar to that of an asynchronous motor.

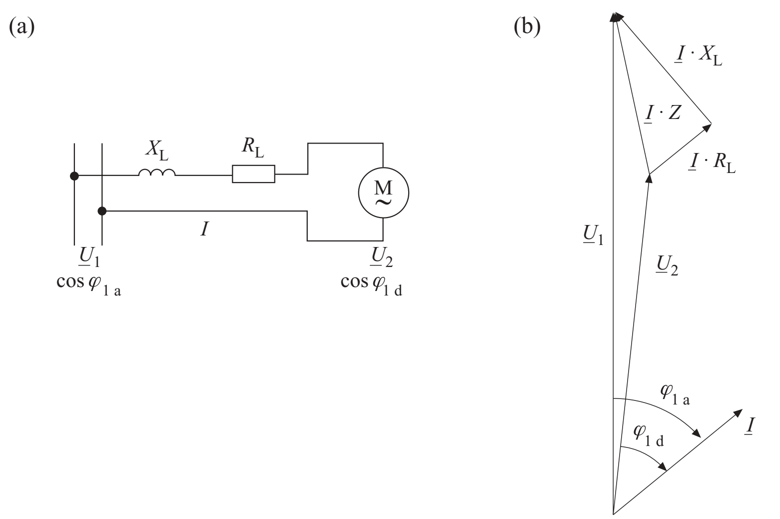

Figure 2.1 Asynchronous motor with connection cable: (a) equivalent circuit diagram; (b) vector diagram.

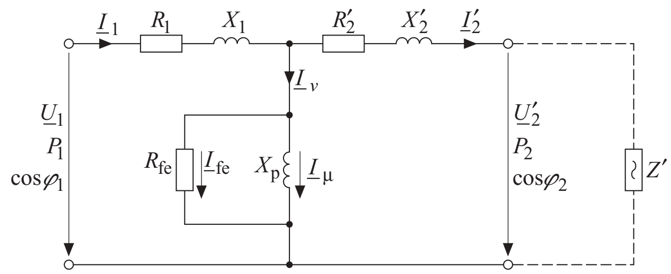

Figure 2.2 Equivalent circuit diagram of a transformer.

The main reactance X_p defines the magnetizing current I_μ and the reactances X_1 and X_2' define the leakage reactance of the transformer. The total reactive power Q is given as the sum of the reactive power for magnetization Q_0 (named series reactive power) and the reactive power to build up the leakage field Q_p (named parallel reactive power):

$$Q = Q_0 + Q_p = 3 \cdot I^2 \cdot X_L + \sqrt{3} \cdot U \cdot I_\mu \tag{2.3}$$

Figure 2.3 indicates the parallel reactive power of LV transformers in relation to the rated power S_r.

2.5 Reactive Power Demand of Consumers

2.5.1 Asynchronous Motors

The reactive power of asynchronous motors (induction motors) depends on the amount of magnetization current and on the stray magnetic field, which is related to the size (volume) of the air gap between the stator and rotor, see Figure 2.4:

$$V_L = \pi \cdot D \cdot b \cdot d \tag{2.4}$$

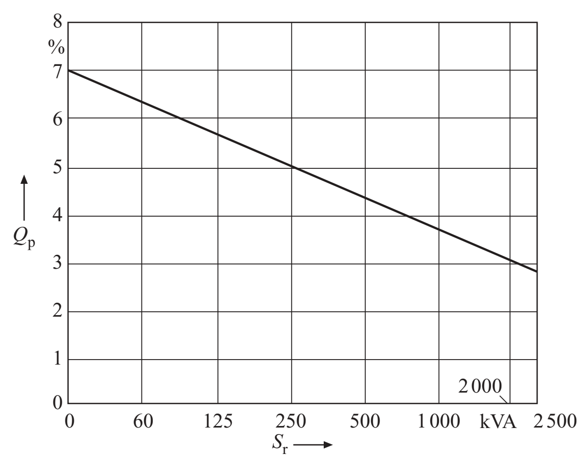

Figure 2.3 Reactive power demand (parallel reactive power) of LV transformers.

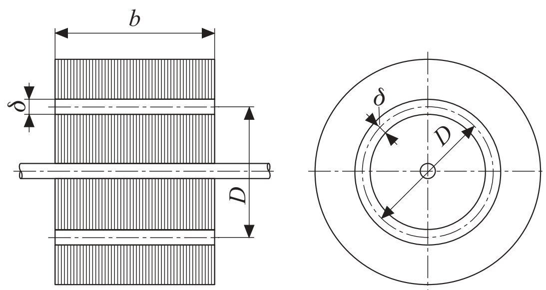

Figure 2.4 Air gap of asynchronous motor.

Motors with low nominal speed have a larger diameter and length of rotor compared with motors having high nominal speed. It can be concluded from this that motors having high nominal speed have a lower reactive power demand and a higher power factor compared with motors with low nominal speed. In order to minimize the reactive power demand of asynchronous motors, the air gap should be as small as possible. Table 2.1 outlines some characteristic values, such as efficiency, power factor and reactive power of asynchronous motors.

The reactive power demand of asynchronous motors is almost independent of the load, either in the case of no-load operation or under full-load conditions. As a result the ratio of active to reactive power and, from this, the power factor is comparatively low when starting asynchronous motors or operating at low load. With increasing load the power factor increases, so overrating of asynchronous motors should be avoided in all circumstances.

The reactive power for nominal operation is given by

$$Q = \sqrt{3} \cdot U \cdot I \cdot \sin \varphi_1 \tag{2.5}$$

In the case of no-load operation the reactive power is

$$Q_0 = \sqrt{3} \cdot U \cdot I_0 \tag{2.6}$$

Table 2.2 presents values for the reactive power of standard asynchronous motors at different ratings.

2.5.2 Transformers

The magnetization power (reactive power) of modern transformers is comparatively low due to the improved properties of transformer iron. Table 2.3 outlines some values of the reactive power demand of three-phase transformers. The reactive power at rated load is up to four times the reactive power at no load due to the leakage reactance.

2.5.3 Control Gear (Ballast) for Gas Discharge Lamps

Gas discharge lamps require either electronic or magnetic control gear (ballast) which consists of a current-limiting resistor (e.g. leakage transformer or choke coil). The ballast for fluorescent

Table 2.1 Characteristic values of LV asynchronous motors.

Part 1: Squirrel cage motors

Asynchronous motors (squirrel cage rotor), $U_n = 230, 400, 500$ V

	Rated active power (kW)	0.18	0.25	0.37	0.55	0.8	1.1	1.5	2.2	3	4	5.5
3000 rpm	$\cos \varphi_1$	0.78	0.81	0.83	0.85	0.88	0.88	0.88	0.89	0.89	0.89	0.9
	$\tan \varphi_1$	0.80	0.72	0.67	0.62	0.57	0.54	0.54	0.51	0.51	0.51	0.48
	Q (kvar)	1.4	0.18	0.25	0.34	0.45	0.59	0.81	1.13	1.53	2.04	2.64
1500 rpm	$\cos \varphi_1$	0.65	0.70	0.73	0.75	0.80	0.83	0.83	0.85	0.86	0.87	0.87
	$\tan \varphi_1$	1.17	1.02	0.94	0.88	0.75	0.67	0.67	0.62	0.59	0.57	0.57
	Q (kvar)	0.21	0.26	0.35	0.48	0.60	0.74	1.00	1.36	1.78	2.28	3.14
1000 rpm	$\cos \varphi_1$	0.58	0.60	0.63	0.68	0.70	0.73	0.75	0.78	0.80	0.81	0.82
	$\tan \varphi_1$	1.40	1.33	1.23	1.08	1.02	0.94	0.88	0.80	0.75	0.72	0.70
	Q (kvar)	0.25	0.33	0.46	0.59	0.82	1.03	1.32	1.76	2.25	2.88	3.84
Efficiency	(%)	69	72	74	76	79	81	82	83	84	86	86

Asynchronous motors (squirrel cage rotor), $U_n = 230, 400, 500$ V

	Rated active power (kW)	7.5	11	15	18.5	22	30	38	50	63	80	100
3000 rpm	$\cos \varphi_1$	0.92	0.92	0.93	0.93	0.94	0.94	0.94	0.95	0.95	0.95	0.95
	$\tan \varphi_1$	0.43	0.43	0.40	0.40	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	Q (kvar)	3.22	4.73	6.00	7.40	7.92	10.8	13.7	18.0	22.7	28.8	36.0
1500 rpm	$\cos \varphi_1$	0.87	0.87	0.87	0.87	0.88	0.89	0.90	0.90	0.90	0.90	0.90
	$\tan \varphi_1$	0.57	0.57	0.57	0.57	0.54	0.51	0.48	0.48	0.48	0.48	0.48
	Q (kvar)	4.27	6.27	8.55	10.5	11.9	15.3	18.4	24.0	30.2	38.4	48.0
1000 rpm	$\cos \varphi_1$	0.83	0.85	0.85	0.85	0.86	0.86	0.87	0.87	0.88	0.88	0.88
	$\tan \varphi_1$	0.67	0.62	0.62	0.62	0.59	0.59	0.57	0.57	0.54	0.54	0.54
	Q (kvar)	5.02	6.82	9.30	11.5	13.0	17.7	21.7	28.5	34.0	43.2	54.0
Efficiency	(%)	87	87	88	89	89	89	89	90	90	91	91

Characteristic values of LV asynchronous motors

Part 2: Slip ring motors

Asynchronous motors (slip ring rotor), $U_n = 230, 400, 500$ V

	Rated active power (kW)	0.8	1.1	1.5	2.2	3	4	5.5	7.5	11
3000 rpm	$\cos \varphi_1$	0.85	0.86	0.87	0.88	0.88	0.89	0.90	0.91	0.92
	$\tan \varphi_1$	0.62	0.59	0.57	0.54	0.54	0.51	0.48	0.46	0.43
	Q (kvar)	0.50	0.65	0.86	1.19	1.62	2.04	2.64	3.42	4.73
1500 rpm	$\cos \varphi_1$	0.75	0.75	0.78	0.80	0.82	0.83	0.84	0.85	0.85
	$\tan \varphi_1$	0.88	0.88	0.80	0.75	0.70	0.67	0.65	0.62	0.62
	Q (kvar)	0.70	0.97	1.20	1.65	2.10	2.68	3.58	4.65	6.82
1000 rpm	$\cos \varphi_1$	0.62	0.70	0.72	0.74	0.76	0.77	0.78	0.81	0.84
	$\tan \varphi_1$	1.27	1.02	0.96	0.91	0.86	0.83	0.80	0.72	0.65
	Q (kvar)	1.01	1.12	1.45	2.00	2.57	3.32	4.40	5.40	7.11
Efficiency	(%)	76	71	76	78	82	83	84	85	86

(*continued*)

Table 2.1 (*Continued*)

Asynchronous motors (slip ring rotor), $U_n = 230, 400, 500$ V										
	Rated active power (kW)	15	18.5	22	30	38	50	63	80	100
3000 rpm	$\cos\varphi_1$	0.93	0.93	0.94	0.94	0.94	0.95	0.95	0.95	0.95
	$\tan\varphi_1$	0.40	0.40	0.36	0.36	0.36	0.36	0.36	0.36	0.36
	Q (kvar)	6.00	7.40	7.92	10.8	13.7	18.0	22.7	28.8	36.0
1500 rpm	$\cos\varphi_1$	0.86	0.86	0.88	0.88	0.88	0.89	0.89	0.89	0.90
	$\tan\varphi_1$	0.59	0.59	0.57	0.54	0.54	0.51	0.51	0.51	0.48
	Q (kvar)	8.85	10.9	12.5	16.2	20.5	25.5	32.1	40.8	48.0
1000 rpm	$\cos\varphi_1$	0.85	0.85	0.86	0.87	0.87	0.88	0.88	0.88	0.88
	$\tan\varphi_1$	0.62	0.62	0.59	0.57	0.57	0.54	0.54	0.54	0.54
	Q (kvar)	9.30	11.5	13.0	17.1	21.7	27.0	34.0	43.2	54.0
Efficiency	(%)	87	87	87	88	88	88	88	89	90

lamps is constructed as a choke coil to limit the current while preheating to a permissible value. Furthermore, the ignition pulse is generated and after ignition the current should be limited to the normal operating current. Fluorescent lamps without compensation have a power factor of $\cos\varphi_1 \approx 0.5$, resulting in a reactive power consumption up to 1.7 times the active power consumption. The fundamental frequency power factor of low-pressure sodium lamps is – due to the leakage transformer – $\cos\varphi_1 \approx 0.3$. Compact fluorescent lamps (with separate or built-in conventional inductive ballast) usually have – depending on the type or power – a power factor of $\cos\varphi_1 \approx 0.3$–$0.5$. In the use of electronic ballasts the power factor becomes close to 1.

Table 2.2 Reactive power (no-load and nominal load) of asynchronous motors.

Rated active power (kW)	Reactive power demand (kvar)			
	Two poles, $n = 3000$ rpm		Four poles, $n = 1500$ rpm	
	No load	Full load	No load	Full load
1.5	0.9	1.1	1.4	1.5
3.0	1.5	2.0	2.3	2.6
5.5	2.6	3.7	3.0	4.3
11.0	4.6	6.9	5.4	7.8
22.0	7.3	13.2	10.2	13.9
30.0	10.0	17.8	13.0	17.6
45.0	13.0	27.0	17.0	26.0
75.0	20.0	42.0	30.0	45.0
90.0	23.0	50.0	33.0	52.0

Table 2.3 Reactive power demand of LV transformers (mean values).

Rated apparent power (kVA)	Impedance voltage (%)	Reactive power losses No load (kvar)	Reactive power losses Full load (kvar)
100	4	3.5	7.5
160	4	5.0	11.4
250	4	7.0	17.0
400	4	10.0	26.0
500	4	12.0	32.0
630	4	14.5	40.0
800	6	17.0	49.0
1000	6	20.0	80.0
1250	6	24.0	99.0
1600	6	28.0	124.0

Source: Siemens AG.

2.6 Summary

The main consumption of reactive power is by equipment with an iron core, such as transformers and motors. The required reactive power depends on the operating voltage and on the actual loading of the equipment. Some types of lamps, especially gas discharge lamps, also have a comparatively high consumption of reactive power depending on the switching arrangement.

3

Effect of Reactive Power on Electricity Generation, Transmission and Distribution

3.1 Chapter Overview

In this chapter the effects of reactive power on power system performance and the design (rating) of equipment are described. The transmission of reactive power through lines and transformers as well as the supply of reactive power by generators in power stations require a higher rating of the equipment. The transmission of reactive power also causes an increased voltage drop in any equipment, which influences significantly the voltage control in power systems.

3.2 Loading of Generators and Equipment

The oscillation of reactive power between generation or source (generators and/or capacitors) and consumption or drain (motors and/or load) causes reactive currents and, from this, additional loading of any equipment (lines, transformers, switchgear) between the source and drain of reactive power. The apparent power and apparent current can be calculated from

$$S = \sqrt{P^2 + Q^2} \tag{3.1}$$

$$I = \frac{S}{\sqrt{3} \cdot U} \tag{3.2a}$$

$$I = \frac{P}{\sqrt{3} \cdot U \cdot \cos\varphi_1} \tag{3.2b}$$

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

Example: The current to transmit active power $P = 300$ kW at voltage $U = 400$ V with $\cos\varphi_1 = 1$ is $I = 433$ A. If the active power is transmitted at $\cos\varphi_1 = 0.5$, the current is $I = 866$ A. The current to be transmitted increases with decreasing fundamental frequency power factor $\cos\varphi_1$ as well as the power losses in the line, which are four times higher. Figure 3.1 outlines the relationship between $\cos\varphi_1$ and the current.

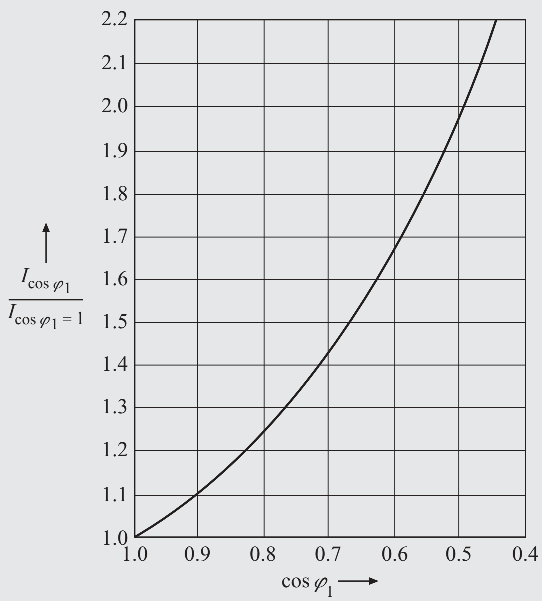

Figure 3.1 Apparent current in relation to $\cos\varphi_1$ at constant active power.

A low fundamental frequency power factor, that is a high reactive load, requires an increased rating of generators in power stations, an increased rated power of transformers and a higher cross-section of cables, conductors and transmission lines. A low fundamental frequency power factor $\cos\varphi_1$ increases the current losses in equipment and increases the voltage drops. This is of great importance in long transmission lines rather than in short lines.

For the operation of electrical power systems, including generating plants, transmission and distribution levels, it is important to transmit the electrical power with a fundamental frequency power factor $\cos\varphi_1$ at the highest possible value, that is near $\cos\varphi_1 = 1$.

3.3 Power System Losses

When considering power system losses, especially the losses of lines, the effect of a low $\cos\varphi_1$ can be seen clearly. The losses P_v increase quadratically with decreasing $\cos\varphi_1$ (e.g. in a three-phase line)

$$P_V = \frac{l \cdot P^2}{\kappa \cdot A \cdot U^2 \cdot (\cos\varphi)^2} \tag{3.3}$$

where

$A =$ cross-section
$l =$ maximum cable length
$P =$ active power to be transmitted
$\kappa =$ electrical conductivity
$U =$ phase-to-phase voltage
$\cos\varphi_1 =$ fundamental frequency power factor

Example: The transmitted power $P = 300$ kW at $\cos\varphi = 1$ causes power losses $P_V = 6$ kW (equal to 2%) which increase to $P_V = 16.7$ kW (equal to 5.5%) if the power is transmitted at $\cos\varphi_1 = 0.6$.

Power losses are very important when extending power systems on any voltage level; that is, at the transmission and distribution levels and even in consumer installations in households and industry.

The power losses of a transmission line are proportional to the square of the current. The current heat losses for a three-phase transmission line are

$$P_V = 3 \cdot I^2 \cdot R_L \tag{3.4}$$

where

$R_L =$ conductor resistance
$I =$ line current

By improving the fundamental frequency power factor from $\cos\varphi_{1a}$ to $\cos\varphi_{1d}$ the losses are reduced by the loss reduction factor k_{PV}:

$$k_{PV} = 1 - \left(\frac{\cos\varphi_{1a}}{\cos\varphi_{1d}}\right)^2 \tag{3.5}$$

Figure 3.2 indicates the loss reduction factor k_{PV} in relation to $\cos\varphi_{1a}$ with $\cos\varphi_{1d}$ as parameter.

Example: The improvement in the fundamental frequency power factor from $\cos\varphi_{1a} = 0.6$ to $\cos\varphi_{1d} = 0.8$ reduces the losses by 43.8%; the improvement from $\cos\varphi_{1a} = 0.6$ to $\cos\varphi_{1d} = 0.9$ reduces the losses by 55.6%.

The losses in the transformer windings are increasing similarly to the line losses. The transformer losses P_v consist of iron losses P_{Fe} and copper losses P_{Cu}. The iron losses are identical to the no-load losses and are independent of the current. The copper losses vary with the square of the current and depend on $\cos\varphi_1$:

$$P_V = P_{Fe} + P_{Cu} \cdot \left(\frac{P}{S_r \cdot \cos\varphi_1}\right)^2 \tag{3.6}$$

Figure 3.3 indicates the typical range of losses of transformers of different types.

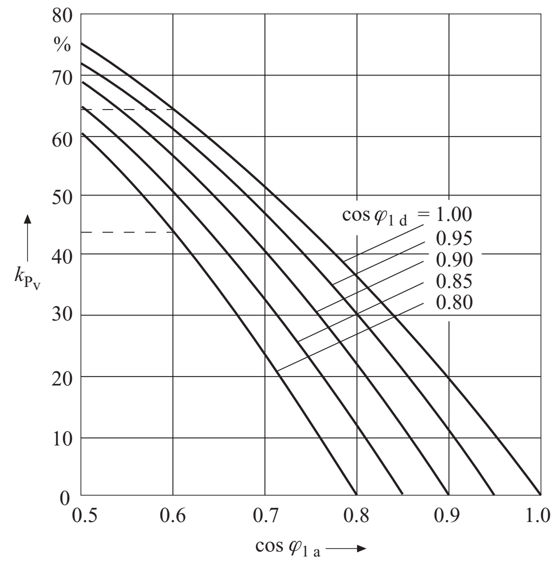

Figure 3.2 Loss reduction factor k_{PV} in relation of the existing cos φ_{1a} and the required cos φ_{1d}.

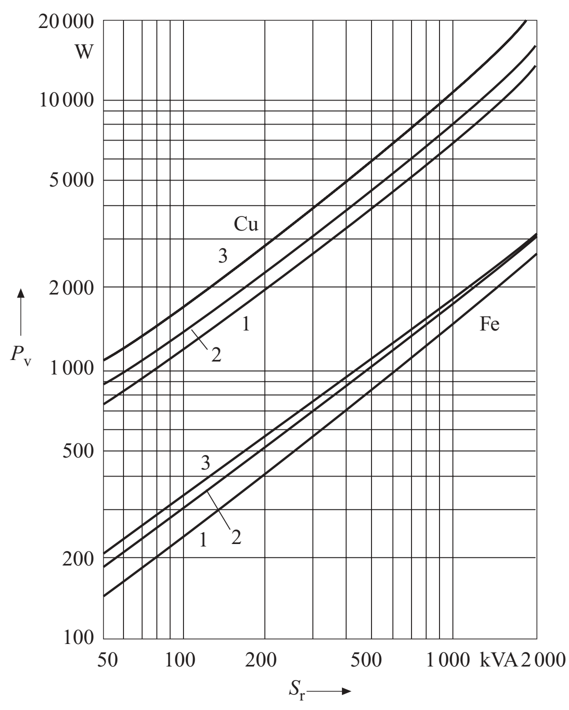

Figure 3.3 Iron and copper losses of transformers: 1, transformer with very low losses; 2, transformer with reduced losses; 3, transformer with normal losses.

Example: The total losses of a transformer with rated power $S_r = 500$ kVA and actual loading $P = 300$ kW at the fundamental frequency power factor cos $\varphi_1 = 0.7$ are given by

$$P_V = 1150\,\mathrm{W} + 6000\,\mathrm{W} \cdot \left(\frac{300\,\mathrm{kW}}{500\,\mathrm{kVA} \cdot 0.7}\right)^2 = 5558\,\mathrm{W}$$

(transformer losses are as in Figure 3.3: normal losses, parameter 3).

By improving the fundamental frequency power factor to nearly cos $\varphi_1 = 1$, the losses are reduced to $P_V = 3310$ W. The saving is approximately 2250 W. The energy saving for an 8-hour shift and 220 working days per year is about 3956 kWh/a.

3.4 Generators

Generators in power stations are designed for a defined apparent power at a defined fundamental frequency power factor, called rated power S_r at rated fundamental frequency power factor cos φ_{1r}. The maximal active power at fixed apparent power of the generator depends on the fundamental frequency power factor cos φ_1 of the system load. Figure 3.4 outlines the operating limits (power chart) of a synchronous generator.

Assume the generator is operating at rated fundamental frequency power factor cos φ_{1r} with rated apparent power as indicated in Figure 3.4. The rated fundamental frequency power factor normally is in the range of cos $\varphi_{1r} = 0.8$–0.85. A reduced fundamental frequency power factor cos φ_1 is only possible when the active power is reduced, due to an increase in the rotor current, needed for excitation of the generator. An increase in the fundamental frequency power factor above its rated value is possible, but only with reduced reactive power, because the active power is limited by the limited power of the turbine.

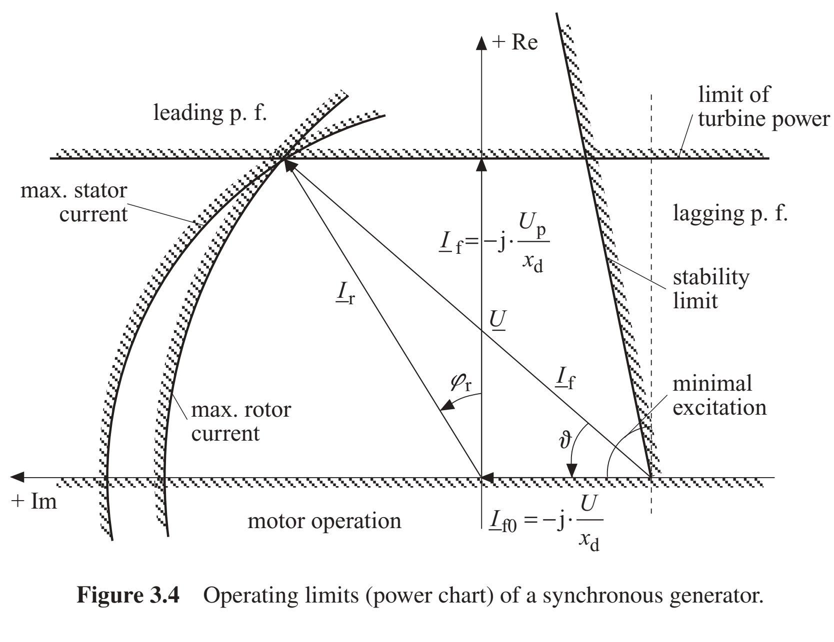

Figure 3.4 Operating limits (power chart) of a synchronous generator.

To increase the generation of reactive power by generators in power stations (power plants), two alternatives are possible:

- Generators have to be operated with partial load only; this measure requires higher investment costs and leads to a lower plant efficiency due to operating with partial load.
- Generators with rated fundamental frequency power factor $\cos\varphi_{1r} \approx 0$ have to be installed; this type of generator is called a phase-shift generator. In addition to the higher investment costs for the phase-shift generator, additional losses, depending on its efficiency, will occur.

A suitable selection and design of generators, particularly for use in combined heat and power plants in industry, will gain in importance in the future. Due to the daily and seasonal variation of the fundamental frequency power factor of the consumer load, determination of the average fundamental frequency power factor of the generator is very important for optimal design of the generator and even for the turbine unit.

3.5 Voltage Drop

3.5.1 General

The permissible voltage drop in electrical power systems is defined in IEC 60038 for different standardized voltages. Furthermore, requirements for the permissible voltages in power systems are defined in DIN EN 50160, describing parameters for voltage quality in low- and medium-voltage systems. Besides technical standards, economic and operational reasons are also of importance, such as the operating costs of energy transfer resulting, besides other items, from the power losses of the lines. Interest rates and the amortization of fixed assets also influence the operating costs. To keep the losses as low as possible, relatively large cross-sections are required, which correspondingly requires increased investment in insulation, transmission towers, cable rights-of-way, and so on.

Determination of the permissible voltage drop and, from this, the selection of a suitable cross-section of conductors are determined by operational requirements with regard to the electricity consumer, for which a suitable voltage quality as defined in DIN EN 50160 should be ensured.

Figure 3.5 outlines the voltage drop in electrical power systems, for example in any equipment such as a line or transformer, for different fundamental frequency power factor.

As can be seen from Figure 3.5, the total voltage drop consists of two parts, the ohmic voltage drop U_R at the ohmic part of the system impedance and the reactive voltage drop U_X at the reactive part of the system impedance. While the ohmic voltage drop in the case of connection of consumer load is always negative, that is it reduces the voltage U_{VP} at the connection point with respect to the system voltage U_N, the reactive voltage drop is negative only for lagging current, that is the reactive fundamental frequency power factor, as indicated in Figure 3.5b. With increasing fundamental frequency power factor up to $\cos\varphi_1 = 1.0$ and further in the capacitive range with leading current, the reactive voltage drop becomes zero ($\cos\varphi_1 = 1.0$) and will be positive ($\cos\varphi_1$ in the capacitive range) with respect to the system voltage U_N, thus increasing the voltage at the connection point, as outlined in Figure 3.5c. The reactive part of the voltage drop gains in importance, especially in medium- and high-voltage systems. The voltage drop can be calculated as

$$\left|\Delta\underline{U}\right| \approx \Delta U = R_1 \cdot I \cdot \cos\varphi_1 + X_1 \cdot I \cdot \sin\varphi_1 \tag{3.7}$$

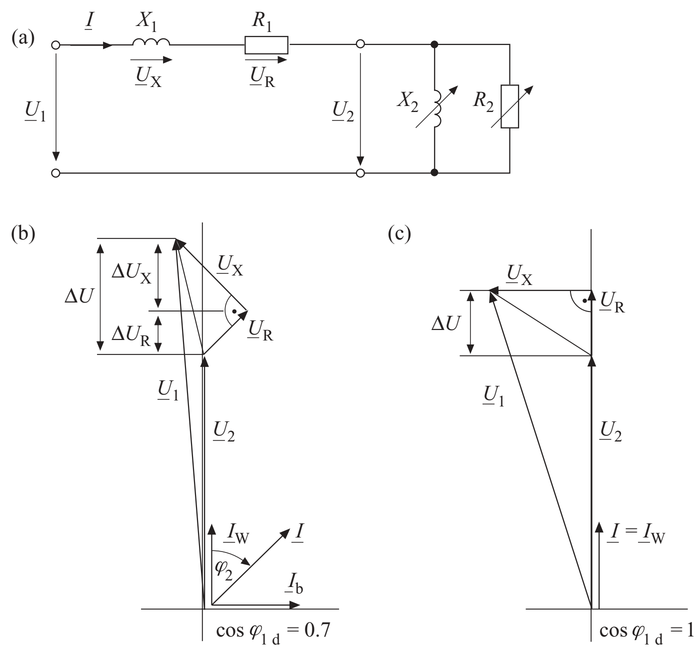

Figure 3.5 Voltage drop in electrical power system: (a) single-line diagram with ohmic–reactive load; (b) vector diagram with $\cos\varphi_1 = 0.7$ and 1.0.

It can be seen from Figure 3.5 that the voltage drop can be reduced by improving the fundamental frequency power factor.

3.5.2 Transferable Power of Lines and Voltage Drop

The voltage drop of a transmission line, mainly represented by a series connection of resistance R and inductance L as outlined in Figure 3.5, can be calculated in the case of a normal length of lines for three-phase AC systems for a given fundamental frequency power factor of the load (at the end of the line) from

$$\Delta U_{3ph} = \sqrt{3} \cdot I \cdot (R \cdot \cos\varphi_1 + \omega L \cdot \sin\varphi_1) \tag{3.8a}$$

and in the case of two phases from

$$\Delta U_{2ph} = 2 \cdot I \cdot (R \cdot \cos\varphi_1 + \omega L \cdot \sin\varphi_1) \tag{3.8b}$$

For a leading fundamental frequency power factor, the voltage drop may be a voltage increase.

The maximal permissible voltage drop in a three-phase AC system is

$$\Delta u = \frac{100\% \cdot P \cdot l}{\kappa \cdot A \cdot U^2} = \frac{100\% \cdot \sqrt{3} \cdot I \cdot \cos\varphi \cdot l}{U \cdot A \cdot \kappa} \tag{3.9}$$

and from this the maximal transferable power will be

$$P_{\max} = \frac{\Delta u \cdot U^2 \cdot A \cdot \kappa}{100\% \cdot l} \tag{3.10}$$

The relative loss in transmittable power Δp as a percentage is

$$\Delta p = \frac{u}{(\cos\varphi_1)^2} \tag{3.11}$$

where

A = cross-section
l = maximum cable length
I = line current
P = active power to be transmitted
κ = electrical conductivity
U = phase-to-phase voltage
u = relative voltage (%)
$\cos\varphi_1$ = fundamental frequency power factor

Example: The transmittable active power of a copper cable with a cross-section of 35 mm^2 is increasing nearly linearly in the range of fundamental frequency power factor $\cos\varphi_1 = 0.4$–0.8. If the fundamental frequency power factor is increased further, the increase in the transmittable power is even greater. As can be seen from Figure 3.6, the transferable power at a given voltage drop is almost doubled if the fundamental frequency power factor $\cos\varphi_1$ is improved from 0.65 to 1.0.

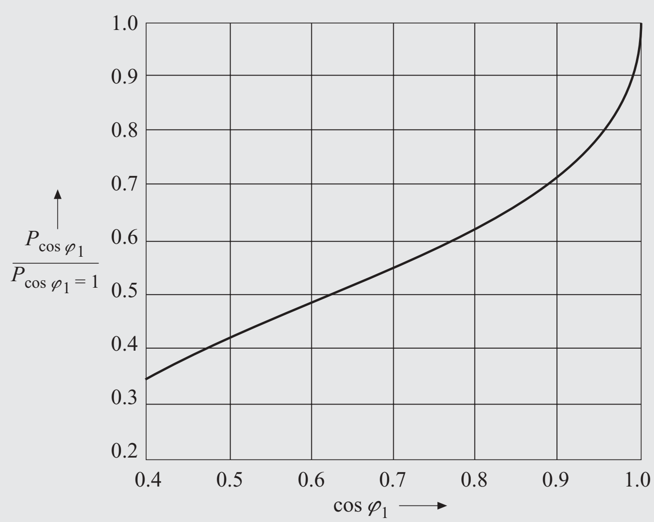

Figure 3.6 Transmittable power and fundamental frequency power factor in the case of a copper cable with a cross-section of 35 mm^2.

3.5.2.1 Determination of Average Fundamental Frequency Power Factor

Normally a number of consumers (loads) having different power and different fundamental frequency power factor are connected to the power system. In order to plan the required reactive power compensation it is necessary to determine the average fundamental frequency power factor of the total consumer load. As the power of the individual consumer load normally differs, the calculation of the pure mean value of the fundamental frequency power factor will lead to incorrect results. The correct value of the average fundamental frequency power factor taking account of the different power can be calculated from

$$\cos\varphi_{1m} = \frac{\sum_{i=1}^{N} P_i \cdot \cos\varphi_{1i}}{\sum_{i=1}^{N} P_i} \tag{3.12}$$

where

P_i = active power of consumer i

$\cos\varphi_{1i}$ = fundamental frequency power factor of consumer i

The average fundamental frequency power factor can also be determined graphically as described below and outlined in Figure 3.7.

The graphical method for determining the average fundamental frequency power factor is based on vector addition of the individual consumer loads. The example in Figure 3.7 sums a load of 8 kW with $\cos\varphi_1 = 0.9$ and a load of 5 kW with $\cos\varphi_1 = 0.6$, corresponding to the

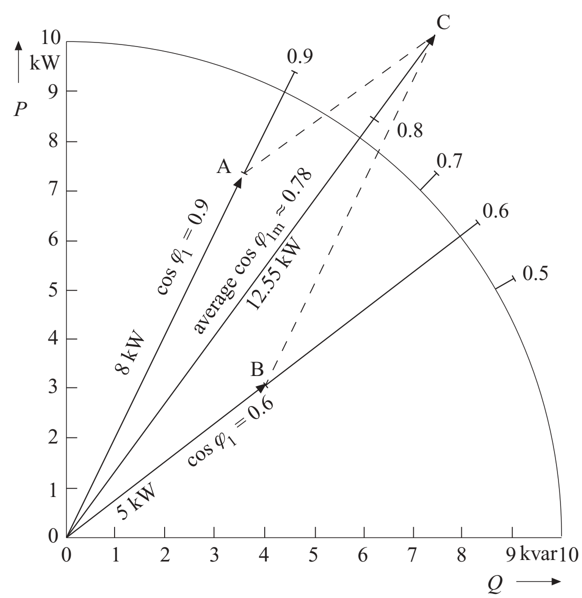

Figure 3.7 Graphical determination of average fundamental frequency power factor for different loads.

vectors $\overrightarrow{\mathrm{OA}}$ and $\overrightarrow{\mathrm{OB}}$. By adding the two vectors, the vector $\overrightarrow{\mathrm{OC}}$ for the total load indicates a total load of 12.55 kW with average fundamental frequency power factor $\cos\varphi_1 = 0.78$. In the case of more than two loads, a similar construction adding all loads has to be applied.

3.5.3 Transformer Voltage Drop

The simplified equivalent circuit of a transformer, suitable for the analysis of short-circuit and loading conditions, consists of a resistance, representing the ohmic winding losses or copper losses, and a reactance, representing the leakage inductance. As already outlined in Figure 3.5, the voltage on the secondary side of the transformer is reduced while loading the transformer. The upper part of Figure 3.5 is outlined in more detail in Figure 3.8.

The voltage drop ΔU can be estimated with sufficient accuracy from

$$\Delta U \approx U_R \cdot \cos\varphi_1 + U_X \cdot \sin\varphi_1 \tag{3.13a}$$

For a partial loading of the transformer, the voltage drop ΔU is proportional to the rated load

$$\Delta U \approx (U_R \cdot \cos\varphi_1 + U_X \cdot \sin\varphi_1) \cdot \frac{I}{I_r} \tag{3.13b}$$

The relative reactive voltage drop u_X is called the leakage voltage:

$$u_X = \sqrt{u_k^2 - u_R^2} \tag{3.14}$$

The relative ohmic voltage drop u_R is determined from

$$u_r = \frac{P_{kr}}{S_r} \cdot 100\% \tag{3.15}$$

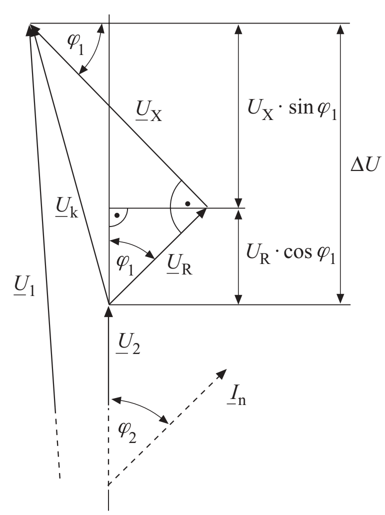

Figure 3.8 Transformer voltage drop and Kapp's triangle.

Table 3.1 Tentative values of u_R, u_X and P_{kr}.

S_r (kVA)	100	160	250	400	630
u_R (%)	1.75	1.43	1.30	1.15	1.03
u_X (%)	3.60	3.72	3.78	3.83	3.86
P_{kr} (kW)	1.75	2.35	3.25	4.60	6.50

where

u_k = impedance voltage
u_R = ohmic part of impedance voltage
u_X = leakage voltage (reactive part of impedance voltage)
P_{kr} = rated short-circuit losses
S_r = rated apparent power
U_1 = transformer voltage at high-voltage side (input voltage)
U_2 = transformer voltage at low-voltage side (full-load voltage or output voltage)
ΔU = voltage drop
I_r = rated current
$\cos \varphi_1$ = fundamental frequency power factor

Table 3.1 outlines some tentative values of u_R, u_X and P_{kr} of transformers according to DIN 42500.

Note that, in relation to Table 3.1, the recommended impedance voltage of low-voltage transformers in distribution systems is $u_k = 4\%$ in order to limit the permissible voltage drop. Low-voltage transformers in industrial systems have a more preferable impedance voltage of $u_k = 6\%$ in order to limit short-circuit currents.

Example: The output voltage (secondary voltage) U_2 of a transformer with $S_r = 2500$ kVA at rated load and $\cos\varphi_1 = 0.8$ is to be determined. The short-circuit losses as on the nameplate are $P_{kr} = 24$ kW and the rated impedance voltage $u_k = 6\%$. The ohmic voltage drop u_R of the transformer is calculated as

$$u_R = \frac{P_{kr}}{S_r} \cdot 100\%$$

$$u_R = \frac{24\,\text{kW}}{2500\,\text{kVA}} \cdot 100\% = 0.96\%$$

The leakage voltage u_X is calculated from

$$u_X = \sqrt{u_k^2 - u_R^2}$$

$$u_X = \sqrt{6^2 - 0.96^2} = 5.92\%$$

The voltage drop is

$$\Delta u \approx u_R \cdot \cos\varphi_1 + u_X \cdot \sin\varphi_1$$

$$\Delta u \approx 0.96\% \cdot 0.8 + 5.92\% \cdot 0.6 = 4.32\%$$

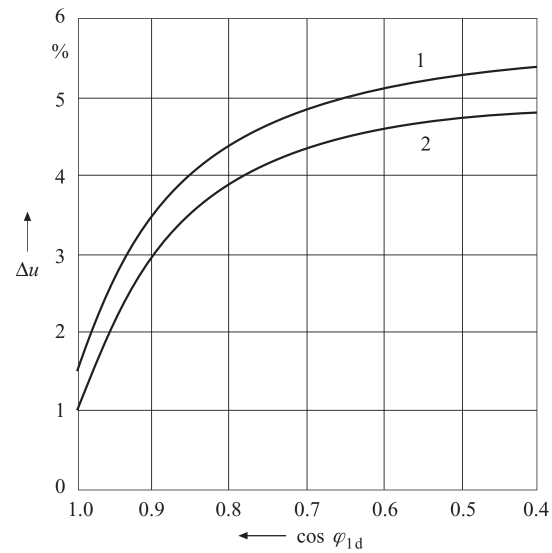

Figure 3.9 Voltage drop and fundamental frequency power factor cos φ_1: 1, normal losses; 2, reduced losses.

Figure 3.9 indicates the voltage drop of transformers with normal and reduced losses depending on the fundamental frequency power factor.

3.6 Available Power of Transformers

The nameplate rating of transformers is expressed as apparent power, because it corresponds at a given voltage (rated voltage) to the highest current (rated current). The active power to be transferred through the transformer is a function of the fundamental frequency power factor cos φ_1 of the load to be supplied.

The higher the fundamental frequency power factor cos φ_1, the higher the available active power to be supplied by the transformer. The improvement is calculated as

$$\Delta S = \left(\frac{1}{\cos\varphi_{1a}} - \frac{1}{\cos\varphi_{1d}}\right) \cdot P = K \cdot P \tag{3.16}$$

where

$\Delta S =$ additional available apparent power
$K =$ improvement factor
$P =$ active power

Example: A transformer having rated apparent power $S_r = 400$ kVA is fully loaded with active power $P = 200$ kW in the case of cos $\varphi_1 = 0.5$. Improving the fundamental frequency power factor to cos $\varphi_1 = 0.8$ will increase the available active power to $P = 320$ kW, and for cos $\varphi_1 = 1.0$ the permissible loading will be $P = 400$ kW, which is equal to the rated apparent power.

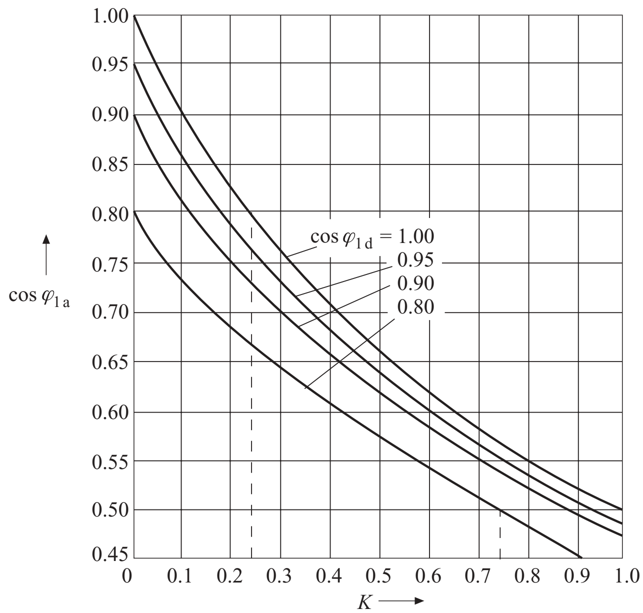

Figure 3.10 Improvement factor K for increase of active power depending on different fundamental frequency power factor.

Figure 3.10 indicates the improvement factor K for different values of the fundamental frequency power factor.

3.7 Summary

The transmission of reactive power through transmission and distribution lines and through transformers has many disadvantages with respect to power system construction and operation. The active losses are increased and a higher cross-section of lines is sometimes required. The reactive losses (transformers) are increased as well. Furthermore, the voltage drops in the system are increased, resulting in the need to choose a higher regulation range of tap-changers for the transformers.

4

Reactive Power in Standard Energy Contracts

4.1 Chapter Overview

This chapter deals with different methods of pricing the reactive energy, to be considered in energy contracts. As the influence of reactive power on the system losses and on the transfer capability of lines and transformers is significant, it is fair to determine a price for the kvarh and to install measuring devices. Different methods (pricing based on reactive energy, based on apparent energy and different amounts for low and high tariffs) are discussed. Although the suggested methods of including the cost for kvarh in energy contracts are mainly based on German practice, the methods can also be applied in any other country.

4.2 Introduction

As mentioned previously, an average power factor lower than $\cos\varphi < 1$ causes additional costs to the electricity utility and power distribution company, which will be charged regularly to the customer with special contracts. This refers to high-consumption customers, such as businesses, trade or industry, which achieve a lower average power factor $\cos\varphi$ during a month or during the billing period. Therefore reactive energy will be measured by means of a separate kvarh meter.

In order to minimize the costs for reactive energy, first of all attention has to be paid to the rules printed in the individual contracts between the electricity utility or power distribution company and the customer. As an economic base the contract contains all technical, economic and legal conditions to be followed by the customer, including negotiated prices per kWh and kvarh.

New structures on the market for electricity suppliers, in the member states of the European Union (EU) especially, have led to changes in the terms of sale within many electricity suppliers. Differences may arise in the structures of contracts worldwide. The following explanations are not applicable to all possible contracts: attention has to be paid to any

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relevant rules and conditions of the electricity utilities in any individual country. Some standard contracts of suppliers can be taken into consideration, as outlined below.

4.3 Reactive Energy to be Considered in Standardized Contracts of Suppliers

An unequivocal differentiation between common clients (e.g. households or small traders) and customers with special contracts is impossible. This is due to many technical and economic facts, for instance the request for power, electrical consumption, period of use and load profile, that should be taken into consideration [1]. In general, customers with a steady request for more than 30 kW can negotiate special contracts with the supplier regarding conditions and prices. The form of contract to be negotiated between the supplier and these special customers should not only be based on common laws, but also follow the principle of contractual freedom.

The electricity utility or power distribution companies usually give an account of charges referring to reactive energy in their special contracts. This means that the supplier charges the negotiated price for reactive energy to the special customer. There is an additional component of pricing by the power distribution companies that is valid for the use of the network by the customer. The power system utilisation fee depends on the expected maximal load, the so-called ordered electrical power, and must be declared by the customer. These data provide the basis for calculating the price by the power distribution company. Another component in the calculation may be added by the supplier, regarding 'power quality', to the price for reactive energy (see Chapter 17).

Note that any reactive energy supplied to the consumer causes additional costs. The reactive energy to be metered will be taken into account in the contracts with the suppliers; they will charge it to those consumers with higher consumption (e.g. $P > 30$ kW, provided a kvar meter is installed). Since the contracts are not uniform, it is recommended that information be acquired on this at the local electricity utility or power distribution company. The electricity utility companies offer two kinds of pricing in their special contracts charging reactive energy:

- Pricing dependent on consumed reactive energy.
- Pricing dependent on consumed apparent energy.

With regard to the economic operation of consumers' installations, it is necessary to obtain information from the supplier about any advantages in pricing and the conditions of the contract. The following sections give an overview of the increased reactive energy to be considered in many standardized special contracts.

4.3.1 Pricing Dependent on Consumed Reactive Energy (kvarh)

Most suppliers issue regulations or conditions for keeping an average power factor above 0.9 lagging per month or per billing period. If the consumption of reactive energy increases above 50% of the consumption of active energy, the additional reactive energy will be charged for. As mentioned above, the reactive energy will be measured by a separate kvarh meter. In general this additional reactive energy (kvarh) will be charged in the range of 10 to 15% of the price for active energy (kWh). Special negotiations with the local supplier on pricing reactive

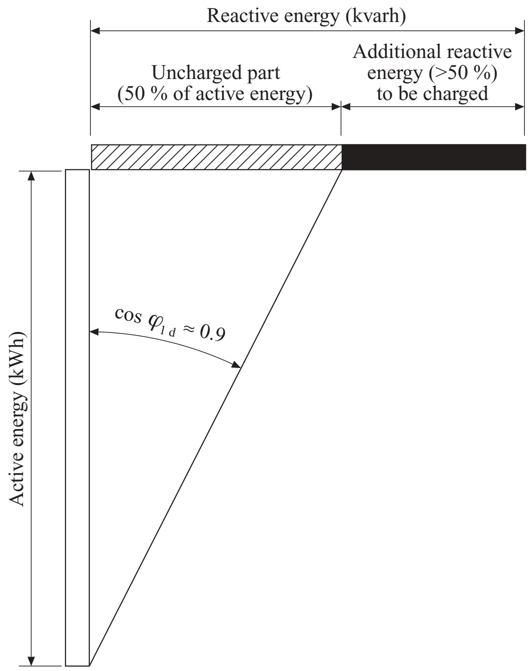

Figure 4.1 Calculation of additional reactive energy to be charged.

energy are possible as well. Furthermore, attention has to be paid to whether electricity utilities charge the additional kvarh for both the high-tariff period (HT = day) or for the low-tariff period (LT = night).

In the case of distributed generation systems, capable of feeding active energy back into the network, special technical considerations with regard to the achieved average power factor have to be taken into account, since values of the power factor could appear within all four quadrants; that is, during generation in overexcited and underexcited operation and for loads with an inductive or capacitive power factor (see Chapters 1 and 16).

Figure 4.1 shows a graphical representation of how to calculate the additional consumption of reactive energy referring to the required power factor, for example cos $\varphi \approx 0.9$, requested by the electricity utility. Sometimes the supplier may ask for a different power factor target with regard to HT and LT periods, because during the night a lower value could be sufficient to avoid an overall leading (capacitive) power factor in the power system. This is requested mainly in urban areas with huge cable networks during the low-load period (LT). Several manufacturers of power factor relays offer automatic switch-over facilities between two power factor targets as features.

Example: The monthly consumption of an industrial consumer installation amounts to:

40 000 kWh of active energy

50 000 kvarh of reactive energy

Thus the monthly average power factor to be achieved is

$$\tan\varphi_a = \frac{\text{reactive energy}}{\text{active energy}} = \frac{50\,000\,\text{kvarh}}{40\,000\,\text{kWh}} = 1.25 \rightarrow \cos\varphi_a = 0.624$$

The electricity utility company charges, according to the contract, the additional kvarh, caused by achieving an average power factor below 0.9, with 15% of the average price for active energy (12 cents per kWh), which results in 1.8 cents per kvarh. Since 50% of consumed active energy forms the amount of reactive energy not to be charged for, then

$$50\% \text{ of } 40\,000\,\text{kWh} = 20\,000\,\text{kvarh}$$

is free of charge.

Out of the total monthly reactive energy of 50 000 kvarh the amount of 30 000 kvarh will be charged at 1.8 cents per kvarh, resulting in a total cost of €540 a month. Within one year the costs might amount to €6480 if the customer does not improve the average power factor by means of reactive power compensation. Additional costs appear (not printed out explicitly on the bill) caused by the increased losses ($I^2 \cdot R$) in the transmission and distribution system (lines and transformers), charged at 12 cents per kWh any time the power factor is lower than unity. This fact is taken into consideration only very rarely!

4.3.2 Pricing Dependent on Consumed Apparent Energy (kVAh)

This method considers the maximal active power, once it has appeared within the billing period. The data of consumed active and reactive energy determine the average $\cos\varphi_m$ to be achieved. These data enable calculation of the maximal apparent power, once it has appeared. The $\cos\varphi_m$ influences considerably the costs to be charged any time it is lower than unity. Assuming constant active power, the metered apparent energy is responsible for the reactive energy to be charged for as outlined in the following equation:

$$S = \frac{P_{\max}}{\cos\varphi_m} \tag{4.1}$$

where

S = apparent power (kVA)
$P_{\max}$ = maximum of active power (kW)
$\cos\varphi_m$ = power factor

This method of charging forces the customer to achieve an average power factor $\cos\varphi_m$ very close to unity. That means the reactive power compensation must be designed accordingly. An additional advantage is that the transmission losses mentioned above (lines and transformers) will be reduced as well. These facts amortize quicker the higher investment for the reactive power compensation.

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Invoice Address

RECEIVED 05.

Supply Address

Billing detail

Fixed Charges

	£
Availability charge 850 @ £1.14/KVA	969.00
Combined HH Data Charges	20.75
Settlement agency fee	1.25
Standing charge	60.47

TOTAL FIXED CHARGES 1051.47

Consumption Charges

	Price per Unit	Total Units	Amount £
Reactive power charge (001)	0.00271	613	1.66
Reactive power adjustment for 31st Mar 11	0.00271	5789	15.68
Unit charge-DAY RATE	0.065654	170482	11192.83
Unit charge-NIGHT RATE	0.044293	62451	2766.14

TOTAL CONSUMPTION CHARGES 13976.31

TOTAL ENERGY CHARGES

Meter Reading Information

Meter Number	Rate	Unit Type	Units
K7	NIGHT RATE	KWH	62451
11	DAY RATE	KWH	170482
		MD	553
		KVARH	77481
		KWH	232933

E - Denotes estimated reading, S - Denotes customer reading

Power demand and other important information
Power factor for this site is 0.948883
Avoid Late Payment Interest charges

Account number	*Period of supply*	*Date of invoice*	*Invoice*
	01 Apr 11 - 30 Apr 11	03 May 11	0027

Figure 4.2 Example of a UK electricity bill.

A typical example of a UK electricity bill for commercial consumers is shown in Figure 4.2, having a peak load of 850 kVA, to be charged at £1.14 per kVA (£969); an additional charge of £20.75 is charged for the provision of a monthly load curve, settlement agency fee and standing charge, amounting to £105 147 for total fixed charges. The consumption charges are given for the day rate (£11 192.83) and night rate (£2766.14). The installation has $\cos\varphi = 0.956$ and reactive power is charged at 27.5% of the kWh consumption (6402 kvarh) with a comparatively low tariff, that is 0.271p per kvarh.

4.4 Importance of Reactive Power in Determining the Costs of Connection

The power demand of an electrical plant must be estimated correctly during any planning period. The declaration of requested (ordered) electrical power is essential for the electricity utility as well as the demand factor, which includes the load factor and the diversity factor as well. These data form the basis of the design of the power system. Furthermore, they enable an optimized contract to be offered to the customer. It results in the ratio of maximum load (power) to the requested load (power) of the supplier. Many electricity utility and power distribution companies use these data for the calculation of connection costs as well as for network costs:

- *Connection costs* refer to the installation costs of the electrical connection between the customer and power system. The supplier charges these costs either totally or partly to the customer.
- *Network costs* are shared costs and refer to the construction costs for the distribution system of the electricity utility.

As mentioned above, the demand for requested power is to be declared as apparent power (kVA) to the supplier; data like the demand factor and the average power factor cos φ_a must also be taken into consideration.

In designing new installations, the average power factor cos φ_a of similar installations should be taken into account, otherwise one has to base the calculations on estimated technical data for the consumers.

4.5 Summary

So-called special customers are able to reduce costs by means of classical reactive power compensation, besides improved power quality by filters. The cost savings are seen in different areas, especially in the reduction of costs referring to reactive energy, to active energy by reducing system losses, the reduction of peak load with respect to active power, reduced investment costs and in the reduction of connecting costs.

Reference

[1] Schlabbach, J. and Rofalski, K.-H. (2008) *Power System Engineering*, Wiley-VCH Verlag GmbH.

5

Methods for the Determination of Reactive Power and Power Factor

5.1 Chapter Overview

It has become increasingly difficult to obtain an accurate evaluation of power factor due to fewer sinusoidal functions of line voltage and current.

The classical method of ascertaining the time delay between zero crossings of voltage and current may no longer be cited in modern industrial plants.

It is better then to compare continuously the ratio between active and reactive power/energy, respectively. By using this method a true indication of power factor is obtained, which is totally independent of the waveform of voltage and current.

Many of today's larger power consumers utilize AC/DC converters, so that non-sinusoidal waveforms are a daily occurrence.

5.2 Methods

There are some methods available for measuring the actual power factor in plants, as follows.

5.2.1 Determination of Power Factor in Single-Phase Grids

One simple method is to measure the apparent power by using an ammeter, a voltmeter and a wattmeter as shown in Figure 5.1. The apparent power (VA) results in the product of voltage (V) with current (A). The active power may be read directly at the wattmeter.

The calculation of power factor is given by the quotient of active power and apparent power:

$$\cos\varphi = \frac{P}{U \cdot I} \tag{5.1}$$

The apparent power is

$$S = U \cdot I \tag{5.2}$$

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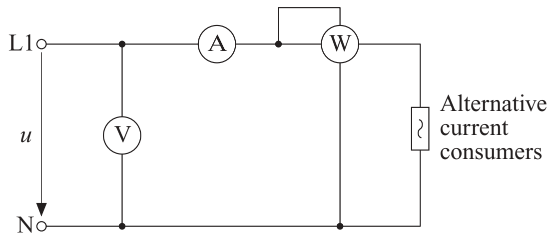


Figure 5.1 Single-phase measurement, using wattmeter, ammeter and voltmeter.

Remark:
For three-phase systems it is best to add a factor of $\sqrt{3}$ and use the delta voltage!

The reactive power is

$$Q = \sqrt{S^2 - P^2} \tag{5.3}$$

5.2.2 Direct Indication of Power Factor by Means of Brueger's Device

One of the earliest devices for the direct indication of the actual power factor was developed by Brueger; it is applicable for single-phase systems as well, and is shown in Figure 5.2. It contains a crossed-coil element. The moving coils (B3, B4) are fixed in a rectangular assembly and pivot on a ball bearing. They are influenced by the magnetic field of two further coils (B1, B2), connected in series, and by the total current flow. One crossed coil is connected in series with a resistance (R), the other one with an inductance (X_L). The crossed coils are connected in parallel to the line voltage L1–N.

B1 and B2 generate a magnetic field synchronously with the current. B3 generates a magnetic field synchronously with the voltage. However, B4 is shifted by 90°, due to the inductance X_L. The position of the movable crossed coils depends on the phase deviation between the voltage and current, in other words phase angle φ. The calibration of these devices under sinusoidal conditions of voltage and current in modern plants is no longer applicable.

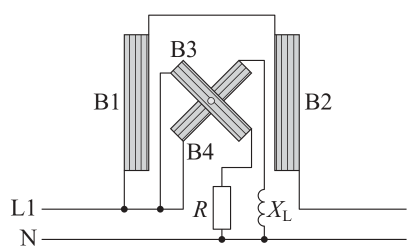


Figure 5.2 Single-phase measurement for power factor by crossed-coil device (Brueger).

5.2.3 Determination of Power Factor in Three-Phase System

In three-phase systems it is possible to obtain the power factor via two wattmeters (W1 and W2) as shown in Figure 5.3.

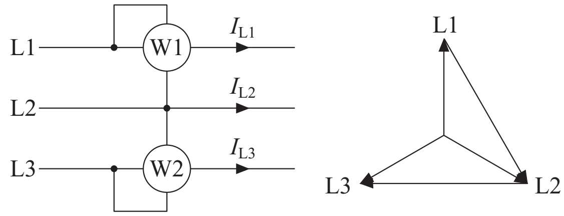


Figure 5.3 Three-phase measurement of power factor by means of two wattmeters in an Aron connection.

This so-called Aron circuit requires the correct polarity at the measuring devices, as high negative values could be indicated due to larger phase deviations. Negative values must be treated correctly in the calculations, of course (see below). The current path of wattmeter W1 measures the current of line L1; the voltage path is connected to lines L1 and L2. Wattmeter W2 measures the current in L3; its voltage path is connected to L3 and L2 (delta voltage). This enables consumers' active power to be read directly in the summation of both values.

The partial active power, indicated by W1, is given by

$$P_{L1} = U \cdot I \cdot \cos(\varphi + 30^\circ) \tag{5.4}$$

$$P_{L3} = U \cdot I \cdot \cos(\varphi - 30^\circ) \tag{5.5}$$

Finally consumers' total active power is given by

$$\begin{aligned} P = P_{L1} + P_{L3} &= \left[\cos(\varphi + 30^\circ) + \cos(\varphi - 30^\circ)\right] \\ &= U \cdot I \cdot 2 \cdot \cos 30^\circ \cdot \cos\varphi \\ &= \sqrt{3} \cdot U \cdot I \cdot \cos\varphi \end{aligned} \tag{5.6}$$

(note that $2 \cdot \cos 30^\circ = \sqrt{3}$). If wattmeter W1 indicates a negative value, the mathematical description is given by the following equation:

$$\begin{aligned} P = P_{L3} - P_{L1} &= U \cdot I \cdot [\cos(\varphi - 30^\circ) - \cos(\varphi + 30^\circ)] \\ &= U \cdot I \cdot 2 \cdot \sin 30^\circ \cdot \sin\varphi = \frac{Q}{\sqrt{3}} \end{aligned} \tag{5.7}$$

Assuming symmetrical delta voltages, consumers' reactive power is given by

$$Q = \sqrt{3} \cdot (P_{L3} - P_{L1}) \tag{5.8}$$

Note also that, in the case of unsymmetrical voltages, deviations will appear in the power factor.

Phase angle φ may also be calculated using following equation as well:

$$\tan\varphi = \frac{Q}{P} = \sqrt{3} \cdot \left(\frac{P_{L3} - P_{L1}}{P_{L1} - P_{L3}}\right) \tag{5.9}$$

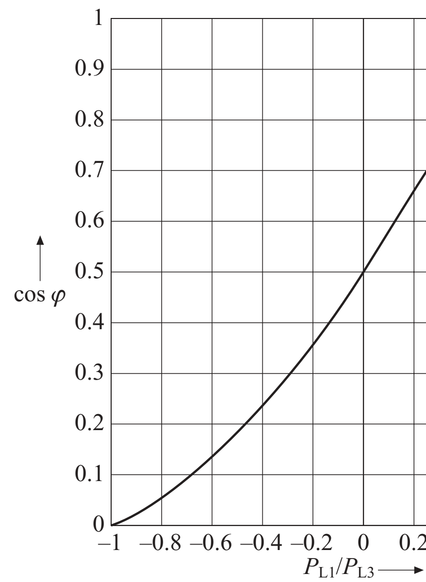


Figure 5.4 Ratio P_{L1}/P_{L3} dependent on $\cos\varphi_1$ using two wattmeters in an Aron connection, assuming symmetrical load.

Consequently, the power factor is

$$\cos\varphi = \frac{1}{\sqrt{1+\tan^2\varphi}} \tag{5.10}$$

The Aron circuit offers the possibility to obtain power factor $\cos\varphi$ directly from the quotient of P_{L1}/P_{L3} with the help of graphical operations (see Figure 5.4).

Reactive power can be ascertained from the indicated values of two wattmeters and the calculated power factor. The following equation enables reactive power to be calculated:

$$\tan\varphi = \frac{\sqrt{1+\cos^2\varphi}}{\cos\varphi} \tag{5.11}$$

Consequently,

$$Q = P \cdot \tan\varphi \tag{5.12}$$

5.2.4 Determination of Power Factor Using Portable Measuring Equipment

If measurements are required, for example, in factories, there are many portable measuring devices on the market. These instruments provide all the necessary measuring devices, like an ammeter, voltmeter, wattmeter and circuits.

Power factor indicators are becoming rarer because power factor control relays indicate the actual power factor digitally as standard. However, it should be considered that the regulators are measuring the current of one line only (see Chapter 10). Further, the power factor does not say anything about the amount of reactive power – just that cos $\varphi = 1$ indicates 'no reactive power existing'!

During the evolution of power factor meters, several different technical measuring methods have been developed. In the beginning it was sufficient to 'seize' the time delay between the zero crossings of current and voltage. With regard to modern technologies, at converters especially, this method is no longer applicable. In energy plants the periodic functions of voltage and current are far away from sinusoidal waveforms. For the current, additional zero crossings may be observed within one period! This led to the development of measuring devices for correct indications independent of the waveforms of voltage and current.

As shown in Figures 1.7d and 1.8e, reactive power represents 'feedback' power. Therefore the best method to measure the power factor, independent of the waveforms of voltage and current, is to compare active with reactive power/energy steadily. The quotient of active and reactive power/energy, respectively, is equal to tan φ. Incidentally, tan φ definitely indicates the percentage of reactive power in relation to active power. For example, tan $\varphi = 0.85$ means that 85% of active power is reactive ('feedback power'). So tan φ evidences much more than cos $\varphi = 0.76$! If the power factor decreases below 0.707, for example to 0.66, reactive power increases to 114% of active power. Figure 5.5 shows a modern reactive power relay with

Figure 5.5 Reactive power controller with digital indication of cos φ independent of the waveform of voltage and current; 50 and 60 Hz. Reproduced by permission of Janitza Electronics GmbH, Germany.

digital indication of the power factor. Its internal electronic measuring device is designed for any desired waveforms of voltage and current.

Another method is to observe the ratio of the instantaneous values of active power to the apparent one. So all reactive power relays with this measuring method are able to control and indicate $\cos \varphi$ independent of the waveform of voltage and current. In older plants it sometimes happens that electromechanical power factor meters are still installed. Deviations in the indicated values in modern reactive power relays are unavoidable, if the mechanical unit has been calibrated with regard to pure sinusoidal functions.

5.2.5 Determination of Power (Factor) via Recorded Data

The best analysis of data for active and reactive power in industrial plants may be carried out using recording equipment that stores data over one week, at least in summer, and winter as well, if possible. Modern units record power factor automatically. However, older units record just the power, active and/or reactive. The average power factor is then calculated via $\tan \varphi = Q/P$ excluding a lot of data within the recording period. Customary attached hardware enables a user to call up $\cos \varphi$ in a file or as a printable diagram (Figure 5.6).

5.2.6 Determination of Power Factor by Means of an Active Energy Meter

This method ensures that the correct power factor is obtained at the point where energy is billed.

Figure 5.6 Portable power analyser with data memory of 512 kB for three-phase networks; GridVis software for *PQ* analysis and reports is included. Reproduced by permission of Janitza Electronics GmbH, Germany.

The method ascertains an industrial plant's power factor with the help of an active energy meter, ammeter and voltmeter. It is recommended that the measuring work is carried out during periods at average load. To calculate the active power it is necessary to get the technical data of the energy meter, as follows for $c =$ disc turns per kWh and $n =$ disc turns per minute:

$$P = \frac{n \cdot 60}{c} \tag{5.13}$$

Apparent power is given by formula

$$S = \frac{\sqrt{3} \cdot U \cdot I}{1000} \tag{5.14}$$

where

$I =$ line current in A (via current transformer)
$U =$ line voltage (delta)
$S =$ apparent power in kVA

Consequently, the power factor is

$$\cos\varphi = \frac{P}{S} \tag{5.15}$$

Example: To determine in a three-phase network the power factor cos φ by means of a three-phase meter for active energy, voltmeter and ammeter. The energy meter has a counting constant $c = 120$ disc turns per kWh. The voltmeter indicates 415 V (delta voltage), the ammeter 241 A. The disc of the energy meter made 200 turns per minute.

Then

$$P = \frac{200 \cdot 60}{120} = 100\,\text{kW}$$

$$S = \frac{\sqrt{3} \cdot 415\,\text{V} \cdot 241\,\text{A}}{1000} = 173.2\,\text{kVA}$$

$$\cos\varphi = \frac{100\,\text{kW}}{173.2\,\text{kVA}} \approx 0.58$$

Thus, for the determination of reactive power,

$$Q = \sqrt{S^2 - P^2} = \sqrt{(173.2\,\text{kVA})^2 - (100\,\text{kW})^2} = 141.4\,\text{kvar}$$

5.2.7 *Determination of Power Factor by Means of an Active and Reactive Energy Meter*

If there are energy meters available for active and reactive energy, they can be used to determine reactive power and power factor as follows.

Active power by energy meter:

$$P = \frac{n_a \cdot 60}{c_a}$$

where
n_a = disc turns per minute for active energy
c_a = counting constant for active energy
P = active power (kW)

Reactive power by energy meter:

$$Q = \frac{n_r \cdot 60}{c_r}$$

where
n_r = disc turns per minute for reactive energy
c_r = counting constant for reactive energy
Q = reactive power (kvar)

Also,

$$\tan\varphi = \frac{Q}{P}$$

By means of either a computer or an electronic calculator, the average power factor may be obtained from trigonometry. Figure 5.7 shows the function of $\cos\varphi$ dependent on the quotient Q/P. It is easy to realize that, in the case of $Q = P$ ($\tan\varphi = 1$), $\cos\varphi = 0.707$.

5.2.8 Determination of Power Factor via the Energy Bill

Another method to determine reactive power is possible by means of the monthly energy bills. In the bills from the energy supplier there are printouts of the consumption of active and reactive energy. It is essential to know the monthly operating hours t of the plant.

Example: An energy bill shows the following data:

Consumption of active energy $W_a = 30\,000$ kWh

Consumption of reactive energy $W_r = 40\,000$ kvar

Operating hours per month $t = 160$ h

Thus

$$\tan\varphi = \frac{W_r}{W_a} = \frac{40\,000\,\text{kvarh}}{30\,000\,\text{kWh}} = 1.33$$

This means that 133% of active energy is reactive.

The trigonometric function $\tan\varphi = 1.33$ can be converted into $\cos\varphi = 0.60$, as shown in Figure 5.7.

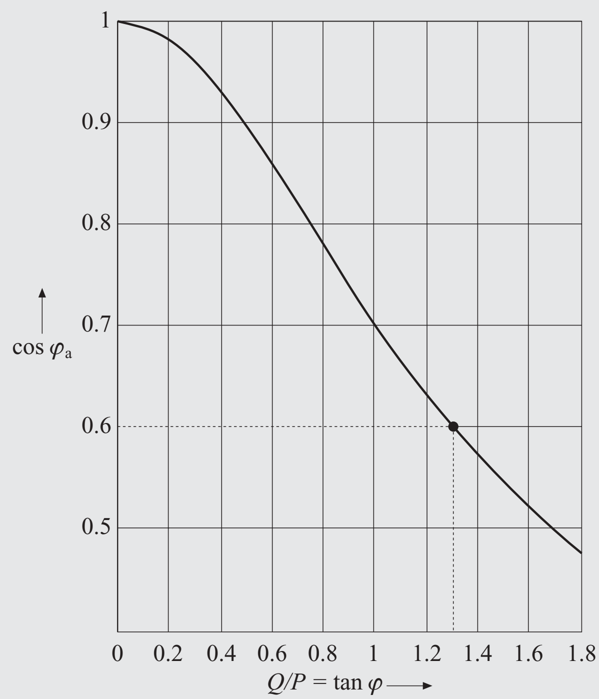


Figure 5.7 Function of the fundamental power factor dependent on the ratio of Q/P.

The reactive power can be calculated easily:

$$Q = \frac{W_r}{t} = \frac{40\,000\,\text{kvarh}}{160\,\text{h}} = 250\,\text{kvar}$$

Assuming there is no compensation bank installed, 250 kvar should be compensated in case an average power factor target of 1 (unity) is required by the energy supplier. If the supplier requests a lower power factor target, then the reactive power to compensate becomes less, of course. Detailed calculations appear in Chapter 8.

5.3 Summary

As detailed in this chapter, different methods are applied to determine reactive power and power factor. Classical power factor indicators designed in at the very beginning of the history of electricity had been calibrated exclusively for sinusoidal waveforms of voltage and current. In today's world with its increasing number of so-called nonlinear consumers, there is a need to design measuring methods in order to determine the power factor correctly for the desired waveforms of voltage and current. This fact is borne out nowadays by many of the reactive power controllers available on the market. It makes the need for individual power factor indicators superfluous.

6

Improvement of Power Factor

6.1 Chapter Overview

This chapter presents different possibilities of limiting or compensating reactive power/energy respectively, as these are required in designing electric motors, during construction or by means of synchronous generators. Further, the choice of correctly rated motors according to their application improves the current power factor. Last but not least, capacitors are the main application in the utilization for compensation banks.

6.2 Basics of Reactive Power Compensation

Referring to Figure 1.11, an ideal inductance (without any active losses) stores energy (+) within the first quarter of the period (0–90°). During the second quarter (90–180°) the stored energy will be fed back (−) to the grid or generator. The same procedure repeats in the third quarter (+) and fourth quarter (−) of the period accordingly. This means that the inductance stores and feeds back the energy twice per period. The current of the ideal inductance is shifted 90° lagging the voltage.

As described in the previous chapters, a low power factor $\cos\varphi$ leads to many disadvantages:

- Increasing voltage losses along the lines.
- Additional wattage losses along the lines.
- Increasing costs for energy and installation.
- Reduced available active power transmitted, reduced active power via the transformer.
- Higher voltage losses at the transformer's secondary terminals.
- Higher wattage losses in the transformer.

As is well known, these disadvantages are avoidable by means of compensating inductive reactive power. For this purpose, fed-back energy of the inductances could be stored briefly in capacitors connected as close as possible in parallel to the inductances. Figure 1.8e shows the reversed 'behaviour' compared with inductances. The capacitor's current is shifted 90° leading the voltage. If the inductance feeds back energy the capacitor stores it, and if the inductance

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

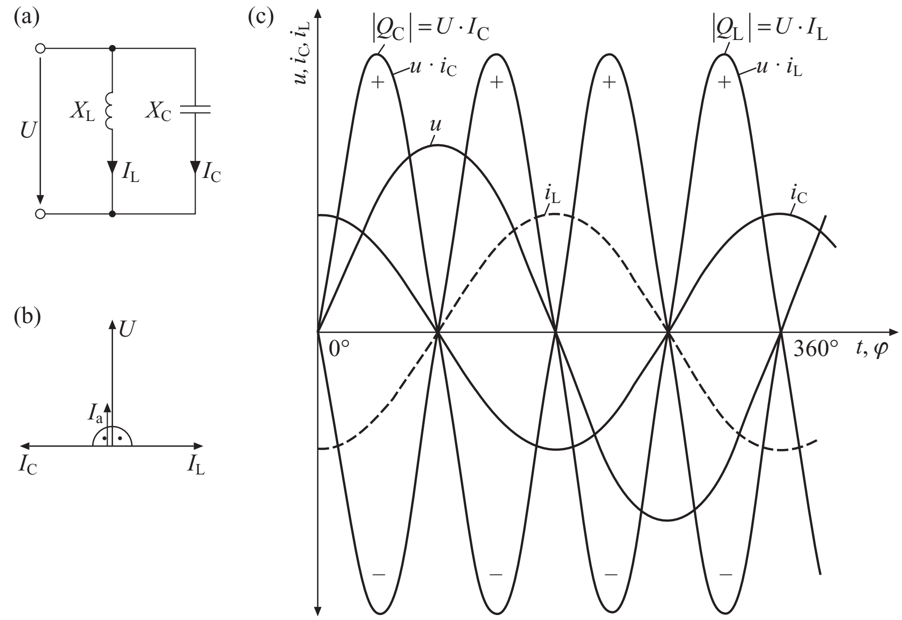


Figure 6.1 Compensation of reactive lagging current: (a) equivalent circuit diagram of an ideal reactor combined with a capacitor, switched in parallel; (b) orthogonal vectors of currents I_L and I_C, I_a and U; (c) time courses of current, voltage and power at full compensation ($\cos\varphi = 1$).

requests energy for building up the magnetic field in its coil the capacitor 'supplies' it. Incidentally, it is easy to understand why this combination of capacitor and inductance forms a swinging circuit.

Figure 6.1c indicates that the positive current (i_L) of the inductance will be compensated by the negative current (i_C) of the capacitor and that, half a period later, the negative current of the coil is compensated by the capacitor's positive current all the time. In this ideal case both currents are in equilibrium, meaning that the reactance of the capacitor (X_C) and that of the inductance (X_L) are equal (see Figure 6.1b) and $\cos\varphi = 1$. If not, the remaining reactive current results in

$$I_r = I_L - I_C \tag{6.1}$$

Real inductances have wattage losses in the copper coil and in the iron core of course. This means that even in the case of total compensation of the reactive vector of the coil, a small active vector (I_a) referring to the losses appears.

Furthermore, connecting capacitors in parallel to the inductances reduces the reactive current I_r. This improves the power factor $\cos\varphi$ and reduces the apparent current on the feed-in lines. There are three methods available to reduce reactive power in industrial plants:

- Limiting reactive power without phase shifting.
- Compensating reactive power by means of rotational phase shifting.
- Compensating reactive power by means of capacitors (banks).

Table 6.1 Power factors dependent on the utilization of small and large motors.

Utilization	100%	75%	50%	25%
Small motors	0.84	0.81	0.70	0.54
Large motors	0.90	0.88	0.84	0.70

6.3 Limitation of Reactive Power without Phase Shifting

There are possibilities for limiting the reactive power of, for example, an asynchronous motor while constructing it. For the purpose of reducing reactive power, the designer and producer of electric motors will focus on keeping the air-gap area between the stator and rotor as small as possible (see Chapter 2, Figure 2.4). Further possibilities occur when planning new industrial plants. For example, all motors should be correctly rated in the nominal active power for their applications. Oversized motors require more reactive power of course and have low efficacy as well. It must be considered that the current power factor depends on the load condition of each motor. Motors in punching machines (in car factories) run in idle condition for most of their operating hours ($\cos\varphi \approx 0.2$); they have to keep their flywheels at a constant revolution per minute and just feed active energy referring to the lost kinetic energy of the flywheel due to the punching procedure. This results in low power factors (Table 6.1).

At three phase, motors with star/delta switches should be considered to run in star connection due to the less than half-load condition ($<50\%$) for a longer period. There are automatic switches available, which choose star or delta connection automatically according to the current load.

As mentioned above, it is recommended that motors are run at their rated power in order to achieve the best power factor $\cos\varphi$.

If in new plants feed-in transformers are necessary, it is best to pay attention to the technical data referring to wattage losses with regard to the copper coils and the iron core. The volume of the iron core determines the approximate amount of reactive power. Experience has shown that cheap primary transformers have higher losses in active power as well as higher amounts of reactive power. This is essential to know, as energy will be metered usually on the high-voltage side.

In larger MV cable networks of industrial plants, it is thus useful, due to the capacitance, to let uncharged MV cables be energized for compensation of the inductive reactive power of the transformer(s), especially in the no-load condition.

6.4 Compensation of Reactive Power by Rotational Phase-Shifting Machines

In some industrial plants, there are large synchronous generators (Figure 6.2) running to improve the power factor $\cos\varphi$. Consequently, the generator's power factor may be controlled by excitation of the magnetic wheel when it is possible to use synchronous generators in the range of up to several hundred kvar just for compensating the reactive power of the plant, exclusively. However, depending on the excitation of the magnetic wheel, the generator's

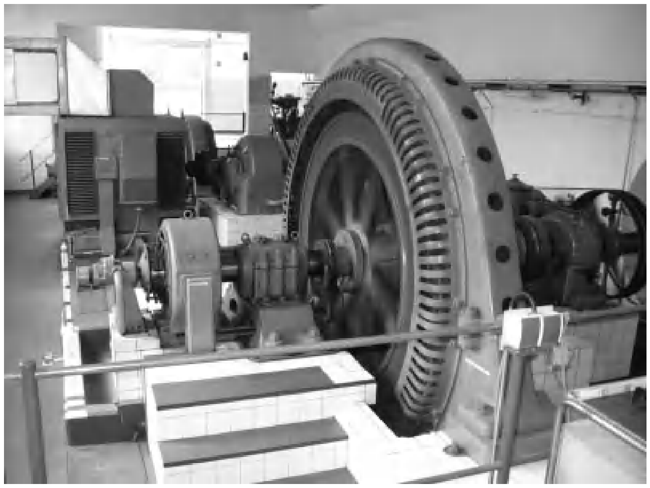


Figure 6.2 A 510 kVA synchronous generator for phase-shifting purposes. Note that, today, these applications for synchronous motors have become rarer. Sometimes they may still be in use in older power stations with a rated power of more than 1000 kVA. Reproduced by permission of Stahlwerk Annahuette Max Aicher & Co. KG, Germany.

power factor could be varied between $\cos\varphi = 0$ and 1. Mainly synchronous generators run with a power factor between 1 and 0.8 leading, if they are used to drive engines in addition. They are mainly used for pumps, ventilators, compressors and converters in the range of several hundred kilowatts to megawatts, when steady loads without peaks are supposed.

When set to $\cos\varphi = 0$ leading by excitation, synchronous generators supply leading reactive power exclusively to the grid. Then they consume active power just for mechanical friction and electrical losses in the copper and iron.

6.5 Compensation of Reactive Power by Means of Capacitors

As mentioned in Section 6.2, the best compensation for lagging reactive power is obtained from components with leading reactive power. According to Figure 6.1, the lagging current I_L must be compensated by the leading current I_C of a capacitor. This means that capacitors are ideal components for compensation tasks. They require little maintenance compared with synchronous motors. The required reactive energy for building up magnetic fields in motors will be supplied by the stored energy in the capacitor; this energy oscillates between the capacitor and inductance all the time and unburdens the feed-in cables. If a well-calculated capacitor bank is installed very close to the inductive consumers, enabling a maximal power factor of $\cos\varphi = 1$ to be obtained, the grid has to supply no additional reactive energy (see Figure 6.3b). All feed-in lines are burdened exclusively with active energy. Figure 6.3a shows the lines between the energy supplier and consumer burdened with active and reactive energy, if there is no existing or just partial compensation ($\cos\varphi < 1$).

An example is given in Figure 6.4a. The customer's uncompensated plant requires cables with a larger cross-section of 50 mm^2 per phase. Figure 6.4b shows the same plant with a compensation bank. The cross-section of the feed-in cable may be reduced to 25 mm^2.

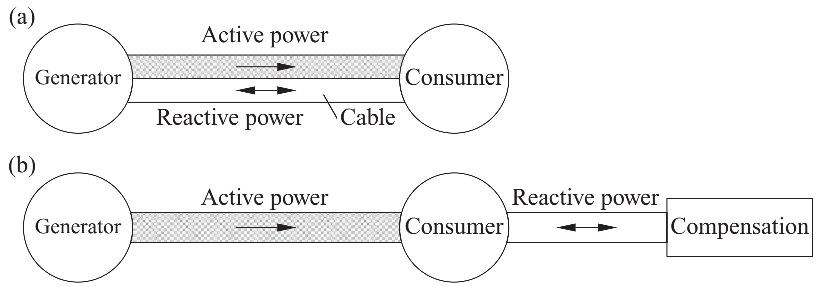


Figure 6.3 Illustration of energy flow.

It should be considered that, for compensation to a lower power factor target than 1, any uncompensated reactive energy adds a further burden to the feed-in lines. As is well known, the active losses then increase in a squared manner to the current I. This represents an essential view as far as the environmental control and reduction of CO_2 is concerned. Figure 6.5 shows the situation for a medium plant. It can be seen clearly how many kWh per metre of cable could be saved within one year! Many customers do not take this into consideration. Active meters do count up additional cable losses, of course.

It is clear that in the case of no compensation, an additional 60 kWh per metre of cable in one year will be measured by the wattmeter but never taken into account! With total compensation to unity, just 38% of active energy losses could be saved, which means that 37 kWh per metre of cable in one year could still occur. This underlines the necessity of compensating reactive power as much as possible. If one were to consider the energy losses along the uncompensated cables and their costs (in kWh prices), a compensation bank, even determined for total compensation to cos $\varphi = 1$, would amortize much quicker. Most specialists do not take this into account in their calculations.

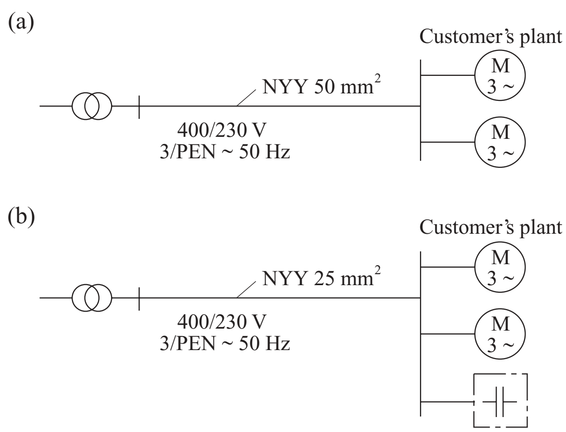


Figure 6.4 Simplified circuit diagram of an industrial plant: (a) without compensation, $S = 108$ kVA, $P = 68$ kW, $I = 156$ A (100%), cos $\varphi_a = 0.63$; (b) with compensation, $S = 69.4$ kVA, $P = 68$ kW, $I = 100$ A (64%), cos $\varphi_d = 0.98$. (NYY = designation for plastic cables; PEN = Potential Earth Neutral (conductor)).

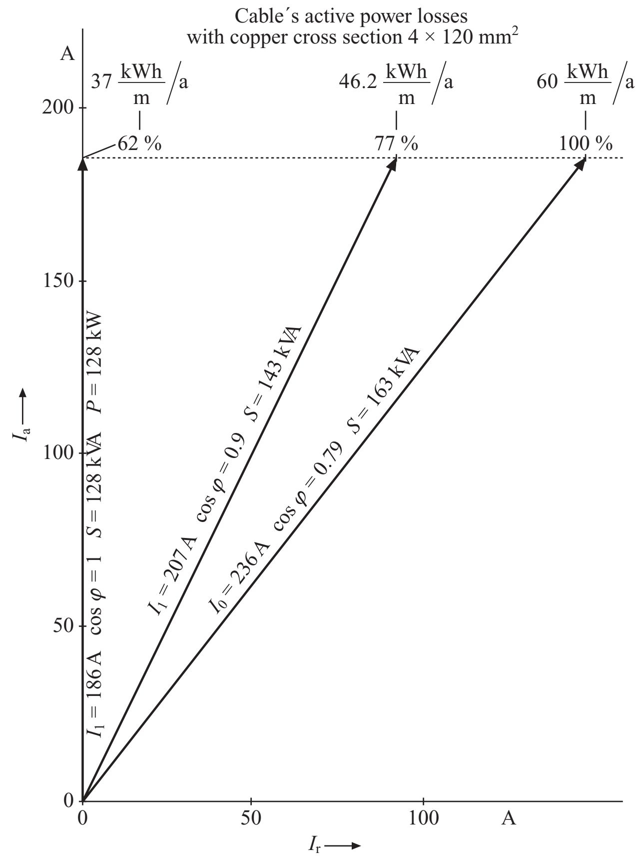


Figure 6.5 Active energy losses, for example in cables with a cross-section of 4 × 120 mm^2 per metre of cable and assuming 2400 operating hours per year.

6.6 Summary

Compensating reactive energy means an improvement in cos φ and in economy primarily.

Table 6.2 shows the utilization of standard transformers and cables depending on the achieved power factor cos φ and underlines the need for compensation banks. Compared with synchronous motors, capacitors are so-called static phase-shifting components.

The following advantages should be emphasized:

- Low wattage losses.
- Long lifetime.
- Simple installation.
- Decentralized applications.
- Simple possibilities for extending.
- Very little maintenance.

Table 6.2 Utilization of electrical devices by compensation of reactive power.

(a) Available active power (kW) at the transformers

Transformers' rated power (kVA)	Power factor cos φ					
	1	0.9	0.8	0.7	0.6	0.5
100	100	90	80	70	60	50
160	160	144	128	112	96	80
200	200	180	160	140	120	100
250	250	225	200	175	150	125
315	315	283	252	220	189	157
400	400	360	320	280	240	200
500	500	450	400	350	300	250
630	630	567	504	441	378	315
800	800	720	640	560	480	400
1000	1000	900	800	700	600	500
1250	1250	1125	1000	875	750	625
1600	1600	1440	1280	1120	960	800
2000	2000	1800	1600	1400	1200	1000

(b) Admissible load for plastic insulated cables at rated voltage $U_r = 400$ V at an ambient temperature of 30 °C. All values are multiplied by a factor of 1.07 or 0.94 at an ambient temperatures of 25 °C or 35 °C, respectively

Cable cross-section (mm^2)	Admissible current (A)	Available active power (kW) at power factor cos φ					
		1	0.9	0.8	0.7	0.6	0.5
4 × 1.5	18	12	10.5	9.5	8	7	6
4 × 2.5	25	16.5	15	13	11.5	10	8
4 × 4	34	22	20	18	15.5	13.5	11
4 × 6	43	28	25	22	20	17	14
4 × 10	60	40	35	31	28	24	20
4 × 16	80	53	47	42	37	32	26
4 × 25	106	70	63	56	48	41	35
4 × 35	131	86	78	69	60	51	43
4 × 50	159	104	94	83	73	63	53
4 × 70	202	132	119	106	93	80	67
4 × 95	244	159	144	128	113	97	80
4 × 120	282	185	166	148	130	111	92
4 × 150	324	212	191	169	148	127	107
4 × 185	371	244	220	200	171	146	122
4 × 240	436	286	257	229	200	173	143

Capacitors, even of different sizes, are easy to assemble into banks, controlled by automatic reactive power controllers. Static capacitors are available for low-, medium- and high-voltage applications as well as for 50 or 60 cps. For special applications, for example induction furnaces, there is a need for capacitors for medium frequencies, sometimes even water-cooled ones. However, the following chapters deal with capacitors for standard grid frequencies.

7

Design, Arrangement and Power of Capacitors

7.1 Chapter Overview

This chapter deals with the attributes of capacitances from the point of view of the desired voltage functions. The comparison with capacitors (see Chapter 1) gives a better understanding of the voltage functions apart from the pure sinusoidal waveform as found in modern industrial plants.

Further, the chapter describes the structure and technology of capacitors produced worldwide. Capacitance is effective anywhere on circuit boards, in overhead lines, in cables, and so on. However, this chapter will focus on the construction and attributes of industrial capacitors as assembled in compensation banks.

7.2 Basics of Capacitors

In general a capacitor has two metallic areas insulated from each other by a so-called dielectric. The capacitance depends on the area of the foils, the distance (a) between them and the dielectric coefficient (ε) of the insulating material. The insulating material and its impregnation determine the dielectric coefficient of the capacitor. The quality of the capacitor is defined by its dielectric dissipation factor $\tan\delta$:

$$\tan\delta = \frac{P_V}{Q_C} = \frac{X_C}{R_V} = \frac{1}{\omega \cdot C \cdot R_V} \tag{7.1}$$

$$P_V = Q_C \cdot \tan\delta \tag{7.2}$$

where

P_V = active power losses of the capacitor
Q_C = reactive power of the capacitor
δ = loss angle (see Figure 7.1c)
I_V = loss current through the insulating material
R_V = the dielectric's resistance
X_C = Capacitor's reactance

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

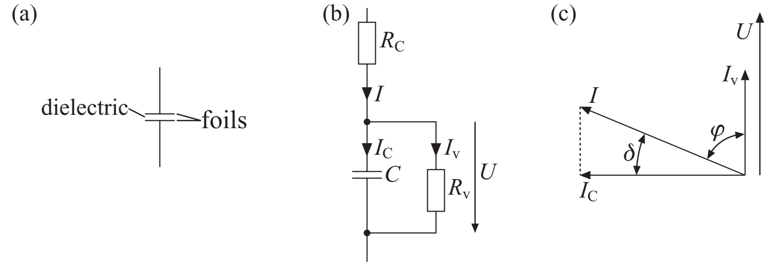


Figure 7.1 Simplified illustration of a capacitor: (a) foils and dielectric; (b) equivalent circuit diagram symbolizing active losses in leads by R_C and in dielectric by R_V; (c) orthogonal components of the capacitor.

The active power losses P_V are given by the product of I_V and U. Any insulating material has a defined active conductance. Even if there are just microamps flowing, when multiplied by the supply voltage U this causes the active power loss of the dielectric, which will be converted into heat within the capacitor. Figure 7.1b shows an equivalent circuit with the capacitor C and the resistance R_V components connected in parallel to the capacitor.

The fact that power capacitors generate heat as well means that they will require locations with a good circulation of the surrounding air. Though active power losses are below 1 W per 1 kvar reactive power of the capacitor, large capacitor banks may generate several hundred watts. Manufacturers of power capacitors declare the active power losses on their products. National standards like DIN VDE 0560 (in Germany) set temperatures which should not be exceeded. Additional active losses (converted to heat) are caused by all the conducting components inside the capacitor ($I^2 \cdot R_C$). Figure 7.1b shows R_C as a series ohmic resistance. The active losses may become significant in the case of harmonics on the supply voltage as far as the instantaneous value of current is described mathematically:

$$I_C = \mathrm{C} \cdot \frac{du}{dt} \tag{7.3}$$

So the capacitor's instantaneous current depends on its capacitance and the 'velocity' of the change of voltage. If there is no change ($du/dt = 0$) the current is equal to zero, for example at DC voltage. The same situation is recognizable in the equivalent mechanical model of a spring (see Section 1.5). A spring compressed by a constant force does not cause any motion; that is, motion = 0. On the other hand, one may observe 'velocities' up to 30 V/μs in modern converters. A 50 kvar capacitor would be charged with current peaks of several kiloamps if not choked!

The capacitance of a capacitor depends on the area of the two plates, considering a plate-type capacitor, the thickness of the insulating material and the dielectric coefficient, as described by following formula:

$$\mathrm{C} = \frac{A \cdot \varepsilon}{d} \tag{7.4}$$

where

A = area of the plates
d = thickness of insulating material
ε = dielectric coefficient ($\varepsilon = \varepsilon_r \cdot \varepsilon_0$)
ε_r = relative dielectric coefficient of the insulating material (≈ 1 in air)
ε_0 = 8.85 pF/m

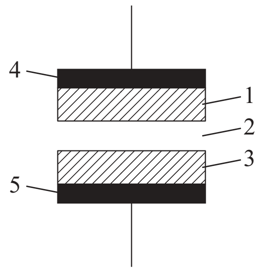


Figure 7.2 Schematic illustration of a plate-type capacitor: 1–3, insulating layers; 4–5, foils.

Figure 7.2 shows the construction of a plate-type capacitor containing two electrodes (plates 4 and 5) and three insulating layers (1,2,3). It is a schematic illustration with regard to the structure of capacitors. To achieve a maximum of capacitance manufacturers of power capacitors have to follow two essential criteria:

- Maximum area of the 'plates' with minimum volume.
- Minimum thickness of insulating layer.

The 'plates' in industrial production are manufactured from very thin plastic foils (dielectric) with a very thin vaporized metallic layer (electrode) on one side only. Two of the 'plates' are wound in rolls and packed in metallic or plastic cups. Manufacturers deliver them in standardized sizes for assembling compensation banks of any requested size.

The unit of measure for capacitance is the farad[1] (F). A capacitor with 1 F of capacitance becomes 1 V of voltage if it is charged up with a current of 1 A for just 1 s. Since 1 A s represents 1 coulomb (C), the mathematical description runs as follows:

$$1\,\mathrm{F} = \frac{1\,\mathrm{C}}{1\,\mathrm{V}} = \frac{1\,\mathrm{A\,s}}{1\,\mathrm{V}} \tag{7.5}$$

As 1 F is a very large unit, divisions of the unit are in use:

1 μF (microfarad) $= 10^{-6}$ F

1 nF (nanofarad) $= 10^{-9}$ F

1 pF (picofarad) $= 10^{-12}$ F

The electric charge stored on a capacitor depends on its capacitance and the supplied voltage:

$$Q = C \cdot U \tag{7.6}$$

where
C = capacitance of the capacitor, unit A s/V
U = supplied voltage, unit V
Q = electric charge, unit A s

[1] Named after Michael Faraday (1791–1867), the English physicist and chemist.

7.3 Reactive Power of Capacitors

The reactive power Q_C in single-phase operation depends on three factors, namely voltage U, capacitance C and frequency f, written mathematically as

$$Q_C = U \cdot I_C \tag{7.7a}$$

$$I_C = \frac{U}{X_C} = U \cdot 2 \cdot \pi \cdot f \cdot C \tag{7.7b}$$

$$Q_C = U^2 \cdot 2 \cdot \pi \cdot f \cdot C \tag{7.7c}$$

Regarding Equation 7.7c, one can recognize that the reactive power mainly depends on the supplied voltage in a squared manner. This means that an increase of 10% due to the rated voltage causes a 21% higher reactive power than rated. The frequency, however, influences the reactive power in a linear manner only. This means that a capacitor with a defined capacitance supplied by an AC voltage of 60 Hz results in 20% more reactive power compared with 50 Hz grids. The nominal reactive power Q_r of a capacitor printed on a factory nameplate always refers to the rated supply voltage U_r (sinusoidal waveform) and the rated frequency f_r. Additional harmonics increase the current of capacitors accordingly, if not reactor protected by serial inductances.

In the case of deviations due to voltage U_r and frequency f_r the actual reactive power is given by

$$Q_{C1} = Q_{Cr} \cdot \left(\frac{U_1}{U_r}\right)^2 \cdot \frac{f_1}{f_r} \tag{7.8}$$

where

U_1 = actual voltage
U_r = rated voltage
f_1 = actual frequency
f_r = rated frequency

If the supply voltage is higher than that rated continually, the lifetime of the capacitor will be reduced. Manufacturers therefore recommend installing, for example, capacitors with a rated voltage of 440 V for use in 400 V grids or even 460 V capacitors for use in 415 V grids, for example in the UK.

Example: A customer wants to compensate its feed-in transformer with a fixed capacitor of 20 kvar on its secondary-side terminal with a rated voltage of 400 V. For safety reasons the customer prefers a capacitor with a rated voltage of 440 V. Which rated reactive power must be printed on the nameplate to achieve 20 kvar at 400 V?

As mentioned above, the reactive power decreases with lower voltage in a squared manner:

$$\frac{Q_r}{Q_l} = \left(\frac{U_r}{U_l}\right)^2$$

Thus

$$Q_r = 20\,\text{kvar} \cdot \left(\frac{440\,\text{V}}{400\,\text{V}}\right)^2 = 20\,\text{kvar} \cdot 1.21 = 24.2\,\text{kvar}$$

Since there is no 24.2 kvar capacitor available, the customer has to buy a 25 kvar capacitor for the rated voltage of 440 V. For use in a 400 V grid the capacitor finally compensates the reactive power of the transformer with 20.7 kvar.

Manufacturers assembling whole compensation banks automatically consider using capacitors with a higher rated voltage than the nominal supply voltage.

7.4 Different Technologies in Manufacturing Capacitors

7.4.1 Capacitors with Paper Insulation

Figure 7.3 shows a schematic construction where two metallic foils (aluminium, approximate thickness 0.01 mm) are insulated from each other by paper. In order to achieve as long a lifetime as possible, the paper must be deprived of any humidity and impregnated afterwards. The impregnation avoids any trapped air in the paper and protects against humidity as well. This technology is used to produce capacitors of mainly medium voltage (MV) . The two foils will be coiled up to achieve as large an area as possible (see Figure 7.3).

7.4.2 Capacitors with Metallized Paper (MP Capacitor)

This technology is used to produce capacitors of low voltage (LV) with less volume compared with paper-insulated capacitors (see Section 7.4.1). The paper is vaporized with a very thin zinc alloy on one side, some to about only 0.1 μm. This zinc alloy has such a very low evaporation level that, in case of any puncture of the insulation by voltage peaks, the heat vaporizes the zinc alloy around the punctured point. The capacitor itself does not failed or become destroyed even after several punctures. One speaks of a so-called ‘self-healing technology’. Figure 7.4 shows a puncture in the layer with its dimension.

The figure shows the point of breakdown caused by a high-voltage peak. The shorted circuit with its electric arc and high temperature vaporized the metallic layer around the puncture and finally the high arc force extinguished the arc. It also shows that around the point of the puncture there is a small area free of metal, which reduces the capacitance a little. However, the reduction is not significant, maybe not even recognizable, and the capacitor itself is able

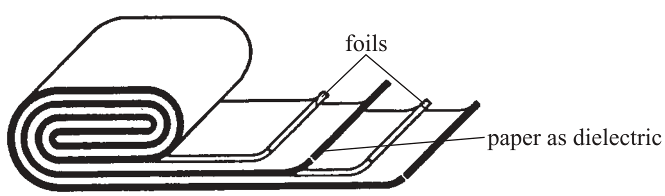


Figure 7.3 Capacitor roll with paper as dielectric.

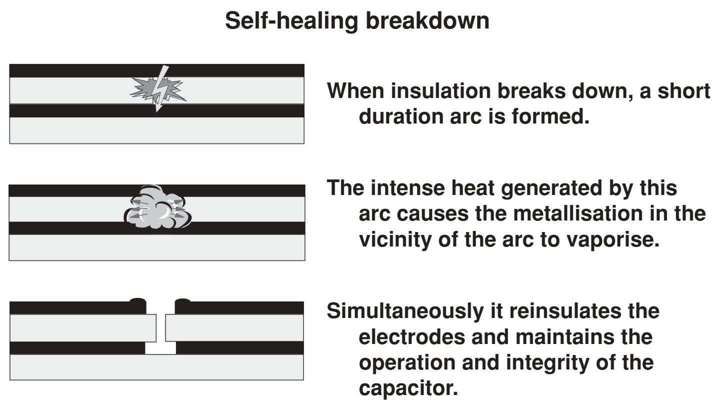


Figure 7.4 Schematic illustration of self-healing technology. Light areas symbolize the polypropylene dielectric, black areas the metallic foils (dimensions not proportional). Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

to compensate further. This self-healing technology is applicable for LV capacitors as well as for MV capacitors as shown in Figure 7.4.

7.4.3 Capacitors with Metallized Plastic Foils

Today's most popular technology in producing LV capacitors utilizes metallized plastic foils. High-level technologies enable the production of very thin foils made from polypropylene (dielectric). The metallic conducting layer (electrode) is vaporized on one side under vacuum conditions. The foils, coiled in rolls and implemented in cylindrical cups, minimize the volume of the capacitor and the weight as well.

This technology offers two significant advantages:

- Reduction of active power loss within the dielectric, down to 0.2 W/kvar.
- Reduction of foil thickness due to higher dielectric strength.

As mentioned above, the active power loss is listed on the manufacturers' nameplate (e.g. 0.2 W/kvar) and refers to nominal conditions regarding voltage without harmonics (sinusoidal waveform). However, harmonics of different intensity are present everywhere in modern plants using converters. An increase in the capacitor's current is unavoidable, which increases the active power loss of conducting components inside the capacitor as well ($I^2 \cdot R$). If the intensity of harmonics becomes too high, it will be necessary to protect the capacitor by serial inductances (see Chapter 17).

7.5 Arrangements and Reactive Power of Capacitors

Power capacitors are available for single-phase and three-phase grids. In ready-assembled banks the capacitors are connected in parallel to achieve the required reactive power for individual compensation tasks. In general the mounting of capacitor banks is simple and economical. Any extension is possible any time. Serial connection of capacitors is very rarely used in LV capacitors but much more in MV capacitors (see Section 7.6).

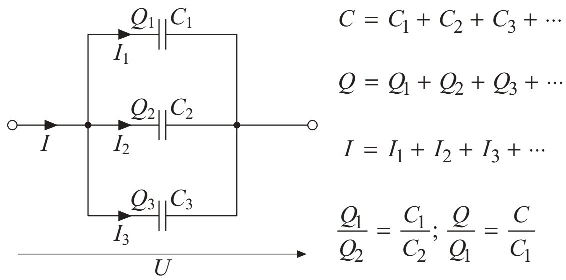


Figure 7.5 Capacitors connected in parallel.

7.5.1 Capacitors Connected in Parallel

Parallel connection of capacitors increases the total capacitance accordingly. The total capacitance is equal to the sum of all the capacitors (Figure 7.5). The rated voltage of each capacitor has to comply with the grid voltage, including at least some tolerance (see Section 7.2). Thus

$$C_t = C_1 + C_2 + C_3 \tag{7.9}$$

$$Q_t = Q_1 + Q_2 + Q_3 \tag{7.10}$$

$$I_t = I_1 + I_2 + I_3 \tag{7.11}$$

$$\frac{Q_1}{Q_2} = \frac{C_1}{C_2} \tag{7.12}$$

$$\frac{Q_t}{Q_1} = \frac{C_t}{C_1} \tag{7.13}$$

7.5.2 Capacitors Connected in Series

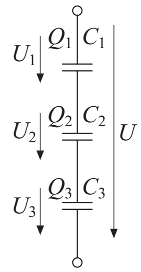
As mentioned above, it is sometimes necessary to assemble capacitors in serial connection at MV capacitors in order to reduce the voltage for each capacitor element. However, series connection does not increase the total capacitance C_t but is reduced due to the series connection of the dielectrics. It is just like increasing the distance of the electrodes in a plate-type capacitor. The voltage for each capacitor, if their capacitances are equal, is divided by the sum of the elements (Figure 7.6). However, if their capacitances are not equal the partial voltage of each capacitor is described mathematically by

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_n} \tag{7.14}$$

$$U_t = U_1 + U_2 + U_3 + \cdots + U_n \tag{7.15}$$

$$\frac{U_1}{U_2} = \frac{C_2}{C_1} \tag{7.16}$$

$$\frac{U_1}{U_t} = \frac{C_t}{C_1} \tag{7.17}$$



$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

$$Q = Q_1 = Q_2 = Q_3 = \cdots$$

$$U = U_1 + U_2 + U_3 + \cdots$$

$$\frac{U_1}{U_2} = \frac{C_2}{C_1}; \frac{U_1}{U} = \frac{C}{C_1}$$

Figure 7.6 Capacitors connected in series.

7.5.3 Star and Delta Connection of Power Capacitors

Power capacitors for applications in three-phase systems are delivered either in star or in delta connection from the factory. On request and for special applications three-phase capacitors are available without any connections, just with six terminals for connecting as required. This enables connections to be made for single-phase or three-phase operation, star or delta connection.

Capacitor banks for LV applications are usually fitted with capacitors in delta connection. If the capacitors were to be connected in star configuration, the total reactive power would result in just one-third compared with the delta configuration. The reason is that each capacitor has line-to-line voltage in delta connection, but in star connection the delta voltage is divided by $1/\sqrt{3}$.

Example: Three capacitors, 15 μF each, are operating in a three-phase grid of 415/240 V 50 cps, first in star connection and then in delta connection. The aim is to calculate which leading reactive power becomes effective for each connection. The calculation is via the imaginary resistance (=reactance) of the capacitor:

$$X_C = \frac{1}{2 \cdot \pi \cdot f \cdot C} = \frac{1\,\mathrm{V\,s}}{2 \cdot 3.14 \cdot 50 \cdot 15 \cdot 10^{-6}\,\mathrm{A\,s}} = 212\,\frac{\mathrm{V}}{\mathrm{A}}\,(\Omega)$$

The leading reactive power of all three capacitors is given by

$$Q_C = \frac{3 \cdot U^2}{X_C}$$

In star connection

$$Q_S = \frac{3 \cdot (240\,\mathrm{V})^2}{212\,\mathrm{V/A}} = 815\,\mathrm{var}$$

In delta connection

$$Q_D = \frac{3 \cdot (415\,\mathrm{V})^2}{212\,\mathrm{V/A}} = 2437\,\mathrm{var}$$

Thus $Q_D \approx 3 \cdot Q_S$.

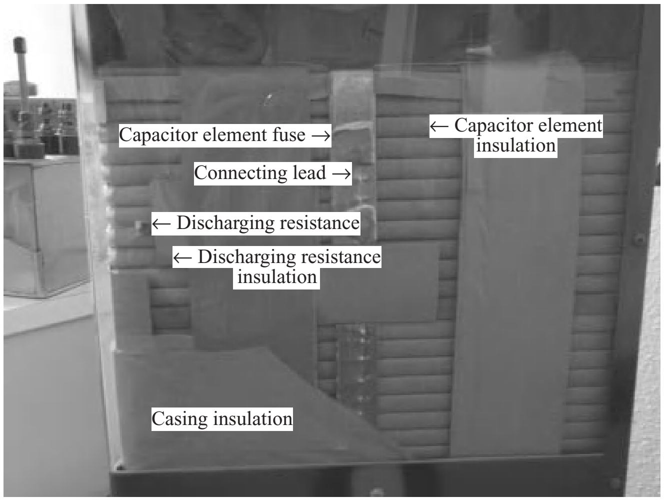


Figure 7.7 Section of an MV capacitor showing the packaging of capacitor elements in a steel enclosure. Reproduced by permission of Condensator Dominit GmbH, Germany.

7.6 Design of MV Capacitors

The assembly and construction of MV capacitors are similar to LV capacitors in respect of wound-up foils with, for example, vaporized layers of aluminium on polypropylene films. The rolls are then flattened and packed in a steel enclosure as shown in Figure 7.7. However, due to the higher rated voltages there are different technologies in use. In Chapter 12, Figures 12.5 and 12.6 outline two different methods of how to assemble an MV capacitor of 300 kvar for a rated voltage of 3.3 kV, 50 Hz and one of 400 kvar, 11 kV, 50 Hz, respectively. Both of the three-phase capacitors are assembled in star connection in order to minimize the electrical tension on each element. However, at the 300 kvar capacitor, four capacitors of 21.9 μF each are soldered in parallel for each phase. The elements are charged with a star voltage of only 1.9 kV. In total $4 \times 21.9\ \mu F = 87.6\ \mu F$ becomes effective per each phase as illustrated in Figure 12.5 (left).

Compared with the 400 kvar capacitor operating at the higher rated voltage of 11 kV, one can recognize seven capacitor elements, of 73.5 μF each, connected in series for each phase due to the high voltage (HV). Thus a total capacity of 10.5 μF becomes effective for each phase (see Section 7.5.2) as shown in Figure 12.6 (left). Due to the series connection of seven elements they are charged with just 0.9 kV each.

This section described two different methods of constructing MV capacitors depending on the rated voltage required. The main goal of the designing engineers of MV capacitors is to keep the electrical tension for each capacitor element as low as possible.

Figure 7.8 shows a 250 kvar, 12kV assembly with capacitor elements soldered in series.

7.7 Long-Term Stability and Ageing of Capacitor Installations

7.7.1 General

The data sheets of manufacturers often indicate a guaranteed lifetime of capacitor units up to 100 000 hours. This information should be regarded as a statistical value – premature failures

Figure 7.8 MV capacitor of 250 kvar, 12 kV, 50 Hz. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

are possible. The guaranteed lifetime is defined at nominal operation conditions, that is at rated voltage and an average ambient temperature of 35 °C, unless otherwise specified. According to EN 60831 [1] and EN 60871 [2], operation of capacitors with higher voltages and higher currents than the nominal values is allowed depending on the duration. Current loading and overvoltage stress reduce the lifetime of the capacitors.

Figure 7.9 indicates the reduction of the lifetime of capacitors with a rated life of 100 000 hours of operation for increased operating temperature. As can be seen from the figure, the lifetime is reduced by 50% for a temperature increase of 7 °C.

7.7.2 *Influence of Operating Voltage*

The relationship between the lifetime of capacitors and operating voltage is outlined in Figure 7.9. IEC 60252-1 [3] describes a method for determining the lifetime of power capacitors with increased voltage U_{Test} during a high-voltage test, U_r being the rated voltage of the capacitor. The test results are multiplied by a correction factor k according to

$$k = \left(\frac{U_{Test}}{U_r}\right)^7 \tag{7.18}$$

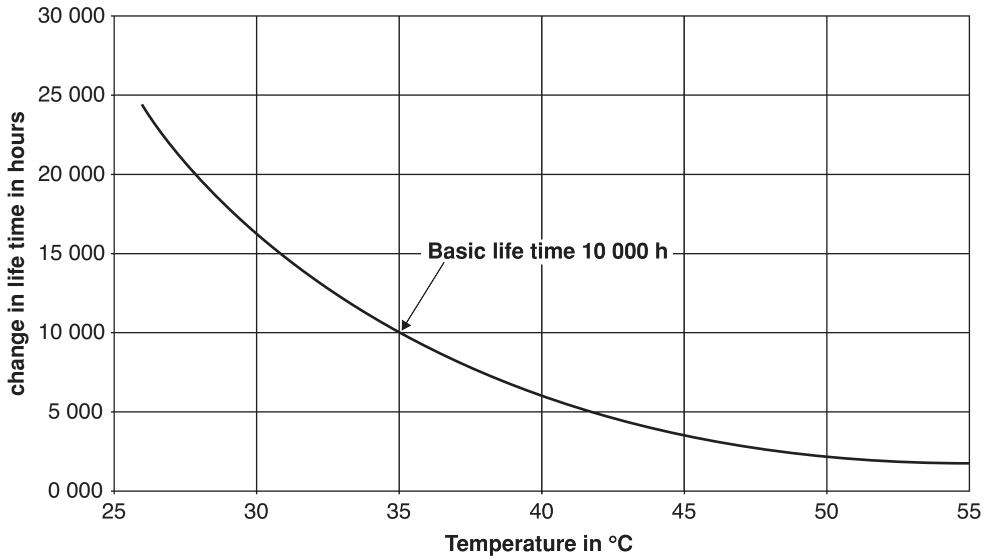


Figure 7.9 Reduction in lifetime of capacitors as a function of temperature.

Although this correction factor *k* was developed for capacitors with paper insulation, which have a significantly higher loss factor than capacitors with standard plastic film insulation, the result can also be applied to paper-insulated capacitors. The increase of continuous operation voltage by 11% reduces the lifetime by 50% as can be seen in Figure 7.10.

The rated voltage of capacitors therefore should be selected according to the actual intended operating voltage.

The new document IEC 33/453/CDV:2009 [4] defines, besides other parameters, four classes of capacitors with different life expectancy as outlined in Table 7.1. Capacitors should be

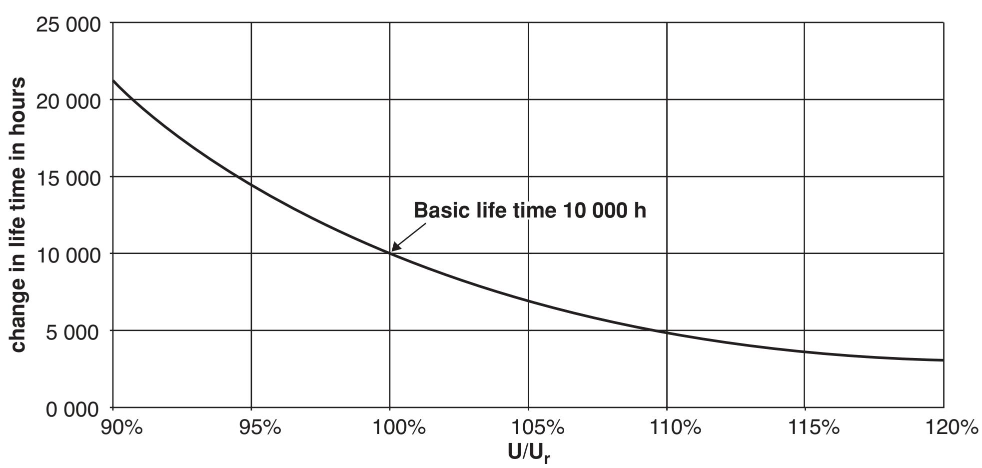


Figure 7.10 Capacitor lifetime as a function of operating voltage.

Table 7.1 Conditions for endurance test of capacitors.

Class of operation	Class A	Class B	Class C	Class D
Life expectancy	30 000 h	10 000 h	3000 h	1000 h
Test conditions	6000 h at $1.25 \cdot U_r$ or 3000 h at $1.35 \cdot U_r$	2000 h at $1.25 \cdot U_r$ or 2000 h at $1.35 \cdot U_r$	2600 h at $1.25 \cdot U_r$	200 h at $1.25 \cdot U_r$

tested with different voltage levels and different test durations in the course of an endurance test procedure.

The test voltage should be applied continuously during the test; a change in the capacitance is permitted during the test but not exceeding 3%. Test durations for life expectancy classes over 30 000 h should be 10% of life expectancy at $1.35 \cdot U_r$ and 20% of life expectancy at $1.25 \cdot U_r$.

The operating classes represent a probable failure rate (short circuits, interruptions, leakage of liquid, change of capacitance exceeding 10% of the rated tolerance limit) not exceeding 3% during the lifetime of the capacitor.

The rated voltage of capacitors therefore should be selected according to the actual intended operating voltage.

7.7.3 Ageing in the Case of Detuned Capacitors

The reduction of lifetime has to be considered as well in the case of detuning capacitor banks by means of a series connection with reactors (see Chapter 19). Ageing of capacitor banks is characterized by a reduction in the capacitance value of the capacitor. A change in the inductance value of the reactor can be neglected. The reduction in the capacitance value therefore results in an increase in the resonance frequency of the detuned capacitor bank. The detuning factor is

$$p = \frac{X_D}{X_C} = L \cdot C \tag{7.19}$$

and the resonance frequency is

$$f_{res} = \frac{f_1}{\sqrt{p}} = \frac{f_1}{\sqrt{L \cdot C}} \tag{7.20}$$

where

$X_D =$ reactance of the detuning reactor
$X_C =$ reactance of the capacitor
$L =$ inductance
$C =$ capacitance
$f_1 =$ fundamental frequency

The fundamental current is reduced by this, but the harmonic currents are increasing due to a shift in the resonance frequency, resulting in an increase in the rms value of the current and an increase of capacitor losses which lead to an increase in the internal temperature of the capacitor.

7.7.4 Ageing due to Switching Operations

In most capacitor installations, electromechanical air contactors are used for switching. Each switching operation (closure) causes an inrush current, the peak value depending on various factors such as switching time, number of parallel capacitors, and so on. The inrush current increases the thermal stress of the capacitors, and thus has an influence on the lifetime. The relation between the number of switching operations and the reduction of lifetime is unpredictable. IEC 60831 defines the number of switching operations as 5000 per year for LV installations [1]; in MV installations the number of switching operations should be limited according to IEC 60871 to 1000 operations per year [2]. It is recommended that these limits are applied to reduce the influence of switching operations on the reduction of lifetime to the lowest extent.

7.8 Summary

This chapter described the design and arrangement of capacitors for LV capacitors as well as for MV capacitors. In principle all capacitors are constructed from two metallic areas insulated by a very thin dielectric that can withstand very high electric field strength up to 75 kV/mm [5]. The chapter also underlined the different technologies used to design and assemble LV and MV capacitors.

Furthermore, it was emphasized that the instantaneous current in a capacitor depends mainly on the fluctuation of the voltage as well as its value of capacitance ($i = C \cdot du/dt$).

Examples of how to calculate the total capacitance of several capacitor elements to be connected in parallel or series have been discussed.

Finally, those factors which influence the life expectancy of capacitors were outlined in detail.

References

[1] IEC 60831. *Shunt power capacitors of the self-healing type for AC systems having a rated voltage up to and including 1000 V.*
[2] IEC 60871. *Shunt power capacitors of the self-healing type for AC systems having a rated voltage above 1000 V.*
[3] IEC 60252-1. *AC motor capacitors – Part 1: General – Performance, testing and rating – Safety requirements – Guidance for installation and operation.*
[4] IEC 33/453/CDV:2009. *AC motor capacitors – Part 1: General – Performance, testing and rating – Safety requirements – Guidance for installation and operation.*
[5] MSD extract, page 2, from Electronicon Kondensatoren GmbH, Gera, Germany.

8

Determination of Required Power of Capacitors

8.1 Chapter Overview

This chapter introduces methods to calculate the required power of capacitors or compensation banks with respect to lagging reactive power of the consumers to be expected. It considers whether partial or full compensation to unity should be favoured. Further, existing compensation banks have to be taken into account as well.

In order to achieve an effective compensation of consumers' reactive lagging power, their demand must be known. The best information on this is given by monthly energy invoices with respect to the consumption of reactive energy. Section 8.3 describes the calculations with respect to plants to be designed from the outset. Chapter 10 on the contrary deals with the extension of existing plants for newly installed consumers.

Essential clues are given by the national energy supplier; for example, which target power factor should be followed, as well as national standards. For this purpose the best cooperation is between the customer, responsible engineers, manufacturers of the capacitors (see Section 7.2), the installer and the electricity supplier. In the extension of an existing plant additional costs could be charged by the supplier with regard to the provided apparent power (kVA) when it becomes necessary, besides a guaranteed minimum of energy consumption.

8.2 Basics of Calculation

As mentioned in Chapter 1, it is best to use the power and current triangles, as shown here in Figure 8.1. The different kinds of power are calculated in single-phase AC systems by the factors of voltage and current as follows:

$$\text{Active power} \quad P = U \cdot I_a \tag{8.1}$$

$$\text{Apparent power} \quad S = U \cdot I \tag{8.2}$$

$$\text{Reactive power} \quad Q = U \cdot I_r \tag{8.3}$$

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

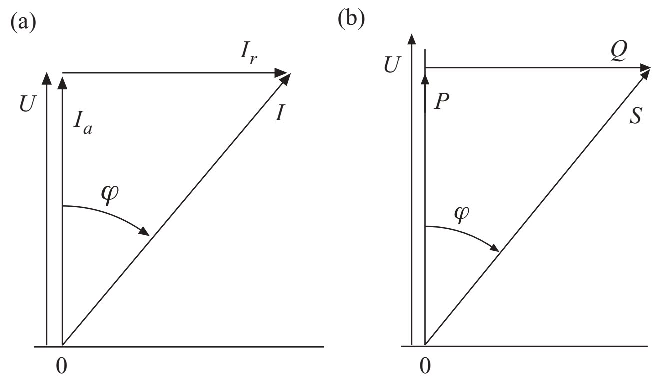


Figure 8.1 Orthogonal component analysis of power and current triangles with reference to vector $\underline{U}$.

where
I_a = active current
I = apparent current
I_r = reactive current
U = system voltage

and

$$\cos\varphi = \frac{I_a}{I}$$

$$\text{Apparent current} \quad I = \sqrt{I_W^2 + I_r^2}$$

$$\text{Active current} \quad I_W = \sqrt{I^2 - I_r^2}$$

$$I_a = I \cdot \cos\varphi$$

$$\text{Reactive current} \quad I_r = \sqrt{I^2 - I_a^2}$$

$$I_r = I \cdot \sin\varphi$$

$$\cos\varphi = \frac{P}{S}, \quad \tan\varphi = \frac{Q}{P}$$

$$\text{Apparent power} \quad S = \sqrt{P^2 + Q^2}$$

$$\text{Active power} \quad P = \sqrt{S^2 - Q^2}$$

$$P = S \cdot \cos\varphi$$

$$\text{Reactive power} \quad Q = \sqrt{S^2 - P^2}$$

$$Q = S \cdot \sin\varphi$$

In three-phase AC systems all values have to be multiplied by a factor of $\sqrt{3}$; further, the delta voltage (line to line) is used for correct calculation.

This method of calculation is limited to time courses of voltage and current similar to sinusoidal forms. For so-called 'nonlinear consumers' this method is not immediately applicable. These kinds of consumers do not draw overcurrent linear to the time course of the voltage. Typical time course current is shown in Figure 21.6a at a six-pulse rectifier. Similar functions are given with modern electronic DC supplying components, for example inside TVs, PCs and energy-saving lamps, to mention just a few. They draw overcurrent for about 2–3 ms if the voltage passes the peak value on the AC side (see Figure 21.1). Although all these 'nonlinear consumers', for example in a TV shop, are connected to the three phases symmetrically, one finds that the current on the neutral conductor does not become zero, as expected, but is overcharged or even overheated (see Figure 19.16b)! This underlines that the triangle method is invalid for nonlinear functions regarding voltage and current. This problem will be discussed in Chapter 21.

First of all, consumers with linear characteristics should be considered. Thus the terms $\cos\varphi_1$ or simply $\cos\varphi$ are to be seen as suitable for sinusoidal or similar procedures exclusively, but not for pulsing procedures.

The triangles in Figure 8.2a-c illustrate the compensation of consumers' reactive power (lagging) by different-sized capacitors, connected in parallel (a) partly, (b) fully compensated and (c) overcompensated.

Regarding Figure 8.2a, the leading reactive power of the capacitor is calculated by the following formula:

$$Q_C = P \cdot (\tan\varphi_a - \tan\varphi_d) \tag{8.4}$$

where

angle φ_a = consumers' actual phase angle
angle φ_d = desired phase angle

In the case of full compensation (Figure 8.2b) the pointers of the reactive load Q_L and of the capacitor Q_C have the same size but opposite direction

$$Q_C = Q_L \tag{8.5}$$

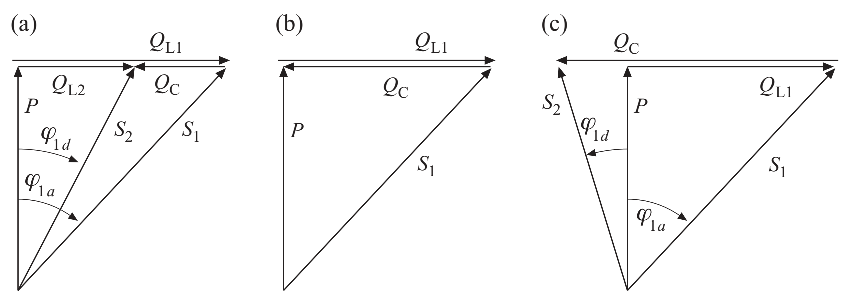


Figure 8.2 Power triangles at (a) partial, (b) full and (c) overcompensation with Q_C = the capacitor's reactive power and Q_L = lagging reactive power.

The power factor increases to unity. Usually the danger of resonance occurs; however, the component of active power becomes effectively a ‘brake’ if one recalls the equivalent mechanical model (Section 1.4).

Figure 8.2c shows the compensation of the same consumer by means of an oversized capacitor. The resulting reactive power becomes a leading characteristic (capacitive). The apparent power S_2 increases again as well as the apparent current. This is followed by higher active power losses on the feed-in cables or busbars respectively. In the overcompensated condition a voltage increase is expected as shown in Figure 8.3b. The location of the so-called Kapp’s triangle causes a higher voltage U_2 at the terminals of the consumer and the capacitor than the voltage U_1 at the feed-in terminals.

Thus overcompensation should be avoided for longer periods, because it could become hazardous, for example in bulbs or other sensitive consumers.

As described in Chapter 10, many industrial plants have feed-in transformers, where the metering equipment is located at the MV side. The reactive energy demand of the transformer will be accounted for, of course. For this purpose it is common practice to install a capacitor at the secondary side of the transformer in order to reduce the reactive energy to be metered. However, if the consumption decreases or even goes down to zero, for example during the night, this fixed connected capacitor causes an increase in the voltage. This increase is usually very small due to the fact that the size of the capacitors for transformers is limited by national standards. The internal rules of electricity suppliers sometimes prescribe that the capacitor

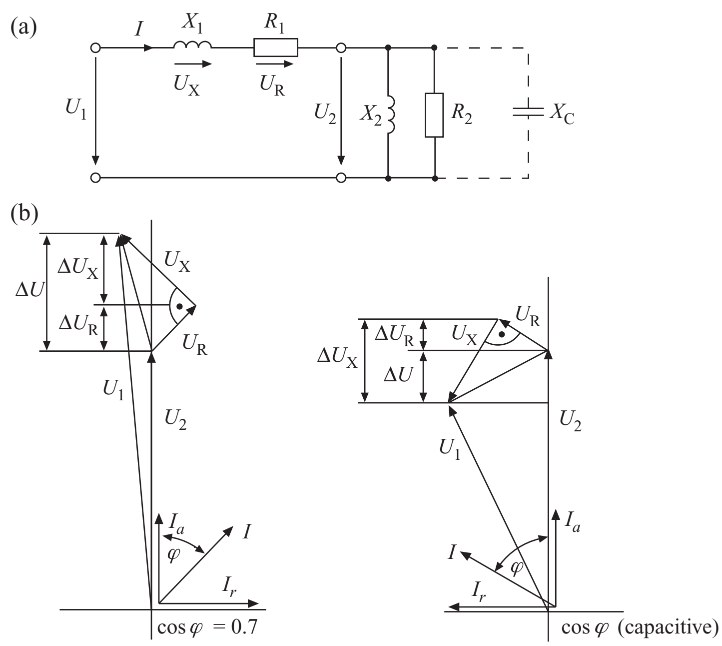


Figure 8.3 Simplified circuit diagram of an electrical network (a) with the relevant orthogonal vectors (b) with predominant inductive load (left) and predominant capacitive load (right).

has to be switched off during low-load periods[1]. For example, in urban networks the energy supply runs via cables. However, cables have capacitive characteristics, so uncompensated transformers compensate the leading reactive power in a reverse fashion. The same situation occurs in overhead lines on the railways. As the overhead wire represents a capacitance, for compensation purposes one can see an inductance coil fitted on a mast after several miles (see cover-page illustration at the bottom right).

The calculation of the relative voltage increase is from the following formula:

$$\Delta u = \frac{u_k \cdot Q_C}{S_r} \tag{8.6}$$

where

$\Delta u =$ relative voltage increase (%)
$u_k =$ impedance voltage (%)
$S_r =$ rated apparent power of the transformer (kVA)
$Q_C =$ reactive power of the capacitor (kvar)

As mentioned in Section 4.4, many electrical power utilities charge for reactive energy consumption below an achieved average power factor per month (the billing period) below 0.9 lagging. Sometimes contracts allow individual regulations to be negotiated between each party. In other words, this means that if the daily consumption of reactive energy increases above that of active energy by more than 50%, additional costs will be charged for the reactive energy.

Other suppliers charge for each reactive energy (kvarh) consumption at a power factor less than 1, even on the leading side as well. For this purpose special metering equipment, counting up each kvarh for the leading and lagging side separately, has been developed. Thus the consumer is obliged to compensate fully to unity (see Figure 8.2b).

Other contracts provide charges for apparent energy consumption (kVAh). The goal of this regulation is to achieve a monthly average power factor of 1 and the compensation bank has to be sized for the maximal reactive power (lagging) to be expected (see Chapter 4).

However, the most popular tariff is to achieve a monthly average power factor higher than 0.9 lagging. Any new industrial plant has to consider the costs, for example, for the compensation bank(s). Installing compensation calculated to achieve a power factor of 1 on average requires about 80% more capacitance compared with compensation achieving 0.9 lagging!

As shown in Figure 6.5, additional active power losses on feed-in lines at partial compensation, to be measured by active energy meters, would amortize the more expensive bank quicker. Further, it is taken into account that capacitor banks are installed mainly at the LV side and energy metering equipment at the MV side (see Chapter 11 on control of reactive power).

8.3 Determination of Compensation at New Projected Plants

In general it is difficult to calculate the average power factor of new machines, because it depends on the individual load conditions and the time periods during which they are running in parallel or not.

[1] Essential information are available by the local electricity supplier or electrical power utility.

Table 8.1 Approximate values of power factor cos φ referring to different industrial plants.

Type of plant	Average power factor cos φ (without compensation)
Food industry	
Butcheries	0.6–0.7
Bakeries	0.6–0.7
Dairies	0.6–0.8
Mills	0.6–0.7
Breweries	0.6–0.7
Cold-storage buildings	0.6–0.7
Wood industry	
Sawmills	0.5–0.7
Driers	0.8–0.9
Furniture factories	0.6–0.7
Metal processing industry	
Tooling machines	0.4–0.6
Welding machines	0.6–0.65
Cranes	0.5–0.6
Water pumps	0.8–0.85
Mechanical workshops	0.5–0.6
Ventilators	0.7–0.8
Compressors	0.7–0.8
Foundries	0.6–0.7

It would be wrong to calculate an average power factor from the technical data printed on the nameplate of each motor, as these data represent the values at nominal conditions. Recall, for example, that punching machines in a car factory spend most of their operating hours in an idle condition, which results in a low power factor. Further, ohmic consumers influence the average power factor as well – they may even improve it – but they do not reduce the demand of reactive power.

Table 8.1 lists some typical plants of different industries and their approximate power factors. This gives a rough idea of values for further calculations. To determine an approximate capacitor bank by excluding the calculated power factor is impossible. The power factor itself does not say anything about the amount of consumers' reactive power to be expected. It is simply the ratio of active to apparent power! Therefore the rated active power of the electric motors has to be included in the calculations, as shown in the following example.

Example: The electrical arrangement is to be planned for a new, small mechanical workshop. It contains consumers with the demand of reactive power as listed below.

The aim is to determine the new compensation bank with regard to a requested target power factor of cos $\varphi_d = 0.9$. From Table 8.1 one can estimate an average cos $\varphi_a = 0.6$.

The sum of all machines listed in Table 8.2 (electrical active power P_1, not the mechanical one) is 31 kW. Since not all the motors are running synchronously, a requested factor is to be considered with an estimate of 0.3 as a realistic value. Any additional ohmic consumers are not taken into account; they do not influence the demand of reactive power.

Table 8.2 Efficiency of different industrial machines.

Number	Motor	P_2 (mechanical)	η (%)	P_1 (electrical)
1	Tinshears	3.00	84	3.57
1	Sawing machine	4.00	83	4.82
1	Crane motors	1.60	82	1.95
1	Compressor	3.00	83	3.61
1	Milling machine	3.50	84	4.17
1	Drilling machine	5.50	86	6.40
1	Ventilator	0.35	70	0.50
1	Punching machine	5.00	83	6.02
	Total			31.04

Therefore the average active power P_1 taking into account the factor $\alpha = 0.3$ results in

$$P = P_{\max} \cdot \alpha = 31\,\text{kW} \cdot 0.3 = 9.3\,\text{kW}$$

The capacitor bank to be installed in order to improve the actual power factor of $\cos\varphi_a = 0.6$ to the desired $\cos\varphi_d = 0.9$ can be calculated from

$$Q_C = P \cdot (\tan\varphi_\text{a} - \tan\varphi_\text{d}) = 9.3\,\text{kW} \cdot (1.33 - 0.48) = 7.9\,\text{kvar}$$

If available on the market, a 10 kvar compensation unit should be sufficient.

Incidentally, remember that the compensation reduces the apparent power input to be declared at the electricity company, which charges less for it (see Chapter 4).

Some example calculations are

$$\overset{\text{without compensation}}{S_1 = \frac{P}{\cos\varphi_a} = \frac{9.3\,\text{kW}}{0.6} = 16\,\text{kVA}}, \quad \overset{\text{with compensation}}{S_2 = \frac{P}{\cos\varphi_d} = \frac{9.3\,\text{kW}}{0.9} \approx 10\,\text{kVA}}$$

Higher compensation, for instance to $\cos\varphi = 0.98$, reduces the apparent power to be ordered further on:

$$S_3 = \frac{9.3\,\text{kW}}{0.98} = 9.5\,\text{kVA}$$

Note that, up to now, any additional ohmic consumers are not taken into account. They increase the apparent power to be declared, of course.

Listed in Table 8.3 are several conversion values for easier determination of the reactive power to be compensated with respect to the different power factor demanded ($\cos\varphi_d$).

Table 8.3 Conversion values ($\tan \varphi_a - \tan \varphi_d$).

At a given		Requested power factor										
tan φ_a	cos φ_a	cos $\varphi_d =$ 0.70	cos $\varphi_d =$ 0.75	cos $\varphi_d =$ 0.80	cos $\varphi_d =$ 0.82	cos $\varphi_d =$ 0.85	cos $\varphi_d =$ 0.87	cos $\varphi_d =$ 0.90	cos $\varphi_d =$ 0.92	cos $\varphi_d =$ 0.95	cos $\varphi_d =$ 0.97	cos $\varphi_d =$ 1.00
4.90	0.20	3.88	4.02	4.15	4.20	4.28	4.33	4.41	4.47	4.57	4.65	4.90
3.87	0.25	2.85	2.99	3.12	3.17	3.25	3.31	3.39	3.45	3.54	3.62	3.87
3.18	0.30	2.16	2.30	2.43	2.48	2.56	2.61	2.70	2.75	2.85	2.93	3.18
2.68	0.35	1.66	1.79	1.93	1.98	2.06	2.11	2.19	2.25	2.35	2.43	2.68
2.29	0.40	1.27	1.41	1.54	1.59	1.67	1.72	1.81	1.87	1.96	2.04	2.29
2.16	0.42	1.14	1.28	1.41	1.46	1.54	1.59	1.68	1.74	1.83	1.91	2.16
2.04	0.44	1.02	1.16	1.29	1.34	1.42	1.47	1.56	1.62	1.71	1.79	2.04
1.93	0.46	0.91	1.05	1.18	1.23	1.31	1.36	1.45	1.50	1.60	1.68	1.93
1.83	0.48	0.81	0.95	1.08	1.13	1.21	1.26	1.34	1.40	1.50	1.58	1.83
1.73	0.50	0.71	0.85	0.98	1.03	1.11	1.17	1.25	1.31	1.40	1.48	1.73
1.64	0.52	0.62	0.76	0.89	0.94	1.02	1.08	1.16	1.22	1.31	1.39	1.64
1.56	0.54	0.54	0.68	0.81	0.86	0.94	0.99	1.07	1.13	1.23	1.31	1.56
1.48	0.56	0.46	0.60	0.73	0.78	0.86	0.91	1.00	1.05	1.15	1.23	1.48
1.40	0.58	0.38	0.52	0.65	0.71	0.78	0.84	0.92	0.98	1.08	1.15	1.40
1.33	0.60	0.31	0.45	0.58	0.64	0.71	0.77	0.85	0.91	1.00	1.08	1.33
1.27	0.62	0.25	0.38	0.52	0.57	0.65	0.70	0.78	0.84	0.94	1.01	1.27
1.20	0.64	0.18	0.32	0.45	0.50	0.58	0.63	0.72	0.77	0.87	0.95	1.20
1.14	0.66	0.12	0.26	0.39	0.44	0.52	0.57	0.65	0.71	0.81	0.89	1.14
1.08	0.68	0.06	0.20	0.33	0.38	0.46	0.51	0.59	0.65	0.75	0.83	1.08
1.02	0.70	—	0.14	0.27	0.32	0.40	0.45	0.54	0.59	0.69	0.77	1.02
0.96	0.72	—	0.08	0.21	0.27	0.34	0.40	0.48	0.54	0.63	0.71	0.96
0.91	0.74		0.03	0.16	0.21	0.29	0.34	0.42	0.48	0.58	0.66	0.91
0.86	0.76		—	0.11	0.16	0.24	0.29	0.37	0.43	0.53	0.60	0.86
0.80	0.78			0.05	0.10	0.18	0.24	0.32	0.38	0.47	0.55	0.80
0.75	0.80			—	0.05	0.13	0.18	0.27	0.32	0.42	0.50	0.75
0.70	0.82				—	0.08	0.13	0.21	0.27	0.37	0.45	0.70
0.65	0.84					0.03	0.08	0.16	0.22	0.32	0.40	0.65
0.59	0.86					—	0.03	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									—	0.01	0.29
0.20	0.98										—	0.20

Example 1: An asynchronous motor with a rated active power of $P_r = 60$ kW has to be compensated.

One finds, from Table 8.3, first column, that $\tan \varphi_a = 1.33$ besides $\cos \varphi_a = 0.6$ in the second. Thus the reactive power of the motor can be calculated from

$$Q = 60\,\mathrm{kW} \cdot 1.33 \approx 80\,\mathrm{kvar}$$

For full compensation to unity ($\cos \varphi_d = 1$) an automatic compensation bank (see Chapter 9) would switch in 80 kvar. However, the demand of reactive power decreases a little when the load conditions are lower than rated. Thus overcompensation could occur. There it is preferable to choose a power factor demand of, for example, $\cos \varphi_d = 0.9$. Table 8.3 indicates, for $\cos \varphi_d = 0.9$, a conversion value of 0.85 at $\cos \varphi_a = 0.6$. Consequently the following reactive power (leading) is requested:

$$Q_C = P \cdot 0.85 = 60\,\mathrm{kW} \cdot 0.85 = 51\,\mathrm{kvar}$$

Another method to determine the requested capacitor size is shown in Figure 8.4.

Choose from the left scale the actual $\cos \varphi_a$ and from the right scale the requested $\cos \varphi_d$. A line connecting these two values crosses the middle scale K. Referring to the example above, the line crosses the scale at 0.85 exactly.

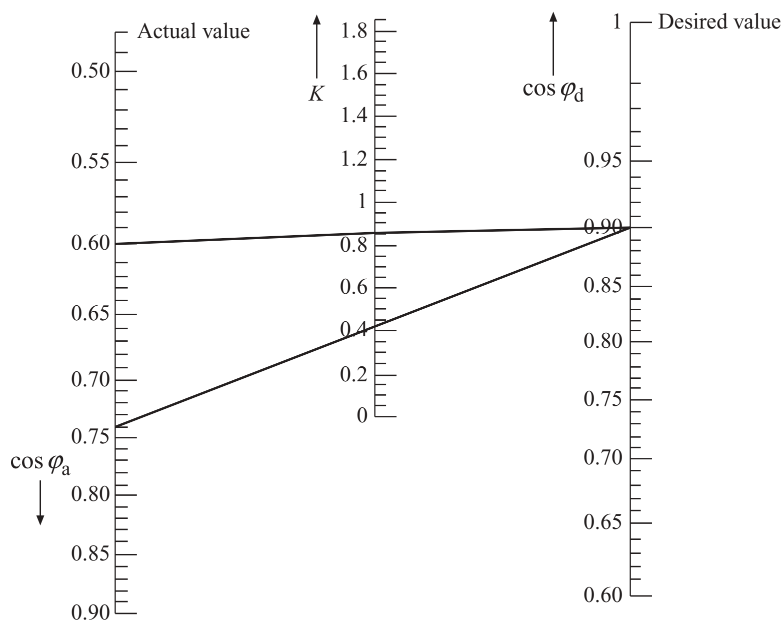


Figure 8.4 Nomograph for the determination of capacitor size regarding compensation of reactive power.

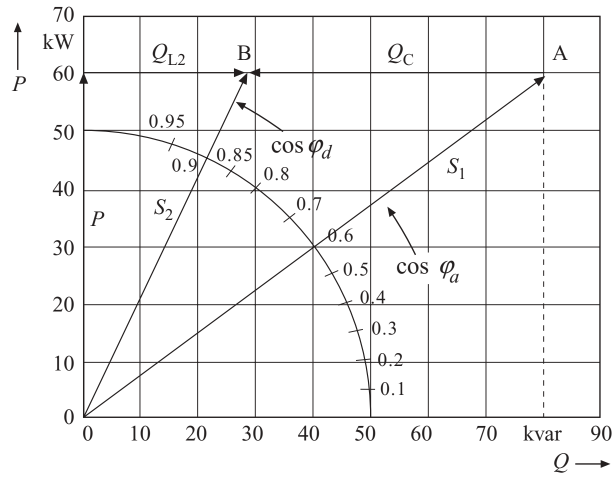


Figure 8.5 Graphical determination of capacitor size regarding compensation of reactive power.

Example 2: A motor with an active power of 200 kW and nominal cos $\varphi_a = 0.74$ has to be compensated to the desired cos $\varphi_d = 0.9$. What capacitor size is necessary?

The line between 0.74 (left scale) and 0.9 (right scale) crosses the middle scale at the value of 0.42. Thus the requested reactive power of the capacitor is

$$Q_C = 200\,\text{kW} \times 0.42 = 84\,\text{kvar}$$

Another method is given in a graphical way using the coordinate system shown in Figure 8.5. The vertical axis scale is for active power, the horizontal one for reactive power. A quadrant between two identical values (here '50') on the rectangular axes is scaled with cos φ values. Most manufacturers of compensation banks offer special software for calculation tasks.

The best explanation is given in the following example.

Example: In a planned new industrial plant, it has been decided to have an average active power of 60 kW at an average power factor of cos $\varphi_a = 0.6$. Using the coordinate system shown in Figure 8.5, the triangle 0–A–60 kW is constructed. Then a line is drawn parallel to the horizontal axis (reactive) at a level of 60 kW. Another line from the origin crosses the arc scale at 0.6 and then up to A determines first of all the requested capacitor size for full compensation. Another line from the origin crosses the arc scale at the desired cos $\varphi_d = 0.9$ and meets at B. Thus the line A to B represents the capacitor size Q_C to be installed. The distance from the vertical axis to B represents the part Q_{L2} to be uncompensated. Identical scaling on both axes for the line A to B represents approximately $Q_C = 50$ kvar. Further, the lengths of the lines 0 to A and 0 to B show the uncompensated and compensated apparent powers, respectively.

In general it is essential to estimate any influences from new equipment to be installed or other modifications with regard to the power quality. As mentioned in Section 8.2, modern ‘nonlinear consumers’ influence the quality of the voltage disadvantageously. Any problems arising from this are commented upon in Chapters 17–20.

8.4 Summary

This chapter introduced several methods to determine the required reactive power of capacitors for compensating inductive loads. Examples in practice were described in calculations or by means of graphical methods. These should be of help before ordering capacitors.

Nowadays many manufacturers of power capacitors are able to transmit relevant computer programs for determining the required capacitors. However, it may be that in very complicated industrial plants, specific individual software has to be developed. Thus this chapter gives a common overview of the basics of this.

Reference

[1] Gaus, J. (1987) Investigation of the need of reactive power compensation in networks distributing energy via cables mainly. Diploma. Ruhr-University.

9

Types of Reactive Power Compensation

9.1 Chapter Overview

In general there are three types of compensation applicable:

1. Single-type compensation.
2. Bulk-type compensation.
3. Central-type compensation.

Sometimes, in large plants, one finds a mixture of all three types. The first rule is to unburden the feed-in leads, cables or busbars, by compensating the reactive power of the consumers as much as possible. The location of compensation banks therefore should be close to the inductive consumers. Current-limiting inductors on fluorescent tubes, for instance, should be connected to a fixed capacitor inside the equipment, because they usually have a very low power factor below 0.6. One part of reactive power increases one part of active power significantly. Thus it does not make sense to compensate all fluorescent tubes or lamps in, say, a huge office building via an automatic bank located in the basement!

For compensation tasks therefore, one distinguishes between power capacitors and capacitors for fluorescent tubes or lamps below 1.5 kvar (DIN VDE 0560).

9.2 Single-Type Compensation

Figure 9.1 shows a typical single-type compensation by a capacitor determined according to Section 8.3, connected in parallel to the motor. Thus the reactive power oscillates between the capacitor and motor via a short cable. A suitable circuit breaker connects both components directly. This single-type compensation has several advantages:

- Saves a separate contactor for the capacitor.
- Saves extended installations.

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

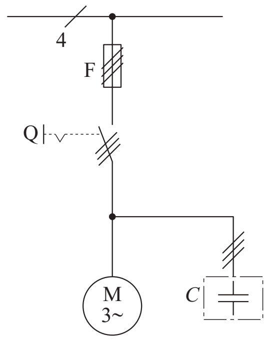


Figure 9.1 Single-type compensation.

- Full or partial discharge of the feed-in lines by reactive power.
- Possibility to combine both components in one casing.
- Reduction of active power losses on the feed-in leads.
- Installation of an automatic power factor relay becomes superfluous.

Single-type compensation should be applicable if the inductive consumer is working for more than 50–70% of the time, preferably at constant or rated power. Typical applications for this method of compensation are in asynchronous motors, (welding) transformers or fluorescent lamps with series inductors.

9.2.1 Single-Type Compensation in Asynchronous Motors

9.2.1.1 Basics

Asynchronous motors request reactive power for the magnetic field to be polarized 50 or 60 times a second. The amount of reactive power depends on the revolutions per minute and the rated active power. According to Table 2.1, one can see that running motors slowly (1500 rpm) requires more reactive power than running them quickly (3000 rpm). This influences the final power factor of course.

The apparent current of the motor depends on the load condition (active current I_a) and the magnetizing current (reactive current I_r), written mathematically as

$$I = \sqrt{I_a^2 + I_r^2} \tag{9.1}$$

The current of a motor running in an idle condition is determined mainly by the reactive current as the active current decreases down nearly to zero. A small part is required for losses in copper and iron and for overcoming mechanical friction. With decreasing active current (power) the power factor $\cos\varphi$ also becomes worse. Figure 9.2 outlines the functions of active current I_a, I_r and power factor $\cos\varphi$ depending on the load condition of the motor. The reactive current (power) varies over a small bandwidth parallel to the horizontal axis of the coordinate system. It is based on constant values of the iron volume on one side and the air gap on the other side. The cause of this small variation is found in the magnetic leakage field and

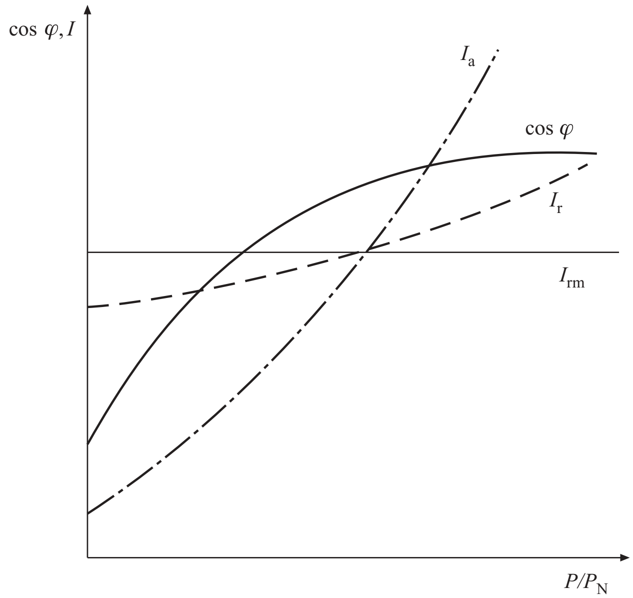


Figure 9.2 Functions of power factor cos φ, active current I_a, reactive current I_r depending on load condition P/P_N. I_{rm} represents the value of reactive current on average.

the nonlinear function of magnetizing the iron. If it were linear, the reactive current (power) would be constant over all load conditions, as shown by the line I_{rm}. It represents the average value of the reactive current (power).

Picking out one example of a 90 kW motor in Table 2.2, the reactive power varies between 33 kvar in idle condition and 52 kvar at full load. The average value (I_{rm}) is about 42 kvar, which means that the reactive power varies by just ± 10 kvar. The nameplates on motors always indicate the power factor at full-load condition. These data enable the requested reactive power to be calculated as follows.

Example: The nameplate of an asynchronous generator indicates $P = 80$ kW with a nominal power factor of cos $\varphi = 0.88$. Determine the reactive power required.

For this purpose the following formula can be used:

$$Q = P \cdot \tan \varphi \tag{9.2}$$

Thus cos φ has to be converted into tan φ. First of all, with regard to the power triangle (see Figure 1.10b), the angle φ is determined: cos $\varphi = 0.88$ refers to an angle φ of 28.36° and tan 28.36° results in 0.54. Thus, 54% of the active power is requested from the reactive one, therefore $0.54 \cdot 80$ kW $= 43$ kvar. Although the generator exports active power, it imports reactive energy from the network. This is detailed in Chapter 16 ('four-quadrant operation').

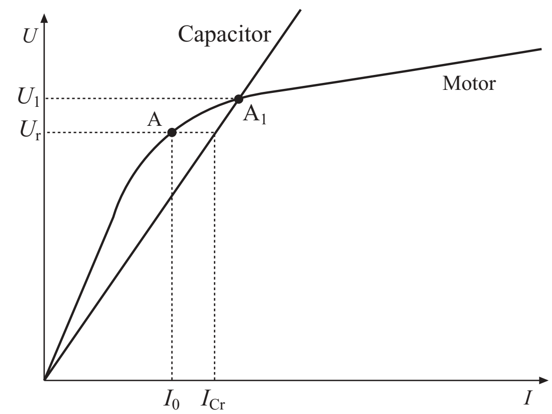


Figure 9.3 Self-exciting compensated motor switched in directly: the motor's magnetizing curve and capacitor's function with reference to voltage and current (I_0 = motor's current in idle condition; I_{Cr} = capacitor's rated current; U_1 = voltage at the terminals of the motor in the self-exciting case; U_r = rated voltage).

9.2.1.2 Self-exciting Motors Switched in Directly

In single-type compensation of asynchronous motors it is worthwhile paying attention to several essential points, as follows.

If the capacitor increases about 90% of the demand of reactive power to be supplied to the motor in idle condition, besides undesired overcompensation, self-exciting and overvoltage could occur during switching off. While the rotor is running down, the motor draws overexciting power from the capacitor. Figure 9.3 outlines the functions of the motor and capacitor depending on voltage and current. The operating point A lies below the saturation point and represents the no-load current at rated voltage U_r. Suppose that more than 90% of the motor's demand of reactive power is now compensated; then one can see that the current of the capacitor is higher than that of the motor at rated voltage U_r.

In switching off the motor and the capacitor (they are connected in parallel) the voltage suddenly increases up to operating point A_1 by a self-exciting procedure. This overvoltage could become hazardous at the terminals with regard to flashover, if industrial dirt is found between them. Due to the electrical losses in copper and iron, the revolutions of the rotor decrease finally to zero. This reduces the self-exciting voltage.

9.2.1.3 Self-exciting Asynchronous Motors to be Started via Star/Delta Connection

The overvoltage may become significantly higher if the motor is started via star/delta connection and after disconnection the capacitor remains connected in parallel to the coils of the motor to be switched into the star position. The motor changes into generator mode and draws over the exciting current from the capacitor. If the rotor is still running, the generated voltage at the terminals may increase to a dangerous amount. Figure 9.4 outlines the operating characteristics of the motor and generator. The capacitor has the well-known linear characteristic

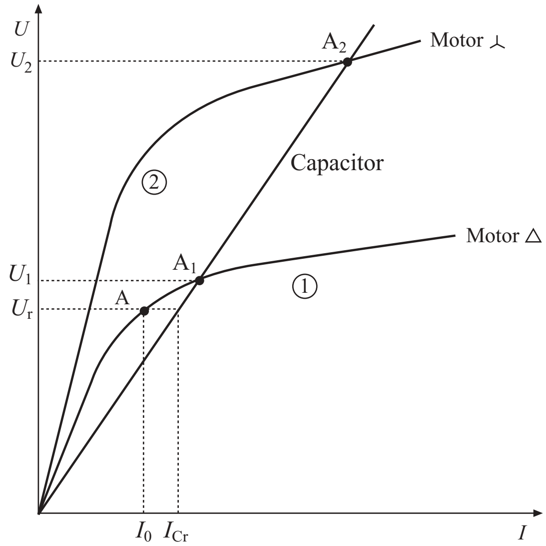


Figure 9.4 Self-exciting compensated motor started by star/delta switching: the motor's magnetizing curve and capacitor's linear function with reference to voltage and current (I_0 = motor's current in idle condition; I_{Cr} = capacitor's rated current; U_1 = voltage at the terminals of the motor in the self-exciting case; U_2 = self-exciting voltage at the motor's terminals in star connection; U_r = rated voltage).

as in Figure 9.3. The electrical characteristic is nonlinear due to the magnetizing procedures running into the saturation area. Figure 9.4 shows two different characteristics, line 1 for operation in delta mode and line 2 for operation in star mode. The crossing point A_2 of line 2 with the electrical characteristic line of the capacitor indicates a dangerous voltage, about 2.5 to 3 times higher than the rated voltage U_r.

The same condition may occur if any protective device like an overcurrent trip disconnects both components from the grid at the same time. Even brief interruptions during changeover from the star to delta connection, and vice versa, represent the same situation. Furthermore, the charged capacitor could get a reverse voltage, which causes very high current peaks.

9.2.1.4 Instructions for Single-Type Compensation of Motors

From an economic point of view, single-type compensation is recommended for motors/generators below 15 kW only. As mentioned above, the determination of the capacitor size should be below 90% of the reactive power demand in the no-load condition in order to avoid any overexcitation and voltage peaks. In three-phase AC networks the following formula is used to determine the capacitance:

$$Q_C = 0.9 \cdot \sqrt{3} \cdot U_r \cdot I_0 \tag{9.3}$$

I_0 represents the current of the motor in idle condition.

In case I_0 is unknown and not available from any documentation or instructions, it is possible to calculate the approximate capacitance by the following formula:

$$Q_C \approx 0.9 \cdot \frac{P_r}{\eta} \left(\frac{1 - \cos\varphi_r}{\cos\varphi_r \cdot \sin\varphi_r} \right) \tag{9.4}$$

where

$P_r =$ rated active power (secondary)
$\eta =$ motor efficacy factor
$\cos\varphi =$ nominal power factor at rated load

Table 9.1 outlines some typical single-type capacitors and their motors with rated active power P_r [1]. Any rules from the local electricity supplier should be followed.

These values are calculated to achieve a desired power factor of approximately 0.95.

Further, the starting mode of the motor must be considered, either switching in directly or via star/delta switching. In general two modes of starting are distinguished:

- the capacitor is connected directly to the motor's terminal (this is the most popular method according to Figure 9.5); or
- the capacitor is switched in via a separate contactor (see Figure 9.7).

These combinations do not require special capacitor fuses because the fuses for the motor grant short-circuit fault protection for the capacitors as well. If a motor protection circuit breaker is used, the overcurrent trip (Figure 9.6) has to be adjusted to a reduced current.

The reduced current I_E to be adjusted may be calculated from two different formulae:

$$\text{either} \quad I_E = \frac{\cos\varphi_r}{\cos\varphi_d} \cdot I_r \tag{9.5}$$

$$\text{or} \quad I_E = \sqrt{I_a^2 + (I_L - I_{Cr})^2} \tag{9.6}$$

where

$I_a = I_r \cdot \cos\varphi_r$

$I_L = \sqrt{I^2 - I_a^2}$

$I_{Cr} = \dfrac{Q_{Cr}}{\sqrt{3} \cdot U}$

with

$I =$ motor's rated current (apparent)
$I_a =$ motor's active current
$I_L =$ motor's reactive current (inductive)
$I_{Cr} =$ capacitor's rated current
$Q_{Cr} =$ capacitor's rated power

In the case of switching in the motor and capacitor directly, there is no need for discharging resistances at the capacitor because the coil of the motor is connected in parallel to the capacitor (see Chapter 15).

Table 9.1 Motors of different rated active power and with rated revolution of 1500 per minute: provided with fixed compensation (single type).

Motor's rated power (kW)	Capacitor's rated power (kvar)
1.0–3.9	≈55% of motor's rated power
4.0–4.9	2
5.0–5.9	2.5
6.0–7.9	3
8.0–10.9	4
11.0–13.9	5
14.0–17.9	6
18.0–21.9	8
22.0–29.9	10
30.0–39.9	≈40% of motor's rated power
Over 40.0	≈35% of motor's rated power

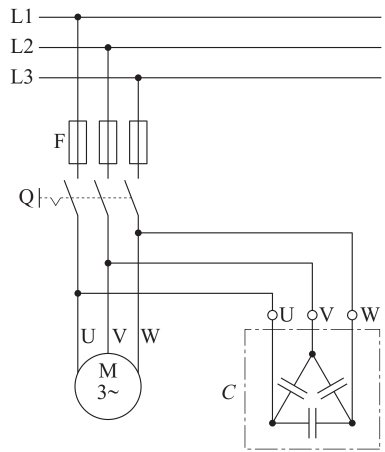


Figure 9.5 Direct switch-in connection for squirrel cage or slip ring motors.

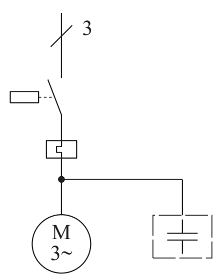


Figure 9.6 Single-type compensation of motors with motor safety switch.

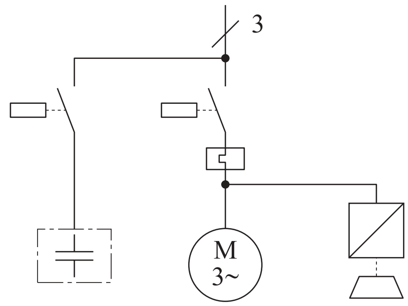


Figure 9.7 Circuit diagram of a crane motor with solenoid actuator and single-type compensation.

Special attention must be paid to motors for applications in cranes, elevators or for braking tasks: one must strictly avoid compensating by capacitors connected directly to the motor. In disconnecting the unit there is a danger of further running on by means of the stored energy in the capacitor. As mentioned in Section 9.2.1.1, there is a possibility of self-exciting the motor after disconnection from the grid if there is a fixed connection between the motor and capacitor. It must be ensured at these plants that the capacitor is disconnected from the motor when switching off the unit. There is the possibility either to install the capacitor before the motor's circuit breaker (see Figure 9.7) or to disconnect the capacitor with a separate circuit breaker (see Figure 9.8). Thus no connection to the motor coil is ensured [1].

Figure 9.7 illustrates a circuit diagram representing a crane motor with a solenoid actuator. The motor and capacitor are controlled by separate circuit breakers. In switching both components via one breaker, the solenoid actuator remains magnetized until the capacitor has been discharged; this means that the load falls off with a time delay.

Even with a reverse-working device (left- or right-turning motors), there is a need for the capacitor to be controlled by a separate circuit breaker as well. This is due to the short time in changing from one turning mode to another, which is insufficient for discharging the capacitor (Figure 9.8).

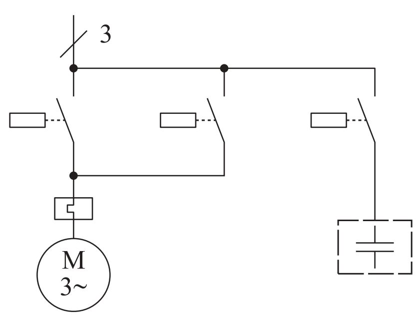


Figure 9.8 Clockwise and anti-clockwise operation with capacitor switched in separately.

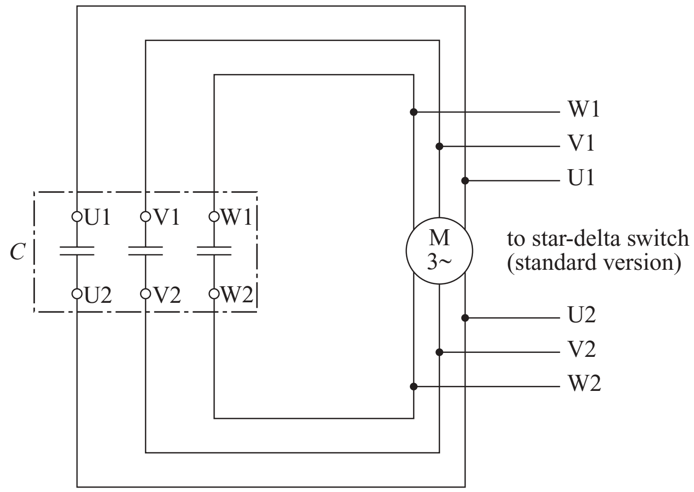


Figure 9.9 Star/delta connection in using a capacitor with six open terminals.

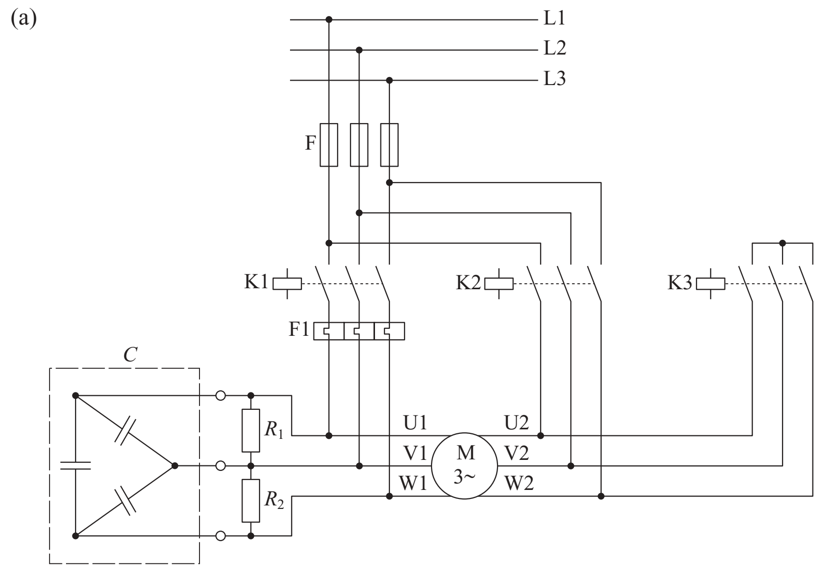
Since the turning mode changes very frequently in motors for cranes, it must be ensured that the capacitor is protected against this. The cheapest and simplest way is to control the capacitor by means of a time-delayed contactor, which disconnects the capacitor during the longer standstill of the motor. In any applications with frequent switching operations it is recommended to use thyristor-controlled capacitors with so-called thyristor tap-changers (see Chapter 14). This enables smooth switching operations without any inrush current peaks due to switching in the voltage synchronously. Mechanical contactors wear out for any switching operation.

For controlling motors (<5 kW), use of a standard star/delta connection is quite sufficient. As mentioned in Section 9.2.1.1, capacitors may not be connected directly to motors (>5 kW); this would cause high wear and tear at the contactors. Further, self-exciting and voltages with reversed polarity could occur.

The use of capacitors with ‘open’ terminals (six-pole version, as shown in Figure 9.9) is very popular.

There is also the possibility to compensate each coil inside the motor (<20 kW approximately) with a single-phase capacitor individually. The rated voltage for the capacitor should be designed for line-to-line voltage at least, due to the fact that the motors will usually be started by star/delta switches. If there is no six-pole capacitor available and motors of more than 20 kW have to be compensated, then it is necessary to control the capacitor (three-pole version) by a separate contactor fitted with discharging resistances (applicable for capacitors; see Chapter 14) according to the method of switching in the capacitor to the motor if it runs exclusively in delta mode. If the cheaper three-pole capacitors are used, there is the possibility to use special star/delta switches that do not interrupt during changing of the mode.

The most practicable solution is to use a separate contactor (applicable for capacitors; see Chapter 14) for the capacitor as shown in Figure 9.10b. This becomes necessary in case of



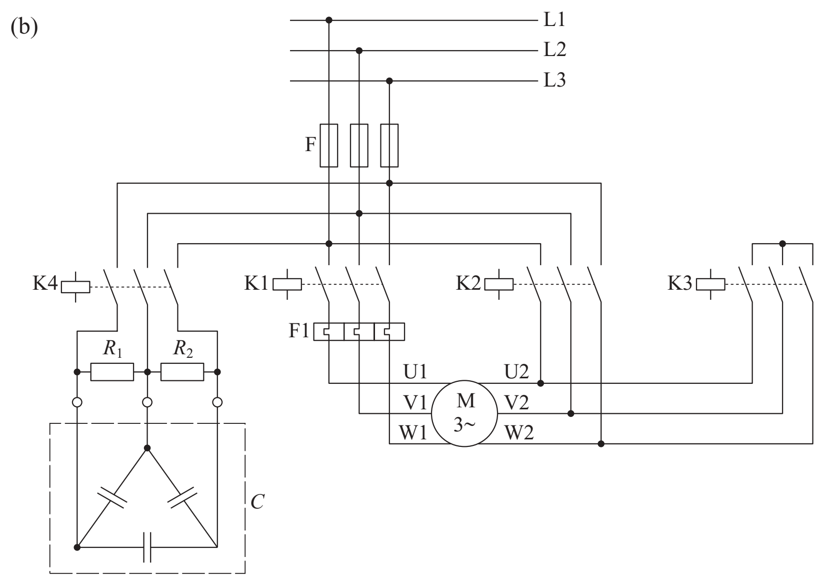


Figure 9.10 Automatic star/delta connection (a) without contactor for the capacitor and (b) with special contactor for the capacitor. K1, grid contactor; K2, delta contactor; K3, star contactor; K4, contactor for the capacitor.

long starting or running out procedures to avoid any self-excitation. The capacitor may be chosen for any motor size.

9.2.2 Single-Type Compensation of Transformers

Power transformers are switched on regularly, day and night. Their demand of reactive power differs depending on the type and brand. In general, during the load period the total reactive power Q_t is composed of two components: reactive power Q_0 during open-circuit operation and reactive power caused by the leakage field at short-circuit reactance.

The following equation describes the total reactive power:

$$Q_t = Q_0 + \frac{u_k}{100} \cdot \left(\frac{S}{S_r}\right)^2 \cdot S_r \tag{9.7}$$

where

u_k = transformer's impedance voltage
Q_0 = reactive power of open-circuit operation
Q_t = transformer's total reactive power
S = load (VA)
S_r = transformer's rated power (VA)

As the load fluctuates permanently, determination of the capacitor should not be chosen according to the maximum peak demand of reactive power, because overcompensation could occur during low-load periods all the time if the capacitor's reactive power oversteps the demand of the transformer. This would cause a voltage increase at the secondary terminals (see Section 8.2), followed by an increased reactive power in a squared manner at the capacitor (additional harmonics make it worse) with the danger of overload at either the capacitor or the transformer (see Section 17.3).

This is why most electricity utilities allow a limited size of capacitor to compensate the transformer's reactive power demand, as given in Table 9.2 [1]. For this purpose information

Table 9.2 Recommended reactive power of capacitors for compensation of transformers.

	Transformer's rated voltage (primary)		
Rated power of the transformer (kVA)	5–10 kV Capacitor's power	15–20 kV Capacitor's power	25–30 kV Capacitor's power
25	2	2.5	3
50	3.5	5	6
75	5	6	7
100	6	8	10
160	10	12.5	15
250	15	18.0	22
315	18	20.0	24
400	20	22.5	28
630	28	32.5	40

should be obtained from the local electricity utility. As mentioned previously, compensation of transformers in urban areas with huge cable networks is not always desirable, because the transformers compensate the reactive power (capacitive) of the cables during low-load periods.

The capacitor must be connected to the secondary terminals of the transformer via a security-load breaker.

When fitting larger capacitors than those listed in Table 9.2 (for instance, to compensate consumers additionally), one has to pay attention to situations where resonance occurs between the transformer and capacitor. This could occur due to existing harmonics in or from the network. It must be ensured that the resonance frequency, composed of the reactances of the transformer's leakage field and the capacitor, is far away from harmonics (e.g. 5th, 7th, 11th or 13th harmonics of the fundamental frequency).

The calculation of the resonance frequency f_{res} is given by the equation

$$f_{res} = f_r \cdot \sqrt{\frac{S_r \cdot 100}{Q_C \cdot u_k}} \tag{9.8}$$

The maximum of the capacitor's permissible reactive power is determined approximately:

$$Q_C \leq \frac{S_r \cdot 100}{n^2 \cdot u_k} \tag{9.9}$$

where

f_r = fundamental frequency of the grid
S_r = transformer's rated power (kVA)
Q_C = capacitor's reactive power (kvar)
u_k = impedance voltage of the transformer (%)
n = ordinal number of the highest critical harmonic

Example: Given data: transformer 630 kVA; impedance voltage 6%. What is the maximum reactive power of a single-type capacitor allowed in order to avoid any danger of resonance up to the 13th harmonic?

Here

$$Q_C = \frac{630\,\text{kVA} \cdot 100}{13^2 \cdot 6} \approx 62\,\text{kvar}$$

Thus the reactive power of the capacitor to be installed should be below 62 kvar.

The capacitor is connected regularly on the LV side of the transformer, as the need for space here is much less compared with HV capacitors for connection on the HV side of the transformer. Furthermore, the investment costs are higher, of course. Figure 9.11b shows the construction of single-type capacitors with integrated fuses, ready for installation. Discharging resistances are fitted inside the unit and are necessary at all times if fuses or breakers are installed between the capacitor and transformer (see Chapter 12).

9.2.3 Single-Type Compensation of Reactive Power for Welding Transformers

In general all types of transformers require reactive power for magnetizing the iron core of the transformer. The amount of reactive power depends on the volume of the iron and varies over a small bandwidth due to the additional magnetization of the leakage field (see Figure 9.2). Figure 9.11a shows the wiring diagram of a fixed compensation for a transformer schematically and Figure 9.11b illustrates an industrial performance of a reactor-protected single-type compensation. First, it should be remarked that this chapter deals with welding transformers controlled exclusively on the secondary side. This means that the switching unit in the welding procedure is to be installed on the secondary side of the transformer. The transformer runs in no-load condition most of the time. The diagram outlined in Figure 9.12a shows the time courses of voltage u, current i and power p. It is clear that the time course of p oscillates around the x-axis nearly symmetrically. This means that imported power (+) is almost identical to exported power (−). The imported energy ($p \cdot t$) is a little more than the exported one and covers the losses (active power) in magnetizing the iron (heat). However, the main part of power is 're'active ('re' stands for 'back'). This 'feedback' (−) energy must be stored in the capacitor in order to avoid any transmission of energy back to the power station and overcharging the leads. Roughly, one may say that the amount of reactive power is constant, and a single-type capacitor, well designed, is sufficient for compensation.

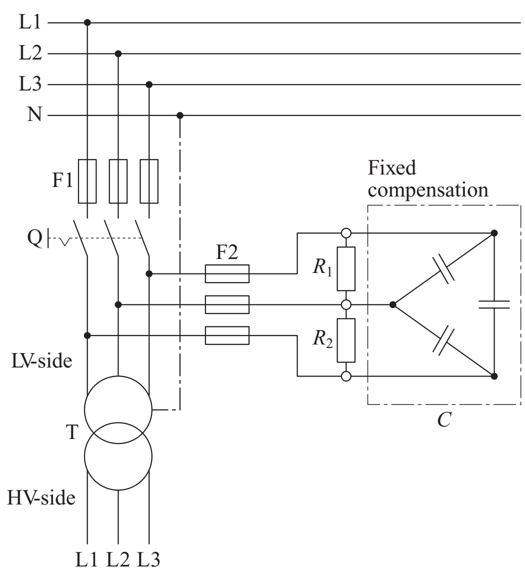


Figure 9.11a Circuit diagram of a fixed compensation for power transformers with fused load circuit breaker and discharging resistances in the case of blown fuses.

Figure 9.11b Reactor-protected capacitor for compensation of power transformers with fused load circuit breaker. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

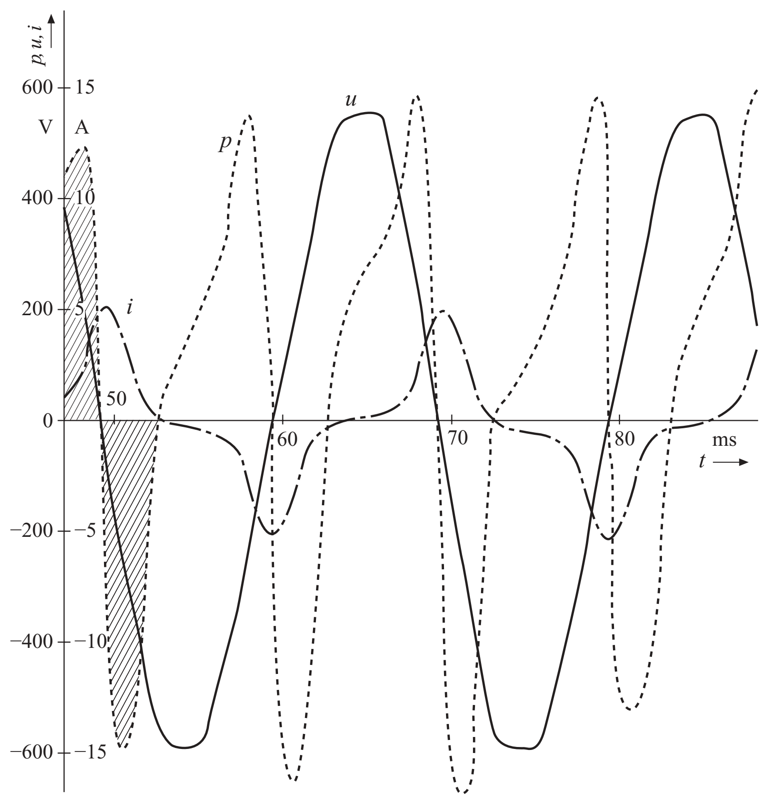


Figure 9.12a Time courses of voltage, current and power of a (welding) transformer in idle condition.

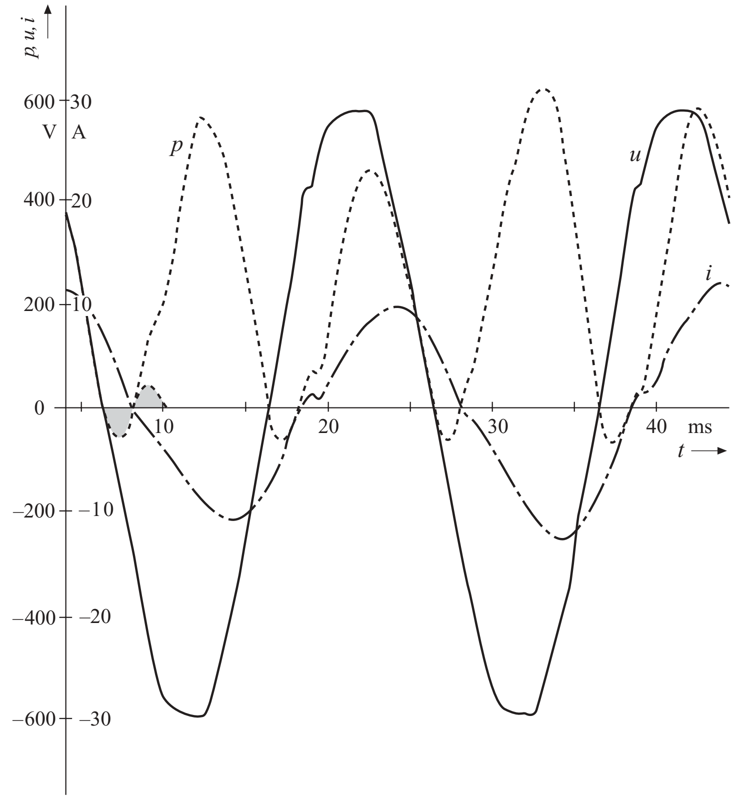


Figure 9.12b Time courses of voltage, current and power during welding procedure; the hatched areas symbolize the reactive power as in Figure 9.12a but at another scale.

In discussions of reactive power the meaning of power factor is well to the fore. However, reactive power is not identical to power factor and vice versa ($Q \neq \cos\varphi \neq Q$); it must always be kept separate. It is clear from Figure 9.13 that the power factor increases strongly as the welding procedure starts, due to the active vector P_a; however, the vector of reactive power 'stands by' in the no-load condition of the transformer. In other words, at industrial installations with multi-stage compensations a power factor relay would not start to control.

Figure 9.12b outlines the functions of current i and power p depending on the voltage u during the welding procedure. Clearly, the time course of the power crosses the x-axis into the negative area as shown in Figure 9.12a. The scale makes it appear smaller.

Figure 9.12c focuses exclusively on the time course of power p during the idle condition (left) and welding procedure (right).

Electrical welding plants cause strong load shocks which influence the waveform of the voltage as seen in Figure 9.12a,b; the waveform contains harmonics. Therefore all electrical plants with welding units of more than 2 kVA must be declared to the electricity supplier. It is common practice to supply the electrical energy for welding machines via a separate power transformer in order to keep active power shocks away from other sensitive consumers within the industrial installation.

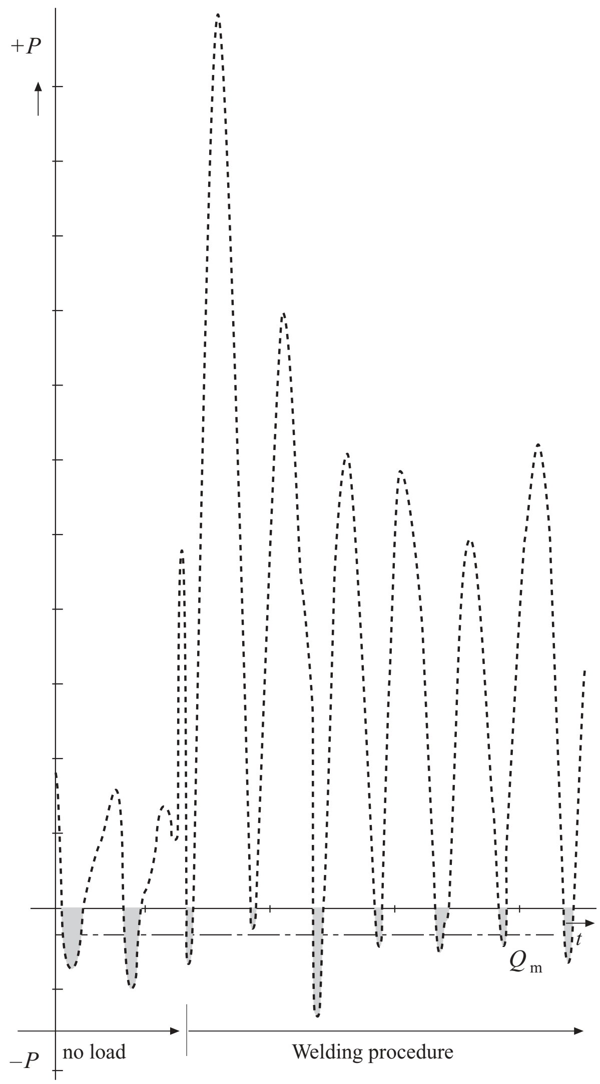


Figure 9.12c Time course of the power of a welding transformer (pulsed secondary).

For spot-welding machines, sometimes the method of primary controlled cycle operation is in use. This means that the transformer is controlled on the primary side by power electronics components. In this case it must be ensured that the capacitor is switched on and off synchronously in parallel to the transformer in order to supply the energy for magnetization and to support the line voltage against the active power shocks as well. It is also necessary to avoid fluctuations of the voltage. Chapters 14 and 20 deal with so-called 'dynamic reactive power compensation'.

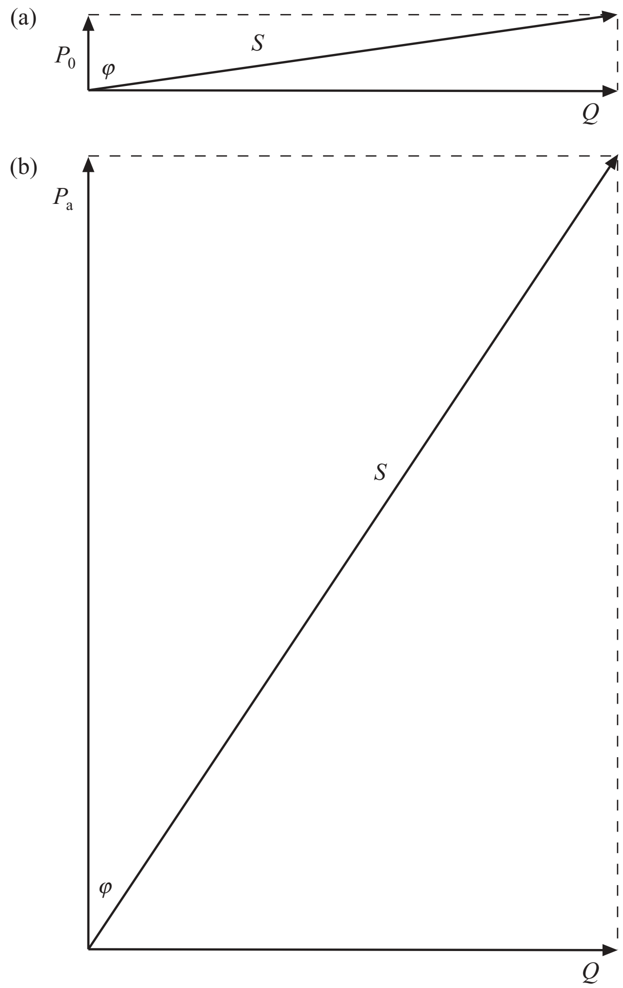


Figure 9.13 Orthogonal vectors of welding transformer (a) in no-load condition and (b) at full-load condition. Power factor cos φ fluctuates but the reactive power does not.

9.2.4 Single-Type Compensation of Fluorescent Lamps

Fluorescent lamps like fluorescent tubes, and halogen and mercury arc lamps, to mention just a few, have a nonlinear characteristic with respect to the time courses of voltage and current. The current would increase catastrophically if no current limiter were installed in series to the lamp. For this reason, inductances and leakage field transformers are in use. Leakage field transformers are connected in series to sodium arc lamps, mercury arc lamps and fluorescent tubes mainly. All other types are fitted with inductances to limit the current. These inductances cause low power factors in the range of 0.4 to 0.6 and leakage field transformers about 0.3 on average. This means that the demand of reactive power is much higher than the demand of

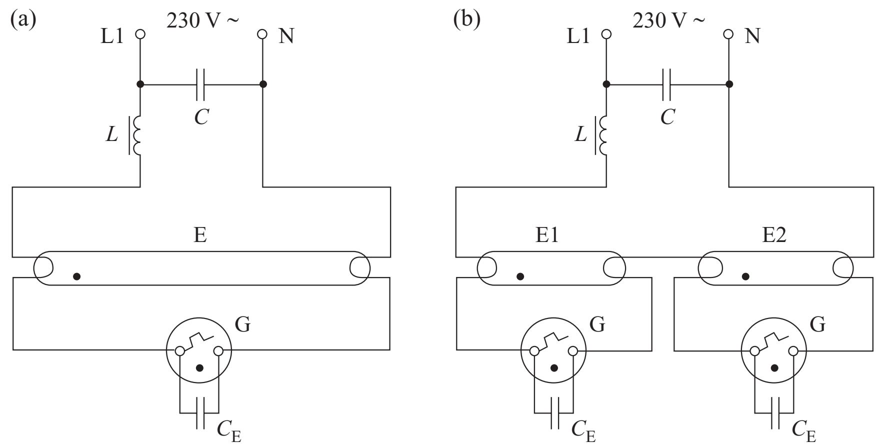


Figure 9.14 Single-type compensation by means of a capacitor connected in parallel: (a) compensating a single tube and (b) compensating two tubes connected in 'tandem'. E, fluorescent tube; L, current-limiting reactor; C, compensation capacitor; C_E, interference capacitor; G, corona igniters.

active power. Due to the very low power factor the single-type capacitor should be fitted very close to the fluorescent lamp in order to unburden the feed-in leads. The determination of the capacitor depends on the current limiter (inductor), the power of the lamp (data available from the producer) and the arrangement.

The producers of fluorescent lamps assemble their units mainly with capacitors for compensation of reactive power or provide the possibility for fitting them later.

Modern lamps include more and more electronic devices to limit the current. In this case there is no need for any capacitor for compensation as the unit is designed to achieve a power factor of around unity.

Compensation of reactive power may be ensured by a capacitor either in parallel (see Figure 9.14) or series connection (see Figure 9.15). The determination of the capacitor depends on the power of the lamp and the inductor used to limit the current.

In single-type compensation by means of a capacitor connected in parallel one can easily find the most economical method. Due to the location of the capacitor close to the inductor, causing reactive energy (inductive), the feed-in leads are not burdened by any reactive energy. As mentioned earlier, it is very uneconomical to compensate anywhere with automatic central compensation; it would cause severe losses (kWh) along the leads due to the oscillating reactive power. Parallel connection of the capacitor has two methods of arrangement (see Figure 9.14a,b): connection in combination with a single fluorescent lamp or with two lights (so-called tandem circuit). The operating voltage of the capacitor is identical to the rated voltage of the line. Sometimes it has to be clarified with the electricity supplier whether such parallel compensation is desired. Another method is series compensation (see Figure 9.15); the capacitor is connected in series to the inductance.

Finally, the most economical method of compensating fluorescent lamps or tubes is in the so-called 'duo-circuit'. This method requests only one capacitor for two lights (see Figure 9.16). The two lights have two different current-limiting devices, one with a standard inductor and

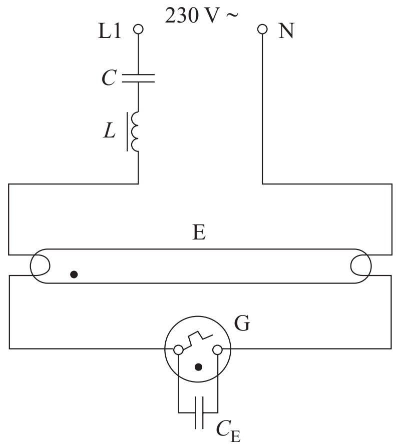


Figure 9.15 Compensation of a fluorescent tube by a capacitor connected in series, 'capacitive circuit'.

the other with a series combination of capacitor and inductor. The rated voltage is to be chosen much higher than the rated voltage of the grid (some are about twice the grid voltage) because of the series connection of the capacitor/inductance. This combination achieves a power factor close to unity.

Table 9.3 lists several values of capacitors for compensation of different types of fluorescent lamps.

The determination of the capacitor's capacitance, reactive power referring to a desired cos φ_d and the rated current of the compensate device (inductor plus lamp) is shown in the following example.

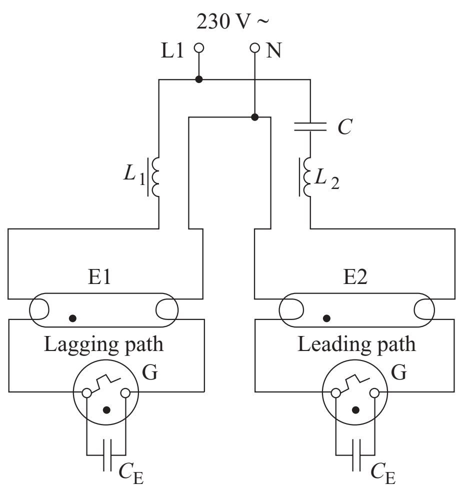


Figure 9.16 Duo-circuit diagram. E, fluorescent tube; L, current-limiting reactor; C, compensation capacitor; C_E, interference capacitor; G, corona igniters.

Table 9.3 Recommended capacities and reactive power of capacitors compensating fluorescent lamps or tubes.

Fluorescent lamps				
	Parallel compensation 230 V, 50 cps		Series compensation (duo) 420/440 V, 50 cps	
Lamp's active power[a] (W)	Capacitance[b] (μF)	Capacitor's reactive power (kvar)	Capacitance[c,d] (μF)	Capacitor's reactive power (kvar)
4; 6; 8; 10; 13	2.0	0.030	—	—
18; 20	4.5	0.068	2.9[e]	0.175[e]
36; 40	4.5	0.068	3.6[f]	0.199[f]
58; 65	7.0	0.106	5.7[f]	0.316[f]
Parallel compensation for mercury arc lamps (high pressure) 230 V, 50 cps				
Lamp's active power (W)[a]	Capacitance[b] (μF)	Capacitor's reactive power (kvar)		
50	7	0.106		
80	8	0.122		
125	10	0.152		
250	18	0.274		
400	25	0.380		
700	40	0.608		
1000	60	0.912		
Parallel compensation for metal arc lamps (halogen) 230 V, 50 cps				
Lamp's active power (W)[a]	Capacitance[b] (μF)	Capacitor's reactive power (kvar)		
75	12	0.18		
150	20	0.30		
250	32	0.48		
360	35	0.53		
1000	85	1.30		
Parallel compensation for sodium arc lamps (high pressure) 230 V, 50 cps				
Lamp's active power (W)[a]	Capacitance[b] (μF)	Capacitor's reactive power (kvar)		
50	8	0.12		
70	12	0.18		
100	12	0.18		
150	20	0.30		
250	32	0.48		
400	50	0.76		
1000	100	1.52		

(*continued*)

Table 9.3 (*Continued*)

Parallel compensation for sodium arc lamps (low pressure) 230 V, 50 cps		
Lamp's active power (W)[a]	Capacitance[b] (μF)	Capacitor's reactive power (kvar)
18	5	0.076
35	20	0.304
55	20	0.304
90	26	0.395
135	45	0.684

[a]Without current limiter.
[b]±10% tolerance of capacitance at parallel compensation.
[c]±5% tolerance of capacitance (capacitor connected in series).
[d]Duo-circuit according to Figure 9.16.
[e]440 V.
[f]420 V.
Note: All values from lists of producers of fluorescent lamps and current limiters (not guaranteed).

Example: The active power of a fluorescent lamp amounts to 40 W at $U = 230$ V, 50 cps. It is desired to achieve a power factor of $\cos \varphi_d = 0.95$.

The following data are calculated:

- Actual power factor $\cos \varphi_a$ without compensation.
- Capacitor's capacitance for parallel compensation.
- Amount of rated current with compensation.

According to the technical data of the producer, there is a current I_1 (without compensation) of 0.41 A listed:

(a) Calculate the actual power factor $\cos \varphi_a$ from the data for apparent and active power:

$$S = U \cdot I_1 = 230\,\text{V} \cdot 0.41\,\text{A} = 94.6\,\text{VA}$$

The total amount of active power is composed of the active power of the lamp, 40 W, and the active power loss of the inductor, 10 W (listed in the technical data of the producer), with a total amount therefore of 50 W.

Thus reactive power (uncompensated) results in

$$Q = \sqrt{S^2 - P^2} = \sqrt{94.6^2 - 50^2} = 80.3\,\text{var}$$

$$\cos \varphi_a = \frac{P}{S} = \frac{50\,\text{W}}{94.6\,\text{VA}} \approx 0.53$$

Determination of the capacitor's reactive power Q_C:

$$\cos\varphi_a = 0.53 \rightarrow \tan\varphi_a = 1.6 \quad \text{and} \quad \cos\varphi_d = 0.95 \rightarrow \tan\varphi_d = 0.33$$

$$Q_C = P \cdot (\tan\varphi_a - \tan\varphi_d) = 50\,\text{W} \cdot (1.6 - 0.33) = 64\,\text{var}$$

The capacitor's capacitance C:

$$C = \frac{Q_C}{2 \cdot \pi \cdot f \cdot U^2} = \frac{64\,\text{var}}{314\,\text{s}^{-1} \times 230^2\ \text{V}^2} \approx 3.85\,\mu\text{F}$$

Calculation of the lamp's compensated rated current I:

$$I = \frac{\sqrt{P^2 + (Q - Q_C)^2}}{U} = \frac{\sqrt{50^2 + (80.3 - 64)^2}}{230} \approx 0.23\,\text{A}$$

This rated current refers to the fundamental frequency of 50 cps (or 60 cps in several countries worldwide). If additional harmonics exist, they increase the current of course (calculations on this appear in Chapter 17).

In the case of phase-angle-controlled fluorescent lamps, compensation of reactive power is possible by means of a capacitor fitted on the primary side of the control device, only. Any single-type compensation as described above is impossible.

Uncompensated leakage field transformers for HV fluorescent tubes have a power factor $\cos\varphi$ of 0.5 to 0.6 approximately. Any compensation of reactive power is possible only at the LV side.

9.3 Bulk-Type Compensation

This method of compensation is applicable for inductive consumers of any kind that are installed locally much closer and for most of the time are in parallel operation. Due to the total reactive power demand, one capacitor is sufficient. One distinguishes between two switching modes either if all consumers are running parallel continually, or if single consumers are running at intervals.

Supposing in the first case that all consumers including the capacitor for compensation are switched in by a contactor, there is then no need for a separate contactor for the capacitor. In the second case (see the dashed line in Figure 9.17) the capacitor has its own contactor. However, the capacitor may be proportionately smaller because not all consumers are switched in at the same time.

Mostly it is best if bulk-type compensation is located at sub-distribution board level. As mentioned earlier, one must not forget that the requested reactive power of the consumers oscillates with the compensation. That requires larger cross-sections of cables of course. Bulk-type compensation is often used for economical reasons, for example in office buildings, shopping centres, factories, and so on.

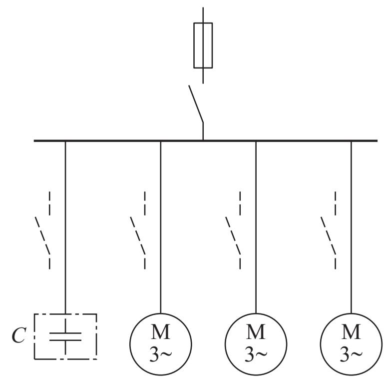


Figure 9.17 Simplified illustration of bulk-type compensation.

Example 1: An office building has three floors fitted with 185 fluorescent lamps, each 65 W. The illumination is controlled and compensated separately by floor. At rated voltage each tube demands 106 var (from the list of technical data), which results in a total amount of 19.6 kvar. Thus a capacitor of 20 kvar for each floor is sufficient, assuming that all fluorescent lamps are connected to the three phases symmetrically (star mode).

Example 2: A factory floor is to be illuminated by mercury arc lamps (high pressure): 27 lamps at 400 W each and 12 lamps at 1000 W each. The demand of reactive power amounts to 0.38 kvar and 0.912 kvar for the 400 W lamp and 1000 W lamp, respectively (from the list of technical data):

Group 1: $27 \cdot 0.38\ \text{kvar} = 10.26\ \text{kvar}$

Group 2: $12 \cdot 0.912\ \text{kvar} = 10.94\ \text{kvar}$

Both of these groups have to be installed at the three phases symmetrically, nine lamps per phase of group 1 and four of group 2. Two capacitors of 11 kvar should be provided for the compensation to achieve a power factor of unity. Since such a standardized capacitor is not available on the market, it is necessary to choose two capacitors of 10 kvar each. The power factor achieved will then be very close to unity.

The method of bulk-type compensation taken into consideration has far lower investment costs than using single-type compensation with 27 single capacitors; installation costs are not considered.

It must be ensured that the lamps and the capacitor(s) have to be switched in and out simultaneously. In the case of switching in single lamps, bulk-type compensation has to be controlled by an automatic power factor relay.

The power capacitors, 10 kvar each, are usually connected in delta (line-to-line) configuration. This has the advantage that the requested reactive power is obtained just by one-third of the capacitance compared with single-type compensation with capacitors in star connection (see Chapter 7.2).

Distributing the lamps to the three phases symmetrically reduces any glimmer of the light due to the mutual electrical phase shifting of 120°. Finally, the lamps should not be protected directly by single-phase fuses but by a three-phase automatic circuit breaker.

Figure 9.18 shows the possibilities of connecting the three groups of lamps compensated either with single-type capacitors (star voltage) or with the method of bulk-type three-phase capacitors (delta voltage).

In selecting switching devices for consumers compensated by bulk-type compensation, it must be considered that the capacitors cause very high inrush currents if the instantaneous voltage of the grid is not identical to the capacitors' voltage. In the worst case inrush currents up to 30 times the rated current could appear and could weld the contacts of the circuit breaker. It is recommended that separate contactors be fitted for the capacitors (>10 kvar) with inrush current-limiting resistances or chokes controlled in parallel with the main circuit breaker of the consumers (see Chapters 14 and 15).

Example: An industrial plant is supplied with electrical energy by a power transformer of 630 kVA for two conveyor belts of 50 kW each, one riddle plant of 140 kW and one concrete mixer of 120 kW. Each aggregate contains several motors of different active power, running simultaneously. Bulk-type compensation is more advantageous than single-type compensation; however, central compensation controlled by an automatic power factor relay is more expensive. Measured data of voltage and current result in an apparent power of 546 kVA. With the help of the total amount of 360 kW (active power), determine the actual power factor cos φ_a.

Here

$$\cos\varphi_a = \frac{360\,\mathrm{kW}}{546\,\mathrm{kVA}} \approx 0.66$$

The power factor is to be improved up to cos $\varphi_d = 0.9$. Table 8.3 indicates, where row cos $\varphi_a = 0.66$ meets column cos $\varphi_d = 0.9$, a conversion value of 0.65. Thus the required reactive power for compensation amounts to

$$Q_C = 360\,\mathrm{kW} \cdot 0.65 = 234\,\mathrm{kvar}$$

Finally, 240 kvar is to be provided, including a small reserve. One single-type capacitor of 20 kvar is to be installed at the secondary side of the power transformer. The remaining 220 kvar is distributed accordingly among the consumers due to their individual demands of reactive power. Two capacitors of 40 kvar each are provided for the two conveyor belts, one capacitor of 80 kvar for the riddle plant and one capacitor of 60 kvar for the concrete mixer.

In determining the reactive power for the compensation of the motors running continually, care must be taken with the calculation. Just to determine the demand of reactive power from

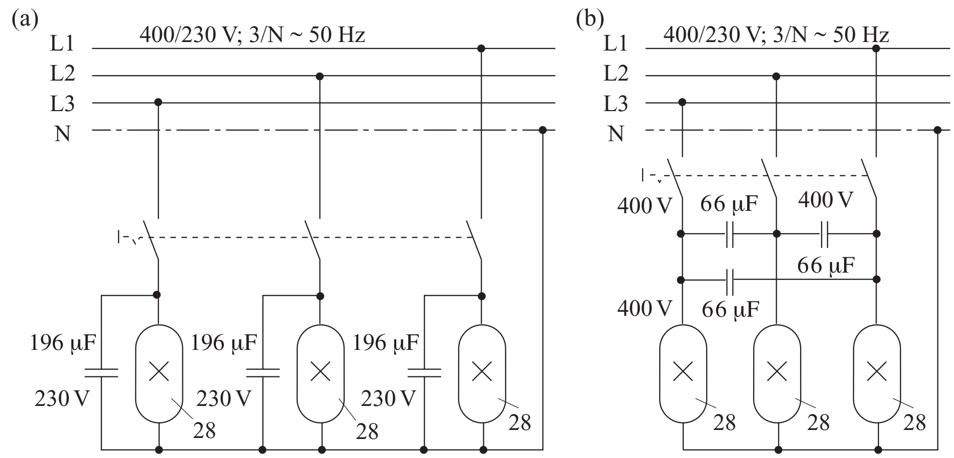


Figure 9.18 Bulk-type compensation: (a) capacitors of 3 kvar each connected in parallel to the tubes (star connected, 230 V); (b) capacitors of 3 kvar each connected in parallel to the tubes (delta connected, 400 V). All tubes have 28mm of diameter.

the motors' total amount of active power leads to undercompensation. The correct demand of reactive power for each motor can be found in Table 9.1.

Remember that, according to Section 9.2.1, the reactive power of the capacitor(s) may not exceed the sum of reactive power in the no-load condition of the motors due to problems with self-excitation.

Applications of bulk-type compensation refer to motors' active power higher than 10 kW in general.

Summary: Single-type or bulk-type compensation is useful for electrical plants with low fluctuations of reactive power. For high fluctuations the demand of the consumers must be considered (see Section 4.5.1). The lower the demand factor, the lower the investment costs for bulk-type compensation. Further reduction may be possible in using single-type compensations additionally.

9.4 Central-Type Compensation

In larger electrical plants with high fluctuations of the load, central-type compensations controlled automatically by a power factor relay are in use. A power factor relay may control single capacitors or groups of them in order to maintain the required target power factor. The automatic compensation banks are usually installed in main or sub-distribution panels (see Figure 9.19).

In very large industrial plants like car factories several LV distribution panels are installed according to the main focus loads. Individual groups of consumers are fed by sub-distribution panels with automatically controlled compensation banks. The power factor relays control the demand of reactive power steadily at the feed-in point of the distribution panel and switch in or out capacitors of different or equal sizes (see Chapter 11). The power factor

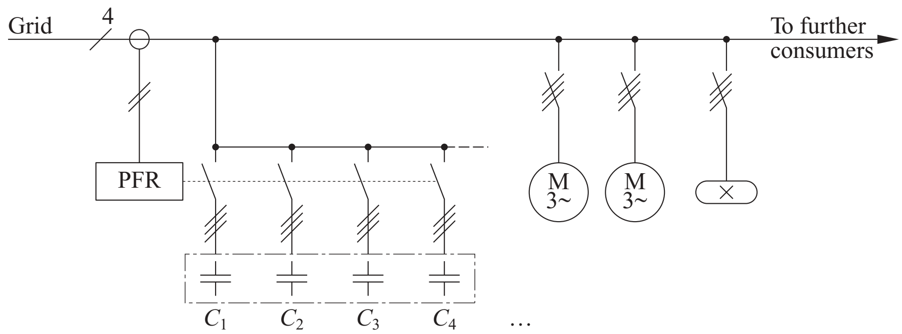


Figure 9.19 Simplified illustration of central-type compensation (PFR = Power Factor Relay (or Regulator)).

relays register fixed connected capacitors too, for example local compensations of fluorescent lamps. However, they are not able to disconnect in case of overcompensation. Therefore, in determining the single-type capacitors a desired power factor of cos φ_d should be below unity (see Figure 9.14a,b). If it is required to achieve a higher power factor at the feed-in point of the distribution panel, the power factor relay does this automatically due to the preadjusted power factor target (see Chapter 11).

It is true that the reactive power oscillates steadily between the consumers and the compensation, and the cables therefore have to transmit the uncompensated load; however, this method of central-type compensation mostly is more economical than single-type compensation because the automatically controlled compensation takes care of the consumers' demand factor and requires less reactive power to be installed.

Summary: Central-type compensation has the following advantages:

- Easy check-up due to its central location.
- Any provided extension of the unit is simple to realize.
- The reactive power of the capacitor bank is adapted to the required demand.
- Considering the demand factor of the consumers, less capacitance has to be installed compared with single-type compensation.

9.5 Mixed Compensation

The question of how to compensate reactive power by the methods described is solved individually by the local arrangements of the consumers. As mentioned above, on one hand it is easier to compensate reactive power at the inductive consumers by means of single-type compensation locally, but on the other hand the sum of the fixed connected capacitors may increase the real demand.

This is why mixed-type compensations are sometimes rich in meaning as illustrated in Figure 9.20. The figure shows an industrial installation with different consumers such as a motor with single-type compensation; the illumination is provided with bulk-type compensation;

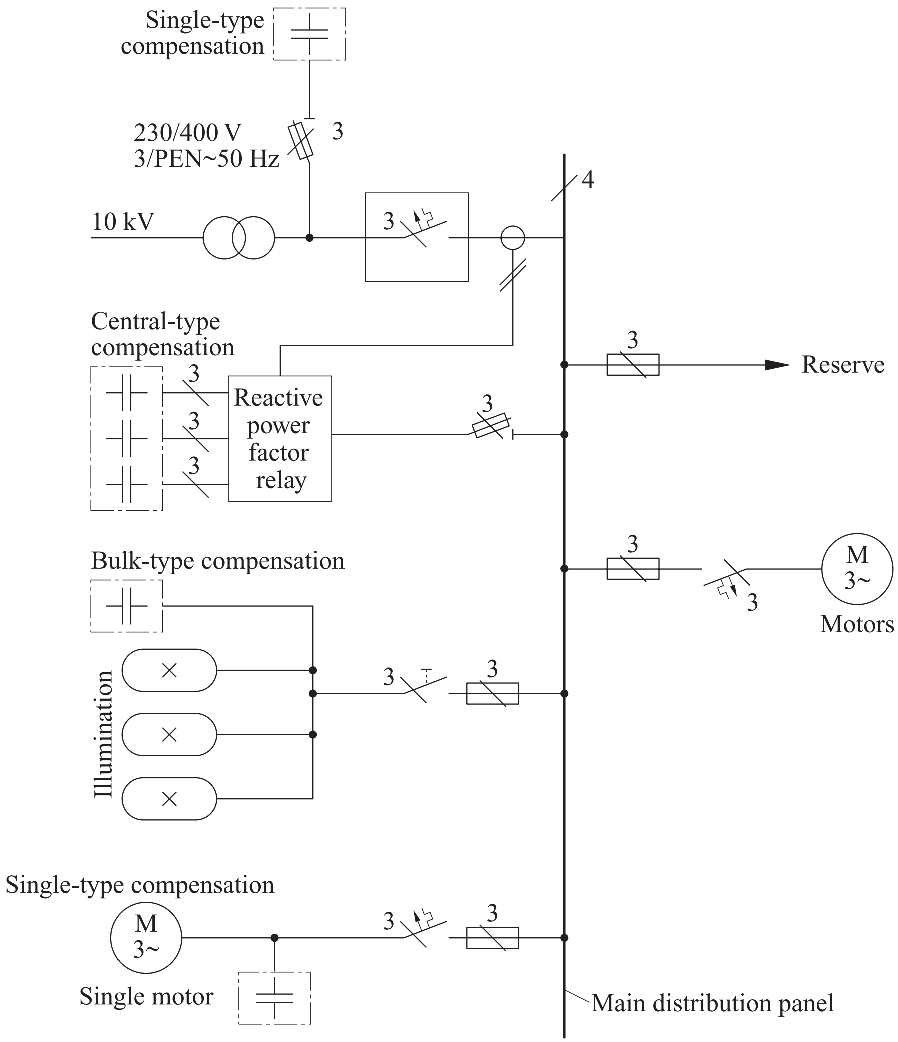


Figure 9.20 Schematic circuit diagram illustrating all four methods of compensation (protective devices not set).

and all the remaining consumers are compensated by the automatically controlled central-type compensation.

9.6 Advantages and Disadvantages of Different Types of Compensations

Listed in Table 9.4 are the advantages and disadvantages of single-type, bulk-type, central-type and mixed compensation.

Table 9.4 Advantages and disadvantages of the different methods of compensation.

Type of compensation	Applications	Advantages	Disadvantages
Single-type compensation	In use at loads with steady consumption Each consumer is connected to a capacitor determined by its demand of reactive power	• Local compensation at the consumer • Reduction of transmission losses along the cables • Any contactor not in use	• Investment costs for many small single capacitors are more than for one capacitor of identical capacitance • No utilization for further compensation tasks in case of consumer's few operating hours
Bulk-type compensation	Several consumers are compensated by one capacitor controlled by a separate contactor, depending on the time the consumers are in operation.	• Lower investment costs for capacitor(s) • Reduction of transmission losses along the cables and less voltage drop	• All cables between capacitor(s) and consumers are burdened additionally by reactive power
Central-type compensation	Preparation of loadings and reactive power (capacitive) at feed-in point	• Optimized utilization of capacitors • Easier supervision • Automatic control of reactive power • Improvement in voltage stability • Extensions possible any time • Better and quick adaption to the actual demand of reactive power	• All cables between capacitor(s) and consumers are burdened additionally by reactive power
Mixed compensation	Single-type compensation of e.g. fluorescent lamps Bulk-type or central-type compensation of the remaining consumers (see Figure 9.20)	• Optimized utilization of capacitors • Easier supervision • Automatic control of reactive power • Improvement in voltage stability • Extensions possible any time • Better and quick adaption to the actual demand of reactive power	• All cables between capacitor(s) and consumers are burdened additionally by reactive power

9.7 Summary

In completing this chapter, the advantages listed in Table 9.4 are matched equally by the disadvantages. It is therefore up to the engineers or technical specialists to make the most economical choice. This will differ from one electrical plant to another. Thus this chapter represents a little 'guide' to making any decisions in designing new tasks in compensating reactive power.

Reference

[1] VDEW (1958) *Leistungskondensatoren. Eine Richtlinie für ihre Aufstellung und ihren Betrieb in Mittel- und Niederspannungsnetzen* (Power Capacitors: A guideline for location and setting into operation in MV- and LV-networks), VWEW-Verlag, Frankfurt.

10

Compensation of Existing Installations

10.1 Chapter Overview

This chapter deals with compensation and its extension to existing installations. In many electrical plants a problem sometimes arises where the existing compensation becomes insufficient to achieve the desired power factor cos φ_d within one billing period. This may be caused by additional machines due to an increase in production. Most customers usually forget to extend the compensation as well until they get a first 'sign' in the monthly energy invoice. However, sometimes it is not noticed by the technical staff, because the invoices are kept in the commercial department and the staff there consider it as just an additional item to be charged, since they may never have heard about compensation of reactive power! It is therefore the responsibility of the technical staff to check electricity invoices from time to time.

10.2 Methods of Determining the Reactive Power for Extension

As mentioned in Chapter 5, there are several methods to determine the size of the capacitor(s) for extension, for example by means of recording devices for active and reactive power, by watt- or varmeters, by an active power meter combined with a volt- and ammeter, and last not least by the energy invoices. Chapter 5 described different devices for obtaining the actual power factor cos φ_a. These different power factor indicators require different technologies for calibration. Classical indicators are calibrated with reference to sinusoidal waveforms of voltage and current, which are no longer given in industrial plants today. Thus it is necessary for a power factor indicator to be implemented in most modern power factor regulators. They are designed for waveforms containing the harmonics one desires. However, remember that the power factor data do not exclusively enable the calculation of the required reactive power (capacitive) for the extension unit; so far, it is just one factor of the product $U \cdot I \cdot \cos\varphi$ or $U \cdot I \cdot \sin\varphi$.

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

10.3 Calculation of the Extension Unit by Means of Energy Invoices

The following examples are individual cases; they are representative of many similar applications.

Example 1: An electrical plant (metal work) on an industrial estate has two power transformers (400 kVA each) connected in parallel on the secondary side in order to feed many consumers with electrical energy. Most of the consumers are motors, some of them with high nominal active power. An analysis of the electricity invoices indicates that a total reactive power of some 310 kvar is required in order to achieve a desired power factor of $\cos \varphi_d = 0.9$. The average demand of active power amounts to 465 kW approximately.

To get a solution, first of all it is necessary to investigate whether single-type compensation is applicable; for example, for the two transformers with 20 kvar each. The remaining 270 kvar is to be compensated by central-type compensation controlled automatically by a reactive power factor relay.

At very large electrical installations, like car factories, it is necessary to consider whether to compensate on the HV or LV side of the transformers. The energy is usually metered on the HV side, which means that the desired power factor $\cos \varphi_d$ is to be achieved at the metering point. There is no doubt that HV compensations are very expensive even when the compensation is controlled by a power factor relay. Each capacitor step is to be switched in and out by expensive circuit breakers (applicable for power capacitors). Another disadvantage is the long switching time delay per step of at least 15 minutes to avoid any overheating from the discharging inductors by the capacitors' energy. Thus rapid control of reactive power becomes impossible. Another disadvantage is that all leads at the LV side are not unburdened by reactive power. Therefore it is necessary to look for alternative solutions like single-type compensations directly at HV motors and central-type compensations at the LV side.

In order to achieve the desired power factor of $\cos \varphi_d \geq 0.9$ at the transfer station, the target power factor at the automatically controlled central-type compensations should be adjusted higher than 0.95 for instance (see Chapter 11).

Example 2: The consumption of a machine factory amounts to 52 000 kWh on average, referring to a high-tariff period. The electricity supplier charges according to the consumption of reactive energy (see Section 4.2.1). The double tariff of a kWh-meter indicates an active power peak of 385 kW within a 15 min period and a consumption of 60 800 kvarh during the high-tariff period.

The power factor on average amounts to $\cos \varphi_a = 0.65$ without compensation. The power factor of the electrical plant is to be improved to a desired power factor of $\cos \varphi_d = 0.9$ at the transfer station.

The factory is to be fed by two power transformers (A and B) of 10 kV/0.4 kV, the first one 400 kVA, the second 250 kVA, connected in parallel at the LV side. The reactive power is to be compensated at the LV side exclusively. Both of the biggest motors of 25 kW rated power and nominal power factor of $\cos \varphi_a = 0.86$ each and the two transformers are to be provided with single-type compensations. All the remaining consumers are to be compensated by central-type compensations.

The aim is to determine:

- The apparent power and current at conditions without and with compensation.
- The required reactive powers of the capacitors for single-type and central-type compensations.
- Additional costs of increased consumption of reactive energy per year.

The steps of the solution and the results are as follows.

Apparent power and current without compensation:

$$P = 385\,\text{kW}, \quad \cos\varphi_a = 0.65, \quad \tan\varphi_a = 1.17$$

$$S_1 = \frac{P}{\cos\varphi_a} = \frac{385\,\text{kW}}{0.65} = 592\,\text{kVA}$$

$$I_1 = \frac{S_1}{\sqrt{3}\cdot U} = \frac{592\,\text{kVA}}{\sqrt{3}\cdot 0.4\,\text{kV}} = 855\,\text{A}$$

where

S_1 = apparent power without compensation

I_1 = apparent current without compensation

Apparent power and apparent current with compensation:

$$P = 385\,\text{kW}, \quad \cos\varphi_d = 0.9, \quad \tan\varphi_d = 0.484$$

$$S_2 = \frac{P}{\cos\varphi_d} = \frac{385\,\text{kW}}{0.9} = 428\,\text{kVA}$$

$$I_2 = \frac{S_2}{\sqrt{3}\cdot U} = \frac{428\,\text{kVA}}{\sqrt{3}\cdot 0.4\,\text{kV}} = 618\,\text{A}$$

Required reactive power of the capacitors:

The total reactive power of the capacitors amounts to

$$Q_C = P\cdot(\tan\varphi_a - \tan\varphi_d) = 385\,\text{kW}\cdot(1.17 - 0.484) = 264\,\text{kvar}$$

With reference to Table 9.1, each motor with $P_r = 25$ kW is to be provided with a single-type capacitor of 10 kvar each. All the remaining consumers are to be compensated with a total sum of 244 kvar by means of a central-type compensation controlled by an automatic power factor relay (see Figure 10.1).

Referring to Figure 2.3, the real demand of parallel reactive power Q_{pA} for the first transformer A (400 kVA) with $u_{k1} = 6\%$ and $u_{r1} = 1.85\%$ yields a value of 0.046 (4.6%), thus

$$Q_{pA} = 0.046\cdot S_A = 0.046\cdot 400\,\text{kVA} = 18.4\,\text{kvar}$$

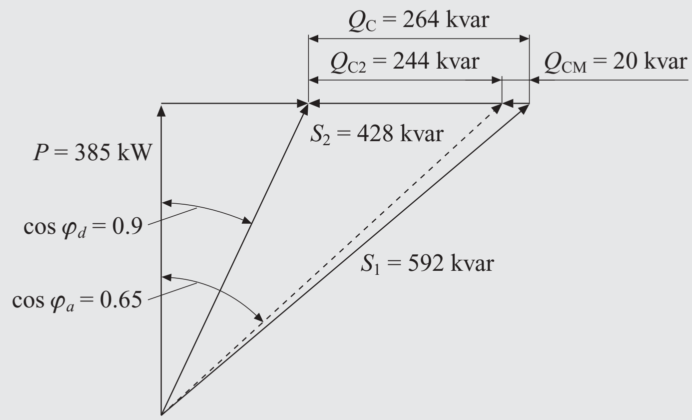


Figure 10.1 Power triangle referring to Example 2

The voltage drop results in

$$u_{xA} = \sqrt{u_{kA}^2 - u_{rA}^2} = \sqrt{6^2 - 1.85^2} = 5.7\%$$

Thus the total demand of reactive power is

$$Q_{LA} = \frac{u_x}{100} \cdot S_A + Q_{PA} = \frac{5.7\%}{100\%} \cdot 400\,\text{kVA} + 18.4\,\text{kvar} = 41.2\,\text{kvar}$$

The total demand of reactive power for the second transformer B (250 kVA) with $u_k = 6\%$, $u_{rB} = 2.08\%$, $u_{xB} = 5.6\%$ and $Q_{PB} = 0.05 \cdot S_2$ (from Figure 2.3) results in

$$Q_{LB} = \frac{5.6\%}{100\%} \cdot 250\,\text{kVA} + 0.05 \cdot 250\,\text{kVA} = 26.5\,\text{kvar}$$

This calculation indicates that the real demand of reactive power for the transformers is higher than 10% of the rated apparent power S_1 and S_2. As mentioned in Section 9.2.2, the capacitors' reactive power for compensation should not refer to the maximum demand of the transformers' reactive power, because it decreases during low-load periods and should avoid a voltage increase at the secondary terminals due to oversized capacitors. According to the general directions of VDEW, dated 1958 (see Table 9.2), the two transformers A and B (400 kVA and 250 kVA only) are to be compensated with 20 kvar and 15 kvar respectively.

Thus the total reactive power of the central-type compensation amounts finally to

$$Q_C = 244\,\text{kvar} - (20\,\text{kvar} + 15\,\text{kvar}) = 209\,\text{kvar}$$

Annual costs to be saved due to compensation of reactive power:

It is a matter of course that tariffs for electrical energy differ worldwide. However, the following calculation is based on a price of 12 cents per kWh; the reactive energy will be charged at 15% of the kWh price. These prices refer to the high-tariff period only. One should check with the local electricity supplier whether reactive energy will be charged during the low-tariff period as well.

The annual consumption of active energy per year with 52 000 kWh on average per month is 52 000 kWh · 12 = 624 000 kWh per year. Reactive energy is to be charged when 50% of 624 000 kWh is exceeded, which means more than 312 000 kvarh per year. The kvar-meter counted 60 800 kvarh on average per month; thus the total demand of reactive energy amounts to 12 · 60 800 kvarh = 729 000 kvarh. Now 312 000 kvarh is free of charge, so 729 000 − 312 000 kvarh = 417 000 kvarh is to be charged:

$$417\,000\,\text{kvarh} \cdot 12\,\text{cents per kWh} \cdot \frac{15\%}{100\%} \approx €7517\text{per year (net)}$$

The investment costs for a compensation unit will amortize within approximately one year.

If customers are charged according to the consumption of apparent energy (see Section 4.2.2), from a commercial viewpoint it is sufficient to compensate to an average power factor in the range of 0.96 to 0.98 (at the transfer station). To improve this to unity ($\cos\varphi = 1$), additional investment costs for the compensation units must be taken into consideration, as shown in Section 10.3.3.

Example 3: The active power of an industrial plant amounts to 110 kW on average at an actual power factor of $\cos\varphi_a = 0.96$. To improve this to $\cos\varphi_d = 0.98$, an additional capacitor with following reactive power is needed:

$$Q_C = P \cdot (\tan\varphi_a - \tan\varphi_d) = 110\,\text{kW} \cdot (0.2916 - 0.2030) \approx 10\,\text{kvar}$$

To improve it further from $\cos\varphi_a = 0.98$ to $\cos\varphi_d = 1$ there is a need for an additional capacitor with

$$Q_C = 110\,\text{kW} \cdot 0.2030 \approx 22\,\text{kvar}$$

This last improvement to unity requires more than a double-sized capacitor compared with the first one (0.96 to 0.98). If the electricity utility does not demand an average power factor of $\cos\varphi = 1$, it is up to the customer whether to invest in the higher costs. Up to now, only the additional costs for reactive energy to be charged have been taken into consideration, and not the costs of additional active losses along the leads to be charged at the more expensive price of active energy (e.g. at 12 cents per kWh; see Figure 6.5).

10.4 Summary

In determining the compensation of reactive power it is pointless calculating according to peak values as this would result in too high a reactive power of the compensation unit. Choosing between the three types of compensations (see Chapter 9) is up to the customer and depends on the structure of the electrical plant, of course. Furthermore, any change in the structure of the network must be taken into consideration with regard to increased harmonics especially. Attention must be paid to any directions from the electricity supplier as well.

Information on this relates to the following actions:

- In measuring the intensity of harmonics (without compensation).
- In measuring reactive and active energy (at the same time and without compensation).
- In theoretical considerations of the danger of resonances.
- In receiving the following data from the network:
  - Short-circuit power at the transfer station of the electricity utility.
  - Rated power and impedance voltage of the power transformers feeding in parallel.
  - Reactive power of the different compensations of any type.
  - Energy invoices for the last 12 months.
  - Any possible occurrences caused by harmonics.

The analysis of harmonics in heavy industrial electrical plants is very difficult and requires special staff. Harmonics may increase the voltage levels and overcharge unchoked capacitors. Further, developments in power electronics have led to an increase in the level of harmonics.

This is the main reason why several countries around the world do not allow the installation of capacitors without serial inductors to protect against harmonics – for example, in Switzerland.

Chapter 17 deals with the problems with harmonics in detail.

11

Control of Reactive Power

11.1 Chapter Overview

This chapter deals with automatically controlled compensation units as manufactured by many companies worldwide. The following subjects focus on this matter:

- Control of reactive power by means of automatic reactive power controllers.
- Step number and related power.
- Threshold value (C/k).
- Reverse control scheme (cos φ).
- Automatic reactive power control.
- No-volt release.
- Reactive power control with multiple feed-ins.
- Parallel operation with multiple feed-ins.
- Reactive power control with mixed measuring.
- Measuring by current transformers.

It is necessary to explain some essential technical terms in order to understand the automatic control of reactive power. Although most power factor regulators automatically recognize, for example, capacitor step sizes, an explanation is appropriate for better understanding.

11.2 General

In networks of electrical plants with many consumers and a steady fluctuation of reactive power there are automatic compensation units regularly in use. These units consist of a control unit with the reactive power controller[1] and several capacitors of different or equal step sizes.

Most of the compensation units are controlled by *capacitor steps*. Stepless control of power capacitors could be possible with today's modern electronic power components (IGBTs) but it is very expensive of course. This chapter deals with compensation units controlled by capacitor

[1] In the literature one can find the term 'power factor relay' as well.

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

steps *exclusively*. In very large electrical installations all three types of compensations (single-, bulk- and central-type compensations) are applicable (see Chapter 9), bearing in mind that the compensations are located as close as possible to the consumers demanding lagging reactive power. Single-type compensation for instance is in use at power transformers (see Chapter 10). They are determined to achieve a power factor in the range of 0.90 to 0.95 approximately. In urban networks, however, it has to be clarified with the electricity supplier whether compensation of power transformers is desired or not. At low-load periods the power transformers should compensate the leading reactive power of the cable networks. Just to give a rough idea, a 110 kV cable of about 3 km in length is comparable with a capacitor of 1.7 Mvar approximately, depending on the type of cable: 150 pF/m per phase is a realistic value for a 110 kV cable. The reactive power in 10 or 20 kV networks is much lower. However, in very large networks, reactive power in the range of Mvar should be calculated as well.

11.2.1 Reactive Power Compensation Units

Manufacturers of compensation units are producing module technology usually. These units consist of capacitor(s), contactor(s), fuses and a reactive power controller as shown in Figures 11.1 and 11.2. The reactive power controller needs two factors for correct control: (a) the voltage taken internally from the compensation unit and (b) the value of the apparent current taken from the feed-in or metering point in using a current transformer with a defined transforming ratio.

Manufacturers' first goal is to produce compensation banks as economically as possible. This is why small units consist of capacitors of different sizes, for example 10, 20 and 40 kvar (ratio 1:2:4) to achieve total 70 kvar switching in seven steps. Bigger compensation banks (>200 kvar) are assembled with capacitors of equal size, for example 50 kvar. The market offers basic and extension modules.

The reactive power controller senses the reactive power steadily at the point where the current transformer has been located. This is the only point that achieves the preadjusted target power factor at the relay. It compares the actual power factor $\cos \varphi_a$ with the desired power factor $\cos \varphi_d$ all the time (see Section 11.3.4) and switches the capacitors on or off if the demand of reactive power exceeds two-thirds of the capacitor's reactive power to be controlled (see Section 11.3.3; C/k value). Detailed descriptions of the function of reactive power controllers are given in Section 11.4.

11.3 Control of Reactive Power by Automatic Reactive Power Controllers

11.3.1 General

Manufacturers of reactive power controllers have improved the technology steadily in the last few years. Microprocessing units implement many additional features in the relay, such as digital indications of power factor and further parameters like harmonics, switching operations and different alarms, just to mention a few. In previous decades this was impossible with power factor relays produced with electromechanical technology. The main task of a reactive power controller is to compensate lagging reactive power by switching capacitors on or off in order to achieve the desired power factor on average per month, for example cos $\varphi = 0.93$. As mentioned earlier, the phase-shifting angle φ is just one factor out of three describing reactive power: $U \cdot I \cdot \sin\varphi$. The controller has to multiply all three factors steadily to recognize the actual reactive power and its demand to maintain the desired power factor.

It is not possible to explain all the power factor relays for any individual brand; instructions are always attached. All that is necessary is to introduce the essential characteristics of control, for instance the switching time delay per step. This parameter is responsible for the lifetime of the compensation unit as the number of switching operations determines the wear and tear of the contactors.

Today's modern reactive power controllers enable the control of power capacitors by small internal relays either via contactors or via thyristors as features for rapid control.

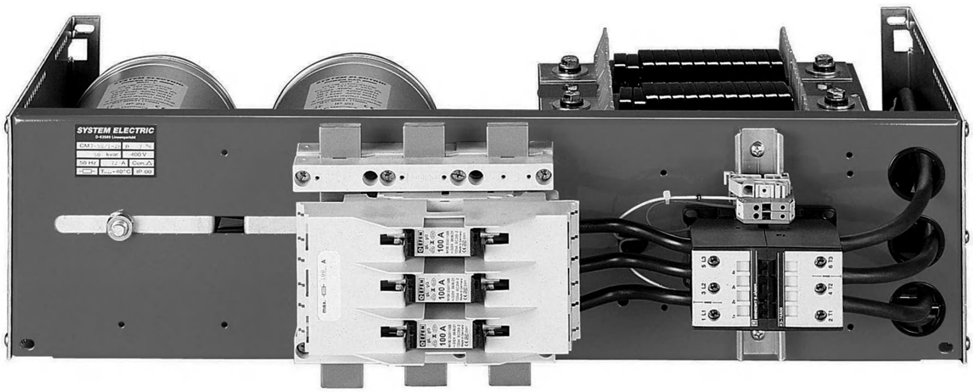


Figure 11.1 A 50 kvar module, 5.67% reactor protected. Reproduced by permission of System Electric Power GmbH, Germany.

11.3.2 Number of Steps and Reactive Power of the Capacitor Steps

Depending on the size of a compensation unit, it is assembled with capacitors of equal size (in bigger units) or of different size. A unit with a total reactive power of, for example, 300 kvar consists of six power capacitors, of 50 kvar each. Thus the number of capacitors is identical to the number of steps: six capacitors controlled by six steps. However, compensation banks with unequal steps, for example 50 kvar and 25 kvar (see Figure 11.2), enable compensation in 'fine-stepping' mode.

Smaller units up to 150 kvar approximately have combinations of different-sized capacitors for economic reasons. A compensation unit with a total of 110 kvar for instance is assembled with four capacitors of 10, 20 and 2×40 kvar (ratio 1:2:4:4) to enable control in 11 steps. Older power factor relays control with a fixed switching program, the so-called 'geometrical switching sequence' (see Figure 11.3); modern relays 'pick out' the correct capacitor size by referring to the actual demand of reactive power directly.

After determination of the total demand of reactive power to be compensated, it is then decided which types of compensation units (see Chapter 9) should be used. With regard to

Figure 11.2 Reactor-protected compensation bank of 400 kvar, 400 V, 50 Hz, 16 × 25 kvar. Reproduced by permission of Frako Kondensatoren und Anlagenbau GmbH, Germany.

their locations, it should be kept in mind that the leads should be unburdened from reactive power at all time. The power losses (kWh) along the leads increase in a squared manner with the apparent power ($I^2 \cdot R$). In smaller installations often one central-type compensation is quite sufficient. The power factor requested by the electricity supplier is to be kept on average within one billing period. Brief deviations from the power factor target must not be controlled quickly. Thus switching time delays per step of 30 to 40 s are quite sufficient. It must be taken into consideration that shorter delays increase the number of switching operations, which often are counted up by modern power factor relays.

Another criterion for choosing compensation banks is the type of consumer: if there are only a few consumers with high rated power, a capacitor bank with rough stepping control is applicable. Installations with many middle- or small-sized consumers require compensation with fine-stepping control. For this purpose more expensive compensation units with up to 12 or even 14 steps are available (Figure 11.4).

During the projecting period, a possible extension in future should be taken into consideration. This is to plan for enough space for the extension unit and furthermore to install a power

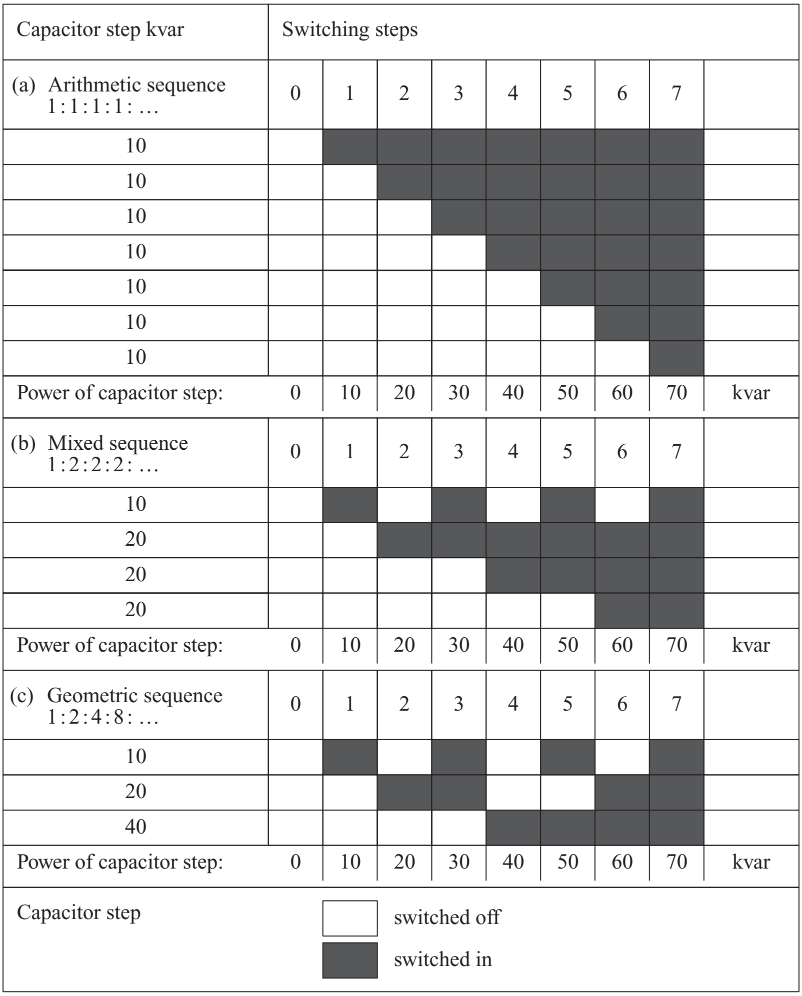


Figure 11.3 Fixed switching programs for equal- or unequal-sized capacitors.

factor relay with the additional control exits. Most of the electronic power factor relays on the market are able to recognize unengaged steps automatically and take them out of operation. If the extension unit is installed, the existing compensation must be ‘volt-free’ including the power factor relay. On completion of the installation, the extended compensation unit will be re-energized; first of all, the power factor relay checks all exits from the outset and recognizes the new capacitor steps (see Figure 11.5a–c).

Older power factor relays still working in many plants around the world follow a strict switching program, for example switching step 1 up to 6 or down from 6 to 1 or 0 (see Figure 11.3, arithmetic sequence). This program contains a major disadvantage with regard to the operating hours per step: in the worst case step 1 is energized all the time compared

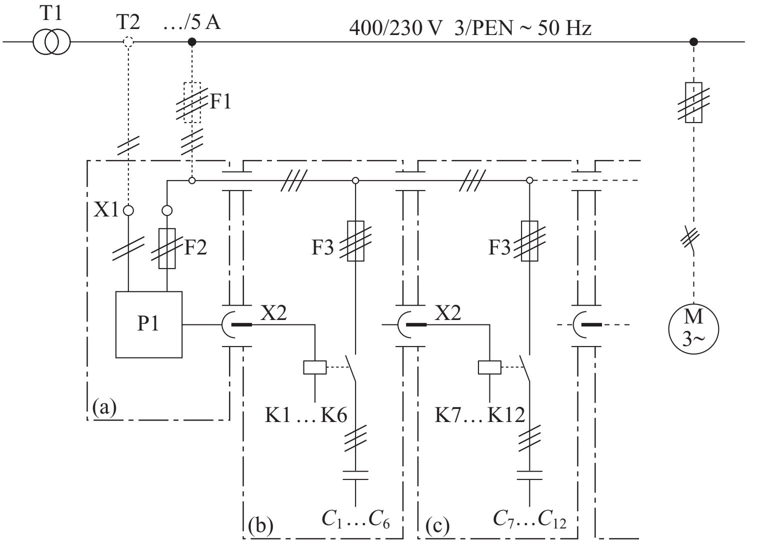


Figure 11.4 Schematic circuit diagram of a compensation unit ready for installation: (a) control unit including power factor relay; (b) basic unit with steps 1–6; (c) extension unit with steps 7–12 (F_1, main fuses; F_2, control fuses; F_3, capacitor fuses; K_1–K_{12}, contactors; P_1, power factor relay; T_1, power transformer; T_2, current transformer (to be installed at the distribution panel), X_1, control terminal; X_2, plug connections between the modules).

Figure 11.5a Power factor controller: 30–525 V, 50/60 Hz; up to 12 control outputs; suitable for four-quadrant operation. Reproduced by permission of Condensator Dominit GmbH, Germany.

Figure 11.5b Reactive power control relay: 400 V/230 V, 50 Hz; 12 control outputs; suitable for four-quadrant-operation. Reproduced by permission of Frako Kondensatoren und Anlagenbau GmbH, Germany.

Figure 11.5c Reactive power controller CONDENSOMATIC 2020: up to 700 V measuring voltage; 50/60 Hz; x A/5 A/1 A; dynamic type:13 ms for switch command; 10 control outputs; suitable for four-quadrant operation. Reproduced by permission of System Electric GmbH, Germany.

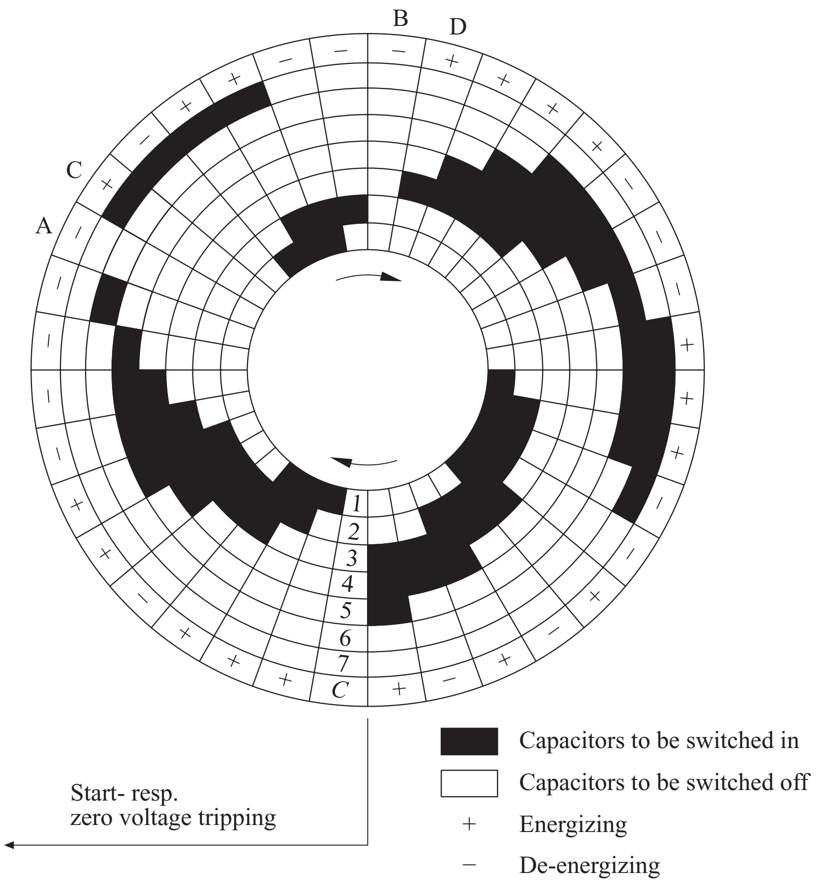


Figure 11.6 Circular or rotational switching program, illustrated as desired.

with step 6 which had never been switched in! Therefore modern power factor relays have changed to the so-called rotational or circular switching program as shown in Figure 11.6. This program distributes the operating hours equally to the capacitors. The capacitor energized for the longest time during the control procedure will be disconnected first and the capacitor which has been switched off the longest time will be connected next. Even for instance at finishing time on Friday (see sectors A & B), if all capacitors are switched off, on Monday morning then capacitor 7 or 3 will be energized first referring to sectors C and D accordingly, provided that there was no zero volt tripping in the meantime.

As mentioned above, smaller compensation units work with capacitors of different sizes, for example 10 kvar, 20 kvar and two capacitors of 40 kvar each. Due to the power ratio 1:2:4:4, the so-called geometric sequence (see Figure 11.3) is used many times. The first step of 10 kvar symbolizes the stepping size of the compensation bank and has the highest number of switching operations during its life. It will be switched in and out four times up to the final step 7, strictly following the switching program. However, modern microprocessor-controlled power factor relays always ‘pick out’ the relevant capacitor, depending on the actual deviation of reactive power. This saves switching operations regarding the 10 and 20 kvar capacitor especially; they will be brought into the control procedure if the actual deviation of reactive power exceeds two-thirds (66%) of either 10 or 20 kvar only. This determines the so-called 'C/k' value to be explained in the next section.

11.3.3 Threshold Level C/k Value

Most compensation banks are controlled stepwise. For this purpose it is essential to 'know' when it is allowed to (de)activate a capacitor step by the power factor relay. The so-called C/k value is calculated by the step size *C* divided by the ratio *k* of the current transformer. It is clear that a capacitor with, for instance, 50 kvar may not be switched in if the power factor relay measures a deviation of just 10 kvar reactive power with regard to the preadjusted power factor target. If so, 40 kvar would 'hang over' to the other side of the line representing the power factor target (see Figure 11.7). The relay would switch off due to the level of 10 kvar. This procedure, called 'hunting' (oscillating), would repeat steadily. This danger occurred in older power factor relays with manual C/k adjustment when it was preset wrongly, or too low. As mentioned at the end of Section 11.3.2, two-thirds (66%) of a step size at least must exist as deviation to enter the control procedure. The percentage may vary between 65 and 85% with reference

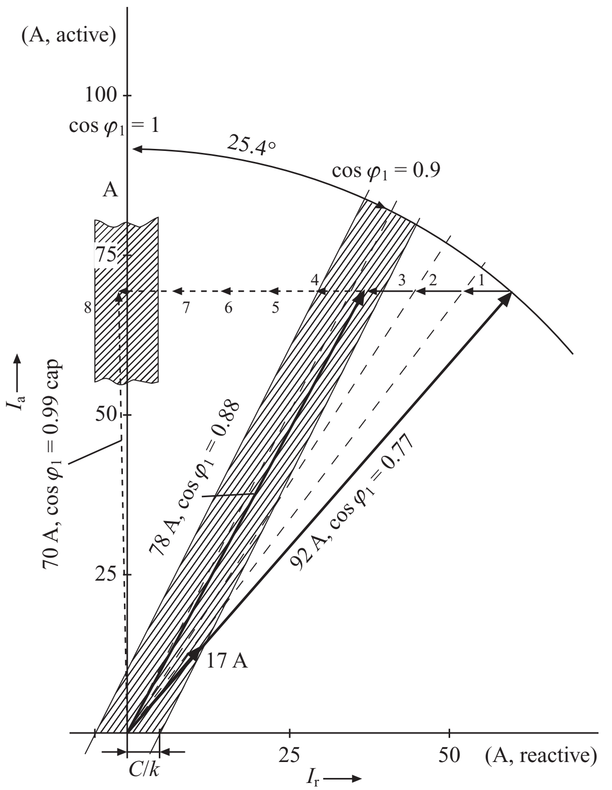


Figure 11.7 Function between cos φ_d line and C/k line.

to realistic tolerances of the capacitor, current transformer and power factor relay itself. The C/k value symbolizes a threshold level running in parallel to both sides symmetrically of the so-called 'reverse line' (see Section 11.3.4) presenting the desired power factor target cos φ_d (see Figure 11.7). Thus the bandwidth of an insensitive zone arises. If the sensed apparent current vector lies within the bandwidth, any control of reactive power is to be stopped. If the vector exceeds the threshold level to the right, the power factor relay has to switch in capacitor steps; if the vector exceeds the threshold level to the left, capacitor steps have to be disconnected in order to bring the vector within the bandwidth again. All power factor relays have to follow the mathematical description accordingly in order to avoid any 'hunting':

$$C/k = (0.65 \text{ to } 0.85) \cdot \frac{Q_C}{\sqrt{3} \cdot U \cdot k} \text{ [Ar]} \tag{11.1}$$

where

C/k = necessary level of reactive current to enter control procedure (Ar = amperes reactive)
Q_C = capacitor step (kvar)
U = delta voltage of the grid (kV)
k = ratio of the current transformer

Example: The aim is to determine the C/k value regarding a capacitor of 50 kvar. A current transformer of 1000 A/5 A ($k = 200$) is in use. Rated voltage is 415 V (phase to phase). Thus

$$C/k = 0.65 \cdot \frac{50\,\text{kvar}}{\sqrt{3} \cdot 0.415\,\text{kV} \cdot 200} \approx 0.23\,\text{Ar or } 0.85 \cdot \frac{50\,\text{kvar}}{\sqrt{3} \cdot 0.415\,\text{kV} \cdot 200} \approx 0.30\,\text{Ar}$$

Thus in older power factor relays provided with manual C/k adjustment, it is allowed to set the C/k value between 0.23 and 0.30 Ar. If the relay strictly follows a geometric switching program of 1:2:4, for example 10, 20 and 2 × 40 kvar, for calculating C/k the smallest step of 10 kvar (stepping size) is to be considered continually.

Table 11.1 lists C/k values depending on step size and the ratio of the current transformer x A/5 A. It is clear that technical limits arise in the sensibility of each power factor relay. It is no longer possible to control a capacitor size of 10 kvar for instance via a current transformer of 2000 A/5 A. Roughly one may say that C/k values below 1% of either 5 A or 1 A mean 0.05 Ar or 0.01 Ar (for a current transformer of 1 A, secondary) is not adjustable.

In modern microprocessor-controlled relays the correct C/k adjustment ensues automatically. They succumb to the minimum of sensibility of 1% as well; at lower values the relays are not able to 'recognize' capacitor steps.

Therefore the C/k value and its meaning are very important to aid understanding. In time, reactive power factor relays with manual C/k adjustment are destined to die out.

Consequently, it is necessary to distinguish between two technologies with regard to the C/k adjustment:

1. Half-automatic C/k adjustment: The market offers power factor relays to set the parameters 'current transformer ratio' and (smallest) 'step size' digitally. Wrong settings may lead to 'hunting' a capacitor step!

Table 11.1 C/k values referring to current transformers x A/5 A.

	Capacitor step C (kvar)														
k	3	4	5	6	7.5	8.3	10	12.5	16.7	20	25	30	33.3	40	50
30/5	0.46	0.60	0.75	0.90											
50/5	0.27	0.36	0.45	0.55	0.68	0.75						C/k			
75/5	0.18	0.24	0.30	0.36	0.45	0.50	0.60	0.75							
100/5	0.14	0.18	0.23	0.28	0.34	0.38	0.45	0.75	0.75	0.90					
150/5	0.09	0.12	0.15	0.18	0.23	0.25	0.30	0.38	0.50	0.50	0.75	0.90			
200/5	0.07	0.09	0.12	0.14	0.17	0.19	0.23	0.28	0.28	0.45	0.57	0.68	0.75	0.90	
300/5	0.05	0.07	0.08	0.09	0.12	0.13	0.15	0.19	0.25	0.30	0.30	0.45	0.50	0.60	0.75
400/5		0.05	0.06	0.07	0.09	0.10	0.12	0.15	0.19	0.23	0.29	0.34	0.38	0.45	0.57
600/5				0.05	0.06	0.07	0.08	0.10	0.13	0.15	0.19	0.23	0.25	0.30	0.38
800/5					0.05	0.05	0.06	0.08	0.10	0.12	0.15	0.17	0.19	0.23	0.29
1000/5							0.05	0.06	0.08	0.09	0.12	0.14	0.15	0.18	0.23
1500/5									0.06	0.07	0.08	0.09	0.10	0.12	0.15
2000/5										0.05	0.06	0.07	0.08	0.09	0.12
2500/5											0.05	0.05	0.07	0.08	0.10
3000/5												0.05	0.06	0.07	0.08
4000/5														0.05	0.06

All values to be divided by 5 if current transformers with secondary 1 A are used.

2. Full automatic C/k adjustment: This makes any setting work superfluous. The relays recognize any capacitor step automatically due to its ‘compensation effect’, which is to be stored in the microprocessing unit and updated continually with regard to fluctuations of the voltage or losses in capacitance. Even possible extensions of single steps in the future will be recognized. The relay considers the tolerance of switching level (65 to 85%) as well. Most advantageously, there is the possibility of controlling capacitor sizes as desired, supposing the minimum level of 1% is ensured (see above). Any strict switching program is no longer fulfilled.

11.3.4 Reverse Control Scheme (cos φ_d Line)

The best way to explain the relationship between C/k value and the power factor target is shown by Figure 11.7. As mentioned in Section 11.3.3, the C/k values symbolized by two parallel lines and symmetrically along the cos φ_d line form a so-called insensitive zone (hatched). If the power factor target is to be adjusted to unity (cos $\varphi_d = 1$) the zone lies parallel to the ordinate of the four-quadrant system (left). Adjusted power factor targets lower than unity (<1) turn the bandwidth either into the fourth quadrant (capacitive, left) or into the first quadrant (inductive, right). The most popular tariff prescribed by the electricity supplier is to achieve a power factor of cos $\varphi_d \geq 0.9$ on average within the billing period (see Section 4.2.1). If a customer operates with a generator, even feeding back active energy into the grid, the consumer will be forced to preset the power factor target of cos $\varphi_d = 1$ all the time (for a detailed explanation see Chapter 16).

Figure 11.8 Two of five cubicles with total reactive power of 1400 kvar, 400 V, 50 Hz for the purpose of compensating reactive power on the MV side (20 kV) via its own transformer of 1600 kVA (see Figure 11.9). Reproduced by permission of Stahlwerk Annahuette Max Aicher & Co KG, Germany.

The current transformer for the power factor relay should be installed close to the metering point, if possible. However, in larger industrial plants energy will be metered on the MV side usually. However the current transformer for the p.f.relay is installed at LV-side. In this case the power factor target is preset higher than 0.9, for example from 0.95 to 0.98, depending on the number of feeding power transformers (uncompensated), to ensure achieving a power factor higher than 0.9 on the MV side. As mentioned above, the transformer(s) draw(s) over reactive energy from the MV side to be metered. The compensation bank for this purpose is to be determined accordingly of course.

As explained in Chapter 4, it is essential to achieve the prescribed power factor of $\cos \varphi_d \geq 0.9$ on average. Instantaneous power factors, indicated by the relay, may vary over a wide range during the daily control procedure. It depends on the load profile and whether the compensation bank is working with large or small capacitor steps (rough or fine stepping).

Large capacitor steps broaden the insensitive zone and small steps curtail it, and increase or decrease the C/k value respectively, as shown on the horizontal axis (abscissa) of the four-quadrant system.

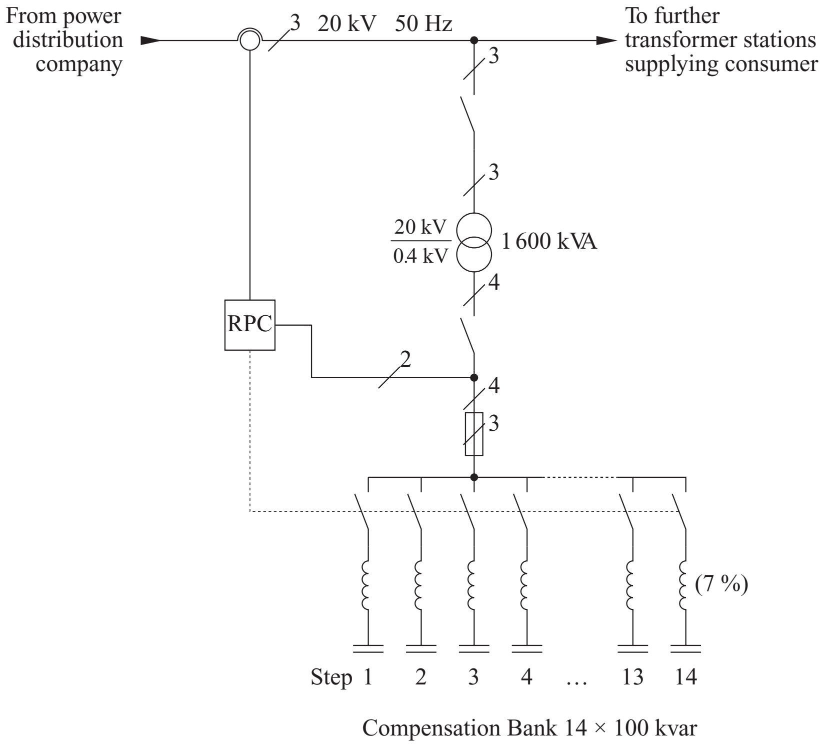


Figure 11.9 Circuit diagram of the described 1400 kvar compensation (RPC = Reactive Power Controller).

Another important point is the ratio of the installed current transformer. If its ratio is determined to be too high, the following control situation may occur: a low apparent vector of, for example, 17 A (see Figure 11.7) at an instantaneous power factor of 0.77 will lie within the bandwidth and the power factor relay will not start to control, though the relay indicates this bad power factor!

The market offers power factor relays with adjustable power factor targets in the range from 0.7 lagging through 1 to 0.9 leading side regularly.

11.3.5 Automatic Reactive Power Control

Regarding Figure 11.7, it can be seen that to achieve the desired power factor of $\cos\varphi_d = 0.9$ approximately, just three capacitor steps are sufficient, compared with the preset power factor of $\cos\varphi_d = 1$, where the relay requests eight capacitor steps to bring the vector back within the hatched bandwidth! This calls for higher investment costs of course, which are negotiated with the customer. However, recall that the leads are to be totally unburdened by the reactive current and the active power losses ($I^2 \cdot R$) will be reduced by 40% approximately (more expensive kWh). The varmeter stands by in case the metering point and the location of the current transformer are identical. As the higher power factor is preset to unity, the fewer active power losses will be metered. The ‘danger’ of overcompensation into the fourth

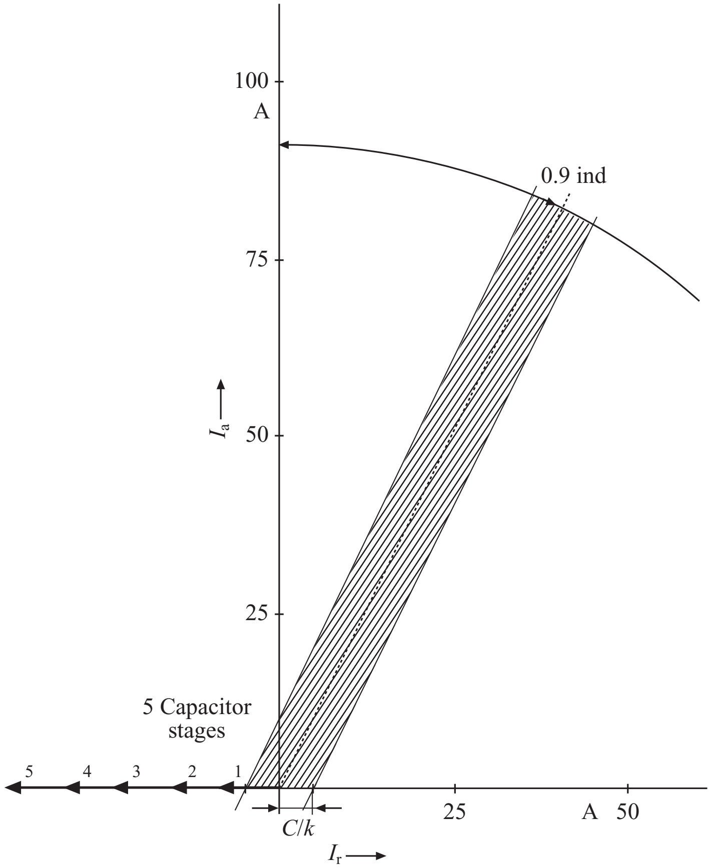


Figure 11.10 Leading load condition in the case when all inductive consumers are disconnected.

quadrant (capacitive) is given daily during the control procedure, as illustrated in Figure 11.10. When switching off all the consumers at finishing time, the power factor relay disconnects all the capacitors step by step according to the preset switching time delay per step, for example 40 seconds. In other words, it is clear that the resulting apparent current vector is in the fourth quadrant (capacitive) exclusively. This does cause a voltage increase, but it runs in the lower range of the percentage and may not be assessed as a 'danger'. It is easy to calculate the ratio of the instantaneous reactive power of the capacitor(s) to the short-circuited power of the grid.

In general no power factor relay is able to avoid capacitive loads during the control procedure. Even at large electrical plants such as car or steel factories, one can find LV capacitor banks connected exclusively to a power transformer in order to compensate reactive power at the MV side, because it is less expensive compared with MV compensation (see Figures 11.8 and 11.9). To limit the voltage increase at the LV side, it is possible to choose a higher tapping point at the tap-changer on the primary side of the power transformer, for example from 20 to 22 kV (e.g. in European countries).

Besides the possibility that control of reactive power may run into the fourth quadrant, the power factor may pass $\cos \varphi_a = 1$. This means that the impedance of the capacitor is identical to the impedance of the inductive consumers but with opposite vectors. This normally leads to the ‘danger’ of resonance; however, the ohmic vector stabilizes the system.

11.3.6 No-Volt Release Function

It is indispensable to have a protective device at each power factor relay, the so-called no-volt release function. With the exception of urban areas, the distribution of electrical energy runs via overhead leads at the MV level (10 to 30 kV in Europe) to distribute electrical energy to various locations. Sometimes there are disturbances, for example earth leakages or even short circuits by branches falling down onto the leads, caused by heavy storms. Then the circuit breaker in the next station switches off the leads briefly for about 200 to 300 ms. If the branch is burnt or falls to the ground in the meantime, the net is able to transmit energy again. However, if the disturbance persists, the circuit breaker switches off again until it has been cleared. This interruption is hazardous to compensation banks because the contactors would disconnect the capacitors briefly and re-energize them in the worst case with double-sized peak voltage in opposition (more than 1100 V, if the capacitor has been disconnected at the instantaneous peak voltage of −565 V and re-energized with +565 V of the 400 V grid). This would generate very high inrush currents in the kiloamp range and the danger of welded contacts.

If the power factor relay recognizes a voltage interruption of longer than 20 to 50 ms, it has to block the controlling procedure for 90 s at least as discharging time of the capacitors. This is called ‘lock-time’. Afterwards it may start to control again.

11.4 How to Wire a Power Factor Relay

In order to measure electrical power the relay needs to get the line voltage and current from a current transformer installed close to the metering point, if possible. To measure reactive power at the power factor relay especially, it must be ensured that the vectors of voltage and current are shifted by 90°. In three-phase systems this is simple to realize by measuring the current in phase L1 and the voltage path is taken from the other two phases L2 and L3. The so-called current path of the power factor relays is standardized to either 5 A (mainly) or 1 A. One has to take into consideration that the ratio of the current transformer is adapted to the load expected and the primary current will be transformed to the secondary side proportionally. An oversized ratio, for example using 1000 A/5 A, but expecting no more than 200 A, leads to an inaccuracy in the control of reactive power. The current transformer must seize both the load of the consumers and the compensation bank. Figure 11.11 illustrates a simplified circuit diagram of how to wire the current path to the terminals k and l of the power factor relay.

In general the reactive power of a three-phase system is measured by means of the current transformer in one phase only chosen as desired, mainly L1 (or A). The correct installation of the current transformer is very important, showing on its side K the feed-in point of the electricity utility and its side L to the consumers including the compensation bank(s). According to Figure 11.12, there is the possibility of measuring the load either on the LV or on the MV side. Alternatively, there is the method of ‘mixed measurement’ as described in Section 11.5.

Most applications use the LV method, because a separate current transformer on the MV side is not available all of the time, not to mention the costs. It is a matter of course that the power transformers are not compensated by the automatic compensation bank on the LV side. Recall that the desired power factor cos φ_d, preset at the relay, is to be achieved at the location of the current transformer exclusively and consumers will be compensated only just downside

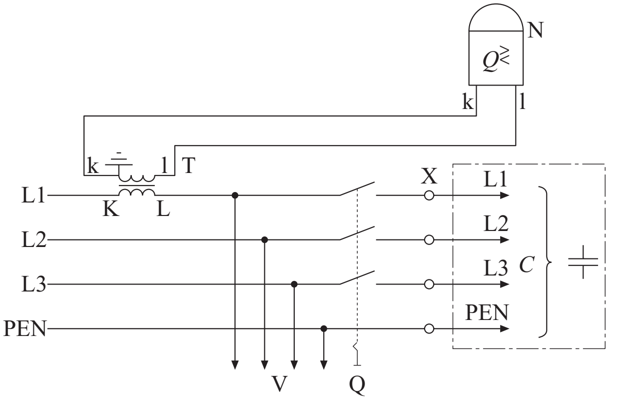


Figure 11.11 Simplified connecting diagram of the current path to the reactive power relay (V, consumers; T, current transformer (c.t.); C, compensation bank; Q, circuit breaker; N, power factor relay; K, terminals).

(the L side of the current transformer), referring to the flow of energy. Detailed descriptions of the selection and location of current transformers are presented in Section 15.2.2.

11.5 Reactive Power Control by 'Mixed Measurement'

The previous section mentioned two possibilities for taking current and voltage either from the LV side or from the MV side for the power factor relay. A third possibility offers

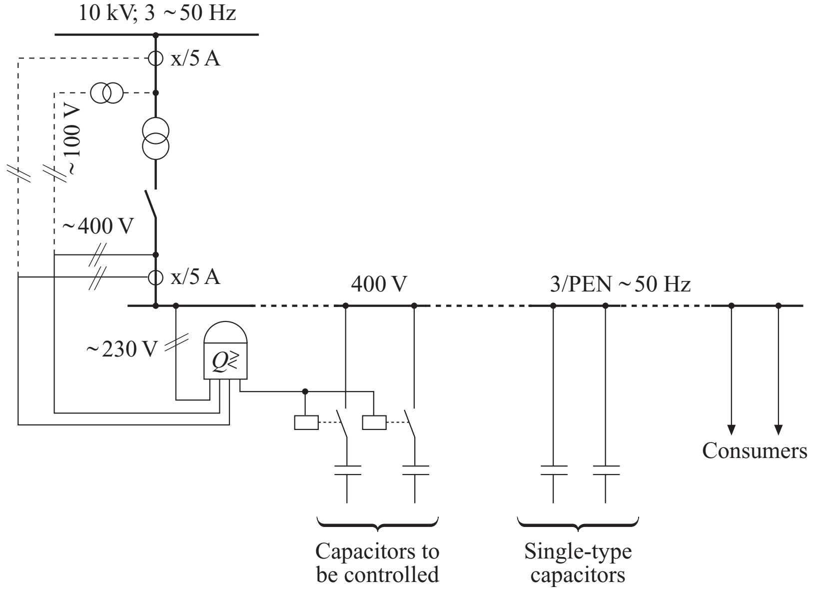


Figure 11.12 Circuit diagram of compensation taking the current and voltage path either from the LV or from the MV side.

so-called ‘mixed measurement’. The voltage path for the power factor relay is taken from the LV side; however, the current path is taken from a current transformer installed at the MV side. Although the mixed measurement is rarely in use, it is very important to discuss. It refers mainly to large industrial plants like car factories or steelworks. This method is considered if a voltage transformer on the MV side is not available. Incidentally, voltage transformers for metering purposes are not allowed to be used.

The method has the advantage that all consumers downside (L-side) from the current transformer are to be compensated, including the power transformer(s), by the compensation bank at the LV side. As described in Section 11.4, the power factor relay’s voltage path and current path have to be shifted at most by 90° electrical against each other, enabling the power factor relay to measure reactive power correctly. It is well known that power transformers have individual vector groups as shown in Figure 11.13. It means, for example, that a transformer

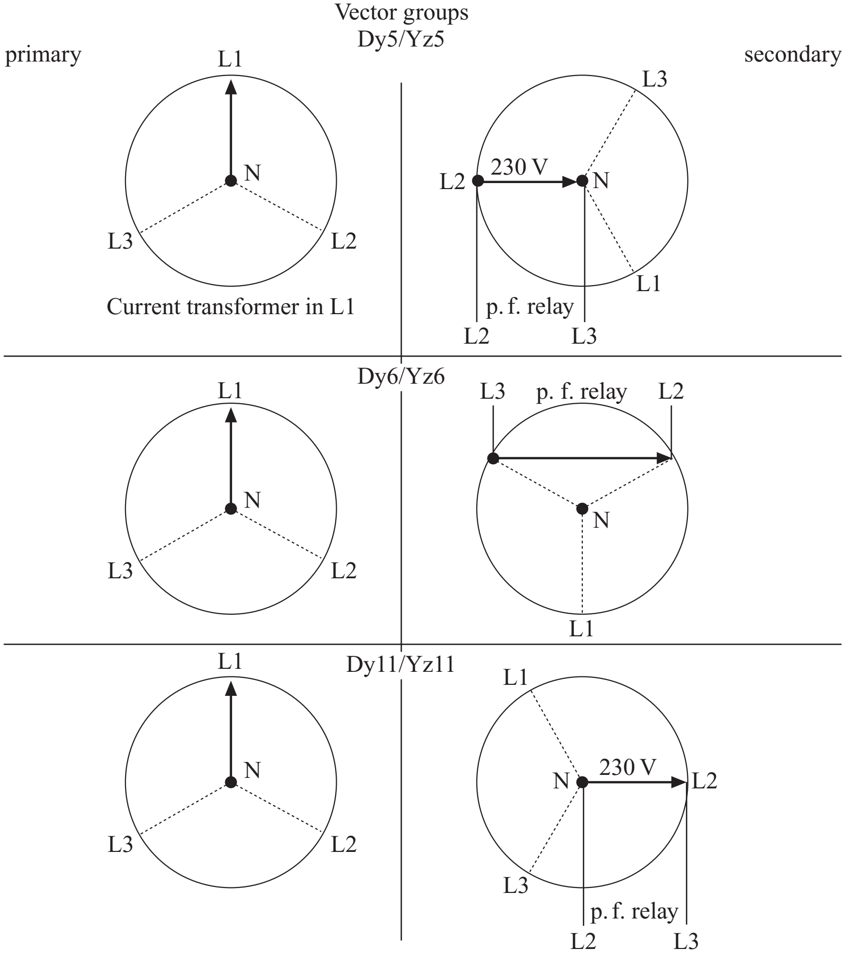


Figure 11.13 Mixed measurements: voltage path taken from the LV side and current path taken from the MV side at power transformers of different vector groups (p.f. = power factor).

with vector group Dy11 shifts all phases at the secondary side $11 \times 30^\circ = 330^\circ$ clockwise compared with the primary side. To get a 90° shifted voltage path for the power factor relay, it is connected with the star voltage L2 against N. Figure 11.13 shows all the possible vector groups for three-phase power transformers.

For the vector groups Dy5/Yz5 or Dy11/Yz11, the voltage path is connected in phase L2 to neutral at the LV side assuming the current transformer is measuring in phase L1 at the MV side. Power transformers with vector group Dy6/Yz6 (rarely) deliver the 90° shifted voltage path for the power factor relay between the phases L2 and L3. Modern power factor relays work with voltage paths in the range of 100 to 500 V. Older relays have to be modified for the voltage path.

This method of mixed measurement requires special attention with regard to the C/k calculation. Here, as before, Equation 11.1 is valid:

$$C/k = 0.65 \cdot \frac{Q_C}{\sqrt{3} \cdot U \cdot k}$$

Example: A compensation bank of 600 kvar (12 steps of 50 kvar each) is to be controlled by mixed measurement with a current transformer of 50 A/5 A ($k = 10$) at the MV side, rated voltage 20 kV.

Most important is the use of the correct voltage in the formula above. In general the voltage level is taken at which the current transformer is measuring all of the time. Thus

$$C/k = \frac{50\,\text{kvar}}{\sqrt{3} \cdot 20\,\text{kV} \cdot 10} = 0.09\,\text{Ar}$$

This value has to be set correctly at power factor relays by manual or half-automatic C/k adjustment (see Section 11.3.3). Power factor relays with fully automatic C/k adjustment measuring according to the so-called compensation effect per step recognize the step sizes automatically. There is nothing else to pay attention to, except that the minimum sensibility of 1% should not be decreased (see Section 11.3.3). Even though the current transformer is not measuring in phase L1 at the MV side but in L2 all the time, it has to find the 90° shifted voltage path. In power transformers with vector group Dy11/Yz11 the voltage is taken from phase L3 against neutral.

Sometimes the neutral lead is not available. In this case the market offers power factor relays that shift the voltage path inside. Then the voltage path must be taken from phases L1 and L3.

11.6 Reactive Power Control with Multiple Feed-ins

11.6.1 Measuring by Means of Summation Current Transformer

Larger electrical plants have multiple feed-ins with two or more power transformers usually working in parallel. Regarding the control of reactive power, there are two solutions possible. The first solution is, according to Figure 11.14, to measure the load via three current transformers of 1500 A/5 A with each incoming supply fed by one power transformer of 1000 kVA. The three current paths are summed in a summation current transformer with three input paths,

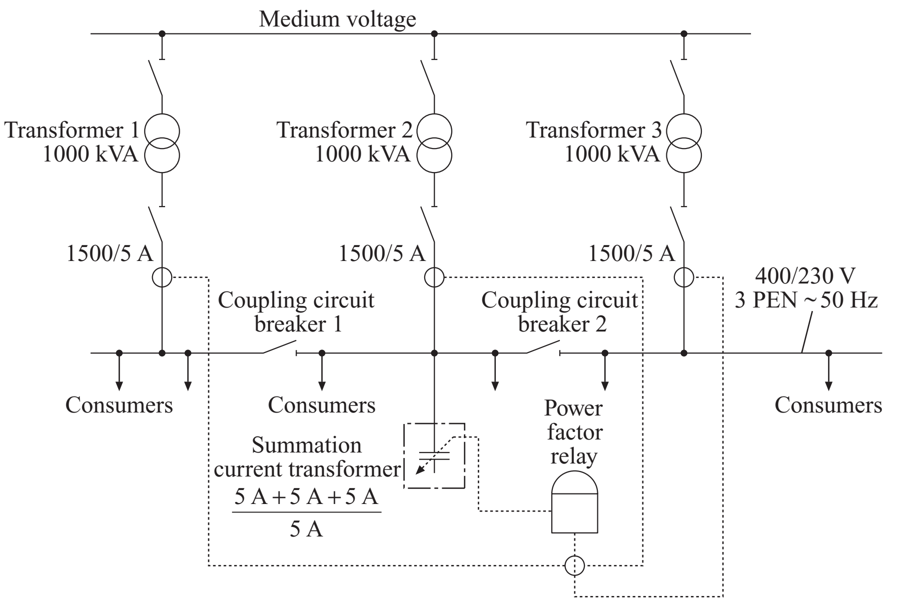


Figure 11.14 Central-type compensation by means of summation current transformer.

of 5 A each, and one output path of 5 A too. This output is wired to the current path of the power factor relay controlling a 12-step central compensation bank of 600 kvar. The method has a big disadvantage: for proper control of reactive power it is necessary to keep the two coupling circuit breakers 1 and 2 closed all the time! In case of any short circuit, all three power transformers generate a very high power as a rule.

Suppose coupling circuit breaker 1 is opened; then the power factor relay is not able to compensate the reactive power of consumers connected to the busbar to the left. However, the relay notes a higher request for capacitors to be switched in. This could lead to overcompensation at transformers 2 and 3; it means that the capacitive reactive power goes up to the busbar of the MV level and via transformer 1 to the consumers to be compensated. This transmission of reactive power causes additional active power losses along the cables and in the transformers of course.

The third disadvantage is that the power factor relay is not able to 'see' in which area reactive power arises, due to the summation current transformer and the central-type compensation connected to the busbar in the middle. Despite this, it is essential to discuss how to calculate the C/k value for correct adjustment.

For this purpose Equation 11.1 is again used:

$$C/k = 0.65 \cdot \frac{Q_C}{\sqrt{3} \cdot U \cdot k}$$

Factor k is to be determined separately:

$$k = \frac{1500\,\text{A} + 1500\,\text{A} + 1500\,\text{A}}{5\,\text{A} + 5\,\text{A} + 5\,\text{A}} \times \frac{5\,\text{A} + 5\,\text{A} + 5\,\text{A}}{5\,\text{A}} = \frac{4500\,\text{A}}{15\,\text{A}} \times \frac{15\,\text{A}}{5\,\text{A}}$$
$$= 300 \cdot 3 = 900$$

The first term symbolizes the total ratio of the three current transformers, and the second, symbolizing the summation transformer to be multiplied, results in a very high total ratio of $k = 900$. It is then necessary to check whether the relay's minimum sensibility of 1% will not be undersized.

Finally the C/k value is to be calculated according to Equation 11.1:

$$C/k = 0.65 \cdot \frac{50\,\text{kvar}}{0.415\,\text{kV} \cdot \sqrt{3} \cdot 900} \approx 0.05\,\text{Ar}$$

This value is adjustable at most power factor relays by manual C/k setting or at relays with half-automatic adaption (see Section 11.3.3).

Suppose a fourth incoming supply with an additional power transformer of 1000 kVA increases the total ratio referring to four current transformers to be summarized up to $k = 1200$ and the C/k value decreases down to 0.038 approximately.

This value decreases the 1% level distinctly. There would be only the possibility of varying the factor of 0.65 up to 0.85 or, in another calculation, to show at which percentage of the step size (50 kvar) a power factor relay with fully automatic C/k adaption would start to control:

$$\frac{0.65}{0.038\,\text{A}} = \frac{x}{0.05\,\text{A}}, \quad \cdot x = 0.65 \cdot \frac{0.05\,\text{A}}{0.038\,\text{A}} = 0.85 \tag{11.2}$$

The relay would (re-)energize the capacitor at a level of 85% referring to 50 kvar, or 42.5 kvar only. Proper control of the capacitors is no longer guaranteed due to the tolerances of the relay and the capacitor as well. Regarding factor k, it does not matter whether all power transformers are in operation or not. Factor k is just a characterizing constant of the entire electrical plant.

As mentioned previously, this method of controlling reactive power has some disadvantages. To install individual compensation banks for each incoming supply is much more suitable, as described in the following section.

11.6.2 Parallel Operation of Compensation Banks for Each Incoming Supply

Referring to Figure 11.15, the advantages can be seen at once. Control of reactive power runs individually for each incoming supply with the help of its own compensation bank, each controlled by an automatic reactive power controller. It does not matter if the position of the coupling circuit breakers 1 and 2 is open or closed. If they are open, the compensation banks operate individually; if they are closed, one encounters the parallel operation, to be discussed next. All three power factor relays working in parallel are preset to the identical power factor target between each other. Regarding the switching time delay per step, there is no need to preset the same value, just an approximate one, for example in the range between 35 and 40 s per step.

The C/k calculation from Equation 11.1 again is simple as no summation current transformer must be considered. Thus the ratio of the current transformer amounts to

$$k = \frac{1500\,\text{A}}{5\,\text{A}} = 300\; C/k = \frac{0.65 \cdot 50\,\text{kvar}}{0.415\,\text{kV} \cdot \sqrt{3} \cdot 300} = 0.15\,\text{Ar}$$

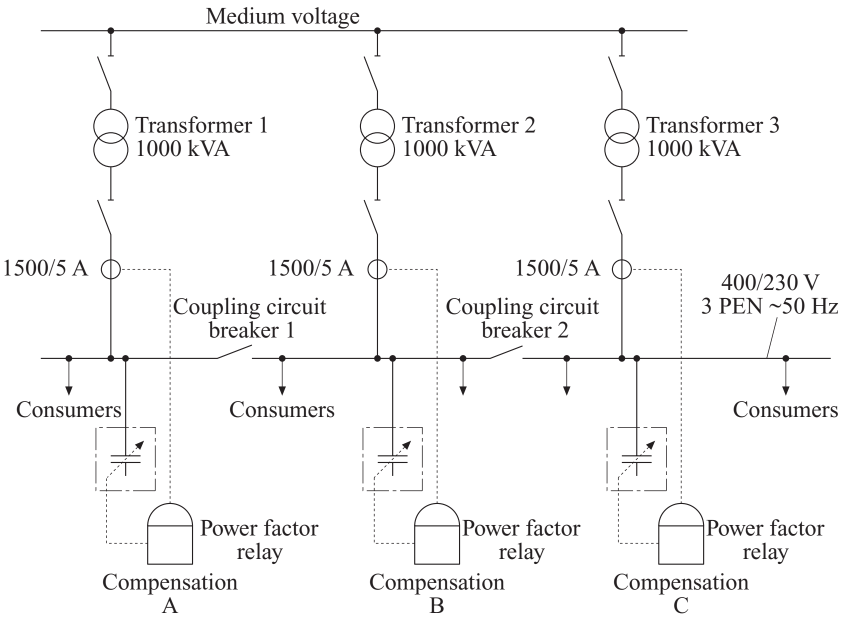


Figure 11.15 Central-type compensation for each incoming supply.

This C/k value is to be preset at each relay with manual or half-automatic C/k adaption identically in the case of open coupling circuit breakers. But what is the situation with closed coupling circuit breakers? The step size of 50 kvar is only one-third measured by the current transformers, supposing the same impedance voltage at the power transformers operating in parallel. This would mean the preset C/k value depends on the position of the coupling circuit breakers and is to be corrected all of the time. This is indeed a major disadvantage if using power factor relays with manual or half-automatic C/k adjustment. Thus the best solution would be to use power factor relays with the feature of 'full automatic C/k adaption' (see Section 11.3.3). They always register the so-called compensation effect for each step independently of the position of the coupling circuit breakers 1 and 2. Even if breaker 2 is open and 1 is closed, the current transformer of compensation bank C registers the full size of the capacitor, but the current transformers of compensation banks A and B only half the size. It is not necessary to discuss the disadvantages of power factor relays with manual or half-automatic C/k adaption further.

During the installation of large electrical plants with currents of more than 1000 A approximately occurring. attention should strictly be paid that, for example, cables from the power transformers to the busbars are of the same length in order to ensure symmetrical load distribution.

Another situation it is essential to mention is the case when one power transformer, for example no. 3, is out of operation due to maintenance and, provided that the coupling circuit breakers are closed of course, that the power factor relay of compensation C is energized but does not get any signal from the current transformer. With regard to Figure 11.7 or Figure 11.10, there is no vector existing that exceeds the C/k threshold level. Older relays would 'stand by' with the number of capacitors switched in as before. They would not be able to establish control until maintenance is finished. Not all brands of power factor relays have the capability to disconnect the capacitor(s) after a defined measurement time of 'no current' or '$I = 0$' is displayed. Thus it is essential to get information on this from the manufacturer.

Summarizing, it is best to focus on the described method in preference to the method of Section 11.6.1 as there are several advantages:

- Control of reactive power independently of the position of the coupling circuit breaker.
- Possibility to limit the power in case of a short circuit.
- De-centralized compensation enabling location much closer to consumers of reactive power.

11.7 Performances of Automatic Compensation Banks

During previous decades manufacturers of automatic compensation banks faced increasing competition worldwide. They were forced to produce as economically as possible. Now, new technologies have been developed compared with the past when capacitors were bigger and heavier. Minimizing capacitors enabled the development of modules containing capacitors (steps) with discharging resistances, fuses, contactors and reactors (if required) assembled in standardized industrial cubicles.

Power factor relays are usually fitted in the doors. Due to reduced active power losses inside the capacitors, today it is possible to assemble compensation banks up to 400 kvar or more within one cubicle of dimensions $(B \times H \times W) = 600$ mm $\times$ 2000 mm $\times$ 400 mm (without reactors).

Smaller compensations up to 150 kvar are available in cubicles for wall mounting (see Figure 11.16a–d). They are all assembled ready for installation; only an additional cable between the current transformer and power factor relay has to be installed.

The following chapters illustrate the performance of compensations of different brands.

Figure 11.16a Compensation bank of 300 kvar; 440 V, 60 Hz; switching in 12 steps of 25 kvar each; reactor protection $p = 7\%$. Reproduced by permission of General Motors do Brasil, Brazil.

Figure 11.16b Compensation bank for wall mounting of 52.5 kvar; 400 V, 50 Hz; switching in seven steps × 7.5 kvar. Reproduced by permission of Frako Kondensatoren und Anlagenbau GmbH, Germany.

Figure 11.16c Compensation bank combining three technologies of reactive power control via air contactors as well as static contactors and control of passive filters. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

Figure 11.16d Compensation bank of 1500 kvar; 690 V, 60 Hz; reactor protection $p = 7\%$; for offshore oil platform. Reproduced by permission of System Electric GmbH, Germany.

11.8 Summary

Nowadays, with, for example, electronic calculators, it is still essential to know the basics of mathematics, of course. The same situation arises with electronic reactive power controllers and power factor relays. Without any knowledge of technical matters, the coherences or functions are difficult to understand.

That is the goal of this Chapter 11: to enable the reader to follow all the technical parameters like the C/k value, C/k threshold lines, reverse control scheme ($\cos\varphi$), switching time delay, no-volt release function, and so on.

Further important aspects are to be noted in the case of industrial plants with more than one feed-in transformer operating in parallel and the position of coupling circuit breakers. They influence the C/k value as described. At these plants, reactive power controllers with fully automatic C/k adaption become a proper application exclusively.

In addition, several figures showing capacitor units and banks illustrate this chapter.

12

Discharging Devices for Power Capacitors

12.1 Chapter Overview

This chapter underlines the importance of components for unloading charged capacitors after disconnection from the grid. For this purpose resistances with fixed connection to the capacitor are mainly in use. Sometimes inductances are used as well if quick discharging is required. During normal operating periods the inductance to be connected in parallel with the capacitor forms a high impedance ($X_L = 2 \cdot \pi \cdot f \cdot L$) due to the power system frequency f. After disconnection, only the ohmic resistance of the coil is effective for a rapid discharge of the capacitor. This provides significant protection with regard to re-energizing the capacitor to be discharged. Furthermore, it avoids any electric shocks to persons touching a disconnected capacitor, which still may be in a charged condition due to missing discharging devices. The capacitor would keep the voltage for a long time because the discharging procedure runs via the insulating resistance between the foils.

12.2 Basis at LV Applications

After disconnection of a power capacitor the instantaneous voltage at the time of disconnection is stored for a long time if there are no discharging devices connected in parallel. This voltage could be any value between 0 V and plus or minus peak voltage. In order to prevent any accidents or high inrush currents the capacitor has to be discharged within a defined time according to DIN VDE 0560. In automatically controlled compensation banks the stored voltage in the capacitor is to be discharged down to less than 10% of the rated voltage before re-energizing again. It must be ensured that the connection between the discharging device and the capacitor is fixed without any fuses or switch.

The time for discharging the capacitor depends on the ohmic resistance and the capacitance of the capacitor:

$$\tau = R \cdot C \tag{12.1}$$

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

where
τ = time constant (s)
R = resistance (Ω)
C = capacitance (μF)

Example 1: The time constant τ for a capacitance of 66 μF and a resistance of 1 MΩ connected in parallel is determined by

$$\tau = R \cdot C = 10^6 \frac{\text{V}}{\text{A}} \times 66 \times 10^{-6} \frac{\text{A s}}{\text{V}} = 66\,\text{s}$$

This time constant indicates the capacitor's loading condition after 66 s, which is 37% of the initial stored voltage. The discharging procedure runs according to an inverse exponential function as outlined in Figure 12.1. The time constant τ scaled on the horizontal axis (abscissa) indicates that the voltage of, for example, 565 V decreases within 66 s down to $0.37 \cdot 565$ V = 209 V if the capacitor has been disconnected at the instantaneous value (+ or −) of the peak voltage. The duration of total discharge of the capacitor lasts about five times the time constant ($5 \cdot 66$ s = 330 s), that is five and half minutes.

To calculate the instantaneous voltage during the discharging procedure requires the following formula, valid for single phase arrangement as shown in Figure 12.2:

$$u = \hat{u} \cdot e^{-t/R \cdot C} \tag{12.2}$$

where
u = voltage of the capacitor after t seconds
$\hat{u}$ = stored voltage after disconnection (e.g. peak voltage as the worst case condition)
R = discharging resistance
C = capacitance of the capacitor
e = base of the natural logarithm ($e = 2.718\,28$)

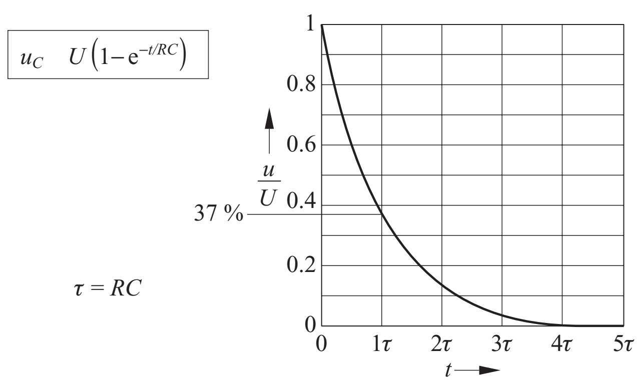


Figure 12.1 Discharging procedure according to the function based on natural logarithm. *Source*: VDE-Verlag GmbH, Berlin and Offenbach, Germany.

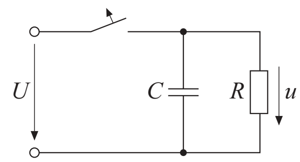


Figure 12.2 Circuit diagram of capacitor and discharging resistance connected in parallel.

Example 2: The discharging resistance for a three-phase capacitor of 10 kvar with a selected time constant of $\tau = 10$ s is to be calculated. The 10 kvar capacitor consists of three foil coils with a capacitance of 66 μF each. To determine the resistance Equation 12.2 has to be modified in terms of natural logarithms:

$$u = \hat{u} \cdot e^{-t/R \cdot C} \Rightarrow \ln u = \ln \hat{u} \cdot \frac{t}{R \cdot C} \Rightarrow R = \frac{\ln \hat{u}}{\ln u} \cdot \frac{t}{C}$$

If the capacitor had been switched off at any value of the voltage, the resistance would have discharged down to 37% of the initial voltage within the time constant $\tau = t = 10$ s. Suppose the instantaneous voltage during the switch-off procedure is identical to the positive peak voltage

$$\hat{u} = 400\,\mathrm{V} \cdot \sqrt{3} = 566\,\mathrm{V}$$

and

$$u = 0.37 \cdot 566\,\mathrm{V} = 209\,\mathrm{V}$$

Then the resistance R is calculated as

$$R = \frac{\ln 566\,\mathrm{V}}{\ln 209\,\mathrm{V}} \cdot \frac{t}{C} = \frac{6.34}{5.34} \cdot \frac{10\,\mathrm{s} \cdot \mathrm{V}}{66 \cdot 10^{-6}\,\mathrm{A\,s}} = 1.187 \cdot \frac{10\,\mathrm{V}}{66\,\mathrm{A}} \cdot 10^{6} \approx 150\,\mathrm{k\Omega}$$

Thus the time constant is

$$\tau = R \cdot C = 150 \cdot 10^{3}\frac{\mathrm{V}}{\mathrm{A}} \cdot 66 \cdot 10^{-6}\frac{\mathrm{A\,s}}{\mathrm{V}} = 9900 \cdot 10^{-3}\,\mathrm{s} \approx 10\,\mathrm{s}$$

The time of voltage decrease down to 10% of the initial voltage ($u \approx 57$ V) is calculated by

$$\begin{aligned} t &= \frac{\ln u}{\ln \hat{u}} \cdot R \cdot C \\ &= \frac{\ln 566\,\mathrm{V}}{\ln 57\,\mathrm{V}} \cdot 150 \cdot 10^{3}\frac{\mathrm{V}}{\mathrm{A}} \cdot 66 \cdot 10^{-6}\frac{\mathrm{A\,s}}{\mathrm{V}} = \frac{6.34}{4.04} \cdot 9900 \cdot 10^{-3} = 1.57 \cdot 9.9\,\mathrm{s} \approx 15.5\,\mathrm{s} \end{aligned}$$

Thus it is recommended to preset the switching time delay at power factor relays not lower than 20 s approximately.

The power loss of the resistance in the case of the capacitor energizing is to be calculated:

$$P = \frac{U^2}{R} = \frac{(400\,\mathrm{V})^2\ \mathrm{A}}{150 \cdot 10^{3}\,\mathrm{V}} = \frac{160 \times 10^{3}\,\mathrm{V}^2 \times \mathrm{A}}{150 \times 10^{3}\,\mathrm{V}} = 1.06\,\mathrm{VA} \approx 1.1\,\mathrm{W}$$

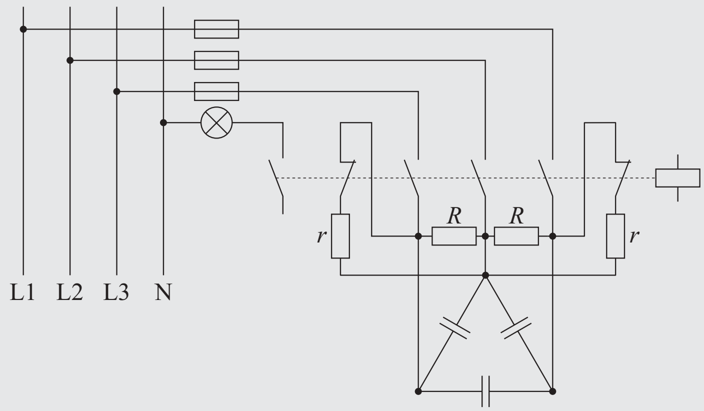


Figure 12.3 Circuit diagram of discharging resistances *R* in V connection including two additional resistances of low ohmic values to be switched in by two auxiliary contacts for rapid discharging.

Thus one has to connect three resistances of 150 kΩ; however, in practice just two resistances in so-called V connection (see Figure 12.3) are generally used. For the correct calculation of the discharging resistance in the calculation above one should set $C = 99$ μF as one and a half single-phase capacitors are effective. This results in two resistances of 100 kΩ each. The power loss for each resistance would amount to 1.6 and 3.2 W total compared with 3.3 W with the three resistances above.

12.2.1 Rapid Discharging with Additional Resistances Switched In

Sometimes, automatic capacitor banks are fitted with contactors having auxiliary contacts (resting contacts) to allow additional resistances with low ohmic values to be switched in for rapid discharge (see Figure 12.3). If the main contacts for the power capacitor are opened the low ohmic resistances are connected in parallel to the high ohmic resistance.

This method enables a quicker discharge of the capacitor due to the lower switching time delay allowed. This need may arise in installations with high fluctuations in reactive power, for example with cranes. Last not least, it must be underlined that any discharging procedure generates heat in the resistances; this means that any electrical energy stored in the capacitor will be converted into heat. This limits the switching operations within a defined time period. On this point, it is worth paying attention to the MV capacitor banks especially (see Section 12.3).

12.2.2 Discharging Capacitors by Means of Reactors

If there are no auxiliary resting contacts available at the contactors, manufacturers of capacitor banks use reactors connected in parallel to the capacitor. As mentioned above, they form high impedances due to the frequency, if the capacitor is energized. After disconnection of the capacitor, only the ohmic resistance of the coil becomes effective in decreasing the stored

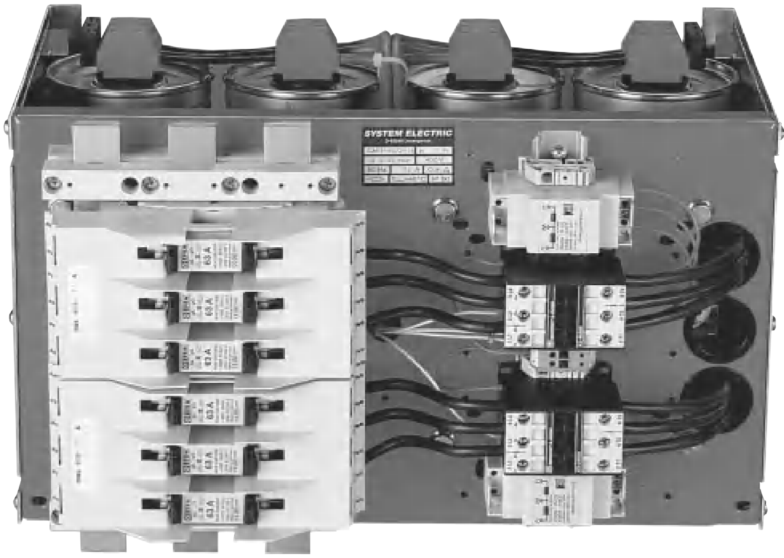


Figure 12.4a Capacitor module of 2 × 25 kvar, 400 V, 50 Hz, fitted with discharging reactors besides the contactors. Reproduced by permission of System Electric GmbH, Germany.

(DC) voltage according to the natural exponential function as described above. There is no doubt that these discharging devices mean higher investment costs; however, for industrial plants with high fluctuations of reactive power they are unavoidable (Figure 12.4a,b).

The rated power of reactors is usually determined in the range of 0.5 to 1% of the capacitor's reactive power.

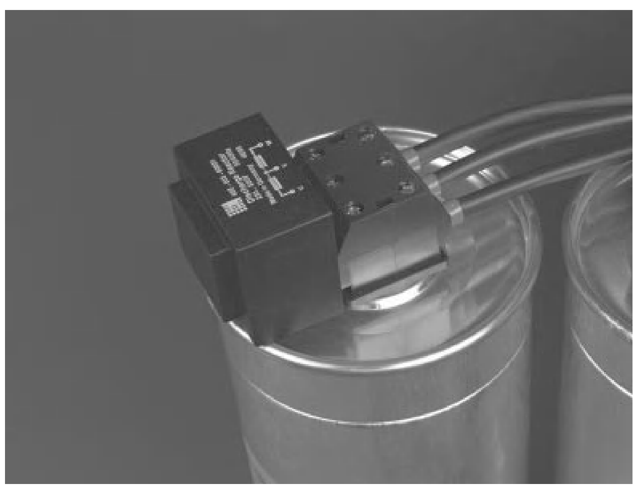


Figure 12.4b Discharging reactors fitted onto the terminal of the capacitor. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

12.3 Discharging Devices in MV Capacitors

In MV capacitors, identical technologies compared with LV capacitors are applicable.

The following Sections 12.3.1 and 12.3.2 describe both technologies, first discharging by resistances and second by reactors or voltage transformers respectively.

12.3.1 MV Capacitors to be Discharged by Resistances

MV capacitors are assembled in several foil coils in series or parallel connection, depending on the rated voltage U_r. Figure 12.5 illustrates the construction of an MV capacitor of 300 kvar, at $U_r = 3.3$ kV. Four capacitors, of 21.9 μF each, to be connected in parallel, form the capacitance per phase in star connection. A discharging resistance of 6.8 MΩ is soldered to each element. Thus a total capacitance of 87.7 μF per phase becomes effective combined with a discharging resistance of 1.7 MΩ each. The power losses of the resistances, 6.8 MΩ each, in case the capacitor is energized, are calculated by

$$P_d = \frac{U^2}{R} \tag{12.3}$$

$$P_d = \left(\frac{3.3 \cdot 10^3\,\mathrm{V}}{\sqrt{3}}\right)^2 \cdot \frac{1\,\mathrm{A}}{6.8 \cdot 10^6\,\mathrm{V}} = \frac{3.64 \cdot 10^6\,\mathrm{V}^2\,\mathrm{A}}{6.8 \cdot 10^6\,\mathrm{V}} \approx 0.54\,\mathrm{W}$$

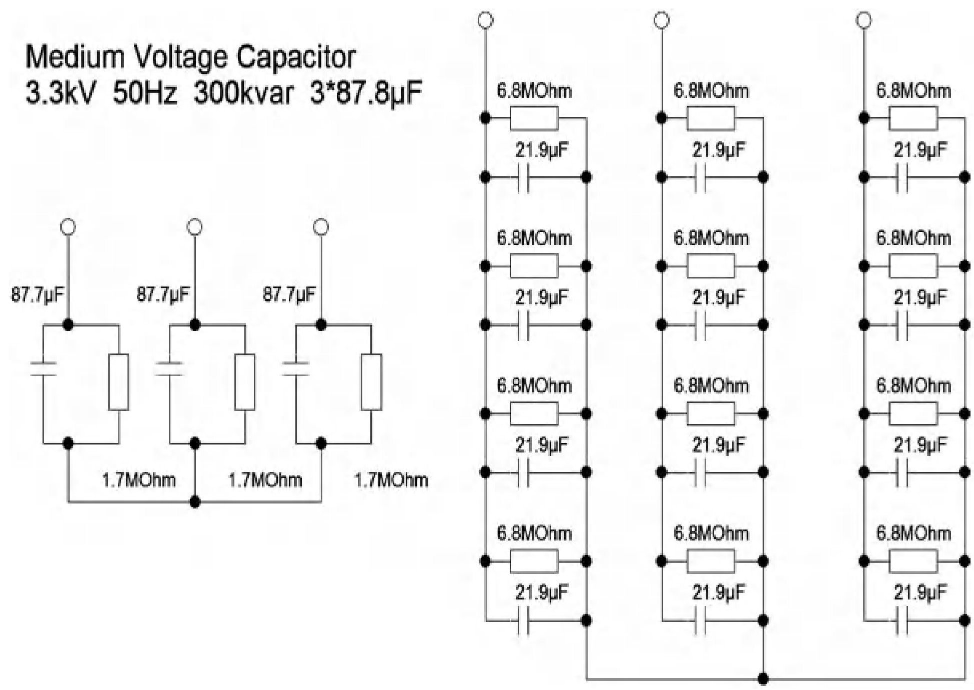


Figure 12.5 Construction of a 300 kvar capacitor at 3.3 kV. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

resulting in a total power loss of approximately 6.5 W for all 12 discharging resistances, where

P_d = power loss of the discharge resistance
U = phase-to-phase voltage
R = resistance (Ω)

With the help of Equation 12.1 the resulting time constant τ is easily calculated:

$$\tau = R \cdot C$$
$$= 1.7\,\mathrm{M\Omega} \cdot 87.7\,\mu\mathrm{F} = 1.7 \cdot 10^6 \frac{\mathrm{V}}{\mathrm{A}} \cdot 87.7 \cdot 10^{-6} \frac{\mathrm{A\,s}}{\mathrm{V}} \approx 150\,\mathrm{s} = 2\,\mathrm{min}\ 30\,\mathrm{s}$$

Remember that after this time the capacitor is not to be discharged down to 0 V but to 37% of the stored voltage after disconnection from the grid (see Figure 12.1; exponential function). An extended calculation is described at the capacitor with reference to Figure 12.6.

Figure 12.6 shows the schematic circuit diagram of an MV capacitor of 400 kvar, 11 kV, 50 Hz. Due to the high rated voltage a series connection of seven single capacitors, of 73.5 µF each, combined with five discharge resistances, of 2.2 MΩ each, in series connection as well and soldered in parallel to the capacitors is to be preferred. The equivalent circuit diagram (left) represents a capacitor unit of 10.5 µF per each phase connected in parallel to 11 MΩ

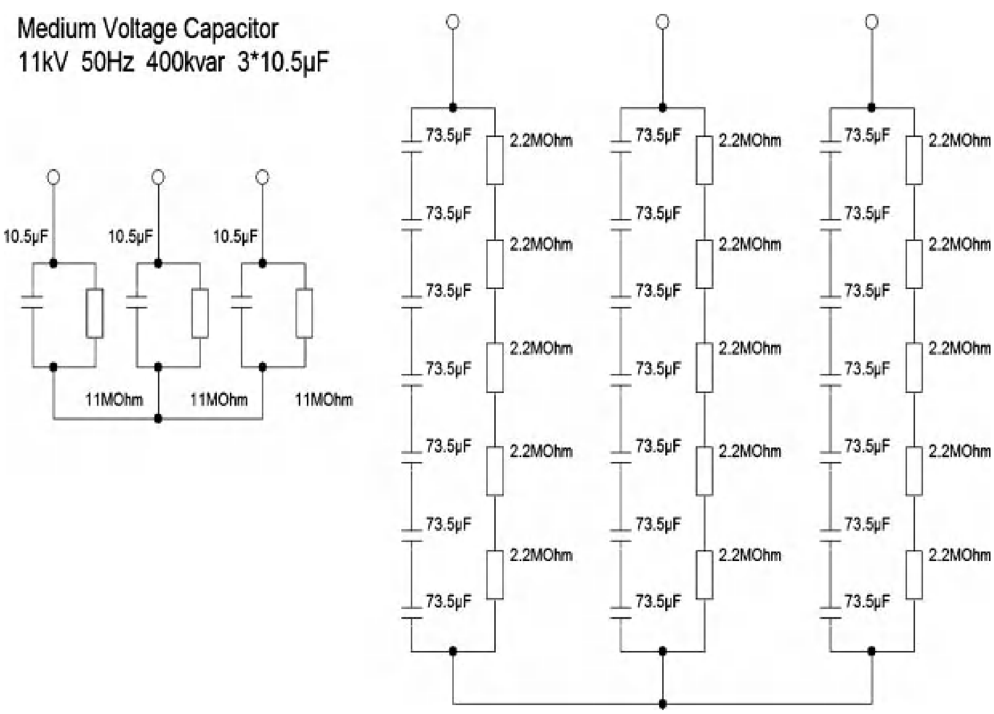


Figure 12.6 Construction of a 400 kvar capacitor, 11 kV, 50 Hz. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

of discharge resistance. Three units, star connected, finally form the three-phase capacitor of 400 kvar, 11 kV, 50 Hz. The time constant per unit as in Equation 12.1 is calculated:

$$\tau = R \cdot C = 11 \cdot 10^6 \frac{\text{V}}{\text{A}} \cdot 10.5 \cdot 10^{-6} \frac{\text{A s}}{\text{V}} = 115.5\,\text{s}$$

In worst case conditions the capacitor is disconnected at the instantaneous peak voltage. After $\tau = 115$ seconds the remaining voltage is 37% of the initial voltage, that is

$$U_\tau = 0.37 \cdot \frac{U_r}{\sqrt{3}}\sqrt{2} = 0.37 \cdot \frac{11 \cdot 10^3\,\text{V}}{\sqrt{3}} \cdot \sqrt{2} \approx 3.3 \cdot 10^3\,\text{V} = 3.3\,\text{kV}$$

Discharging down to zero takes a time of five times the time constant $\tau = 115.5\ \text{s} \cdot 5 \approx 580\ \text{s} \approx 10$ minutes. This determines the approximate switching time delay in the case of automatic switching by a power factor controller.

12.3.2 MV Capacitors to be Discharged by Reactors

For rapid discharging of MV capacitors, sometimes reactors or voltage transformers connected in parallel are used. There is no doubt that this technology requires higher investment costs. However, first of all it must be stressed that a rapid discharge procedure does not enable rapid automatic control by means of a power factor controller. Due to the high electric charge which may be stored after disconnection of the MV capacitor, the charge will be converted into heat as mentioned above. This is the reason why reactors may not discharge more than 4 to 6 times per hour in order to allow sufficient time to cool down the reactor.

The main advantage of reactors or voltage transformers is the high impedance while the capacitor is being energized; however, after disconnection only the ohmic resistance of the copper coil becomes effective in discharging the capacitor quickly. The following section gives a rough idea of which amount of energy is to be converted into heat in discharging a disconnected MV capacitor.

12.4 Calculation of the Electric Charge to be Stored on an MV Capacitor

A 200 kvar capacitor operating at 11 kV rated voltage and at a frequency of 60 Hz stores the highest amount of electrical energy, in the worst case, if it is switched off at peak voltage of the grid, that is $11\ \text{kV} \cdot \sqrt{2} = 15.55$ kV. The three-phase capacitor contains three coils of foil or combinations of them for a reactive power of 66.6 kvar each. Figure 12.7 illustrates the package of foil-elements of a single phase MV-capacitor. First of all it is necessary to calculate the capacitance per phase via its impedance X_C:

$$X_C = \frac{U^2}{Q_C} \tag{12.4}$$

$$X_C = \frac{(11 \cdot 10^3\,\text{V})^2}{66.6 \cdot 10^3\,\text{var}} = \frac{121 \cdot 10^6\,\text{V}^2}{66.6 \cdot 10^3\,\text{VA}} = 1.82 \cdot 10^3 = (j)1.82\ \text{k}\Omega \text{ per phase}$$

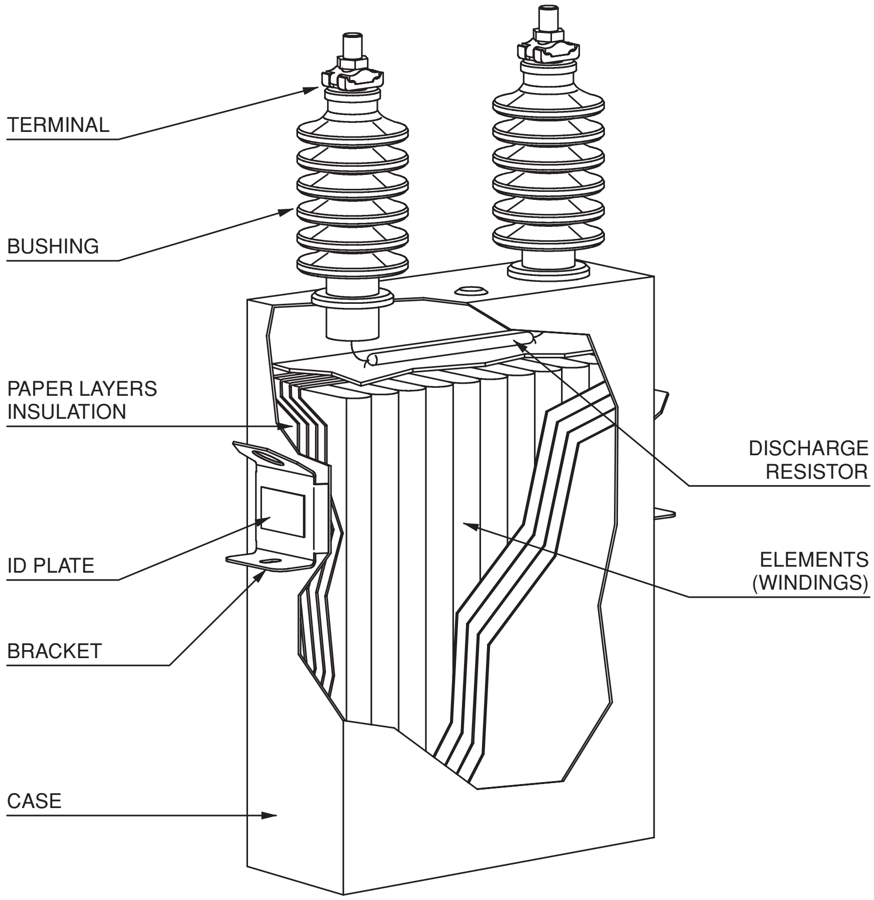


Figure 12.7 Section of an MV capacitor showing alternatively the location of one discharging resistance soldered directly onto the terminals inside the enclosure. Reproduced by permission of IESA, Brazil.

Thus the capacitance per phase is

$$C = \frac{1}{\omega \cdot X_C} \tag{12.5}$$

$$C = \frac{1}{2 \cdot \pi \cdot f \cdot X_C} = \frac{1}{2 \cdot 3.142 \cdot 60\,\mathrm{s}^{-1} \cdot 1.82 \cdot 10^{-3}\,\mathrm{k}\Omega}$$

$$= 0.001\,457 \cdot 10^{-3} \frac{\mathrm{A\,s}}{\mathrm{V}} = 1.457\,\mu\mathrm{F} \text{ per phase}$$

The electric charge Q on the capacitor is the product of the instantaneous voltage u and capacitance C:

$$Q = u \cdot C \tag{12.6}$$

Thus

$$Q = 11 \cdot 10^3 \text{ V} \cdot \sqrt{2} \cdot 1.457 \cdot 10^{-6} \frac{\text{A s}}{\text{V}} \approx 23 \cdot 10^{-3} \text{ A s}$$

This high electric charge to unload requires a well-determined discharging device, with regard to the electrical energy to be converted into heat. The stored energy W_C on the capacitor is calculated from a reactive power of 66.6 kvar multiplied by the time referring to a quarter period of 60 Hz frequency (see Figure 1.8). One full period lasts 16.66 ms; thus one-quarter is equal to 4.16 ms. Then

$$W_C = 66.6 \cdot 10^3 \text{ var} \cdot 4.16 \cdot 10^{-3} \text{ s} \approx 277 \text{ VA s [W s]}$$

Just considering the energy of 277 W over 1 s (or 2770 W within 0.1 s) becomes effective while discharging by reactors or voltage transformers.

12.5 Summary

Both technologies of unloading capacitors by means of resistances or reactors are applicable for LV capacitors as well as for MV capacitors. The described examples consider the fact that MV capacitors require a longer switching time delay preset at the reactive power controller compared with LV capacitors in the case of automatic control. The reason lies in the significantly higher amount of energy which may be stored on MV capacitors, which may overheat or even destroy the discharging devices, since the electrical energy is converted into heat. These facts must be kept in mind at all times.

13

Protection of Capacitors and Compensations

13.1 Chapter Overview

This chapter deals with protective devices for capacitors and compensations with regard to overcurrent, short circuit, overvoltage and overtemperature. Further methods are also described as a 'self-healing procedure' for capacitors and protection against punctures inside the capacitor caused by voltage peaks due to switching operations or incoming disturbances. Removal of heat due to active power losses inside the capacitor is discussed as well as ambient temperature at detuned capacitor banks.

13.2 Protection against Overcurrent and Short Circuit

Overcurrent tripping devices protect the capacitors from being overburdened. This may be caused by overvoltages, harmonics or resonances. Recall that the instantaneous current of a capacitor depends on the 'speed' of voltage change ($i = C \cdot du/dt$). Any protection against internal faults, for example punctures, is not guaranteed (see Section 13.5).

For this kind of protection relays are suitable with a delayed thermal tripping function preset to the capacitor's maximum of admissible current (see Section 14.3).

The most important task is to protect an electrical installation against short circuit. In LV installations, for this purpose fuses or circuit breakers fitted with the feature of magnetic tripping are mainly in use. One of these devices is provided for protection against short circuits inside a capacitor bank (connecting cables and switching devices such as contactors included). In using, for example, fuses, they must possess a 'slow-blowing characteristic' due to current peaks during the switching-in procedures of the capacitor(s).

In using circuit breakers with magnetic tripping, they must be preset to a triggering level of about 9 to 12 times the rated current of the capacitor bank (see Section 14.2).

For single protection for each capacitor of a compensation bank, it is recommended to install overcurrent relays with thermal tripping. Inrush currents will not affect the relay, thus a preset

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

value of 1.5 times the rated current is quite sufficient. Remember that among the protecting devices neither the incoming fuses nor the circuit breakers recognize any overcurrents of single capacitors inside the bank. Thus it makes sense to install bimetallic over current relays with a thermal tripping feature at capacitor banks of more than 300 kvar.

13.3 Overvoltage Protection

Capacitors may cause undesired overvoltages, for example if all consumers are to be switched off at finishing time. Automatically controlled capacitor banks disconnect the energized capacitors 'step by step'. During this procedure the customer's installation becomes fully capacitive (see Figure 11.10). Further reasons for a voltage increase, like resonances, reflections or interferences, may occur.

Thus it is recommended to install an overvoltage relay, especially at central-type compensations. The relay is to be preset according to a triggering level of 1.1 to 1.15 times the rated voltage approximately, to disconnect all the remaining energized capacitors at the same time. The relay avoids overcurrent situations as well and is provided to protect all other devices in the vicinity.

13.4 Protection against Overtemperatures

The lifetime of a capacitor depends on several factors like overvoltage and overcurrent, but mainly on temperature in the dielectric (see Figure 7.3). Thus sufficient cooling is an essential factor for the capacitor's lifetime. Several manufacturers therefore provide on request an observation of ambient temperature inside larger compensation banks using thermal relays. The observation device is preset to the maximum of admissible temperature of the capacitor (listed in the instructions). On exceeding this level an auxiliary contact disconnects the capacitor immediately. This avoids any destruction of the capacitor, but overtemperatures reduce the lifetime of the capacitor significantly (see Section 7.7). In general it is best to pay attention to the technical data on this in the manufacturer's instructions. Listed preset values referring to the temperature level must be strictly followed.[1]

Most of the temperature increase found in reactor-protected capacitor banks is due to the active power losses in the reactors, caused by eddy currents in the iron core and in the coil (copper/aluminium). The reactors are then provided with positive temperature coefficient (ptc) thermistor detectors that trigger an electronic relay to disconnect the choked capacitor step in case of overheating.

13.5 Protection against Internal Faults

Internal faults, like punctures in the foil coil, lead to the spreading of gas inside the capacitor. Within the casing, there will be a high pressure which deforms the casing and presents the danger of exploding if there is no internal protection against it (see Section 13.5.3).

[1] Specified in DIN EN 60831 (VDE 0560 part 46) and DIN EN 60931-1 (VDE 0560 part 48).

The capacitor may be destroyed either by voltage flashover or by overheating, ‘passing away by heat’.

13.5.1 Protection against Voltage Flashover

Brief overvoltage peaks may cause a flashover within the foil coil of the capacitor. Further reasons may be faults in the dielectric due to ageing or material defects. Consequences result in a short circuit or even an explosion in the unit caused by an internal electric arc.

If the capacitor is assembled from several single windings of foil and just one of these has been destroyed, the capacitor is able to compensate with a reduced capacity further on. Any fuses would not be blown if just one partial coil became defective and the current increased a little. The following section describes some protective technologies like ‘self-healing’ and protection against overheating and pressure.

13.5.2 Self-healing Technology

In the case of any flashover within the foil coil of the capacitor, the dielectric burns out at this point and the very thin metallic layer evaporates around the puncture and forms a new insulation between the layers (Figure 13.1).

This self-healing procedure takes time in the range of microseconds (μs). Figure 7.4 in Chapter 7 illustrates the self-healing technology schematically. The capacitance of the capacitor will be reduced a little, but in practice one might not be able to measure it. There is no short-circuit current possible due to the high-resistance fault characteristic of the self-healing dielectric. Special short-circuit current-limiting capacitor fuses are not necessary. Functional switching devices are quite sufficient for tripping.

13.5.3 Protection against Overheating and Internal Overpressure

Self-healing procedures may be repeated by overburdening the capacitor either electrically or thermally. During this procedure, gas formation increases the internal pressure and deforms the capacitor’s casing or tube. Figure 13.2 shows a cylindrical tube schematically and its

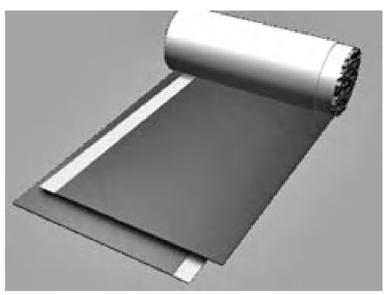


Figure 13.1 Cylindrical winding of self-healing film for MV capacitors. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

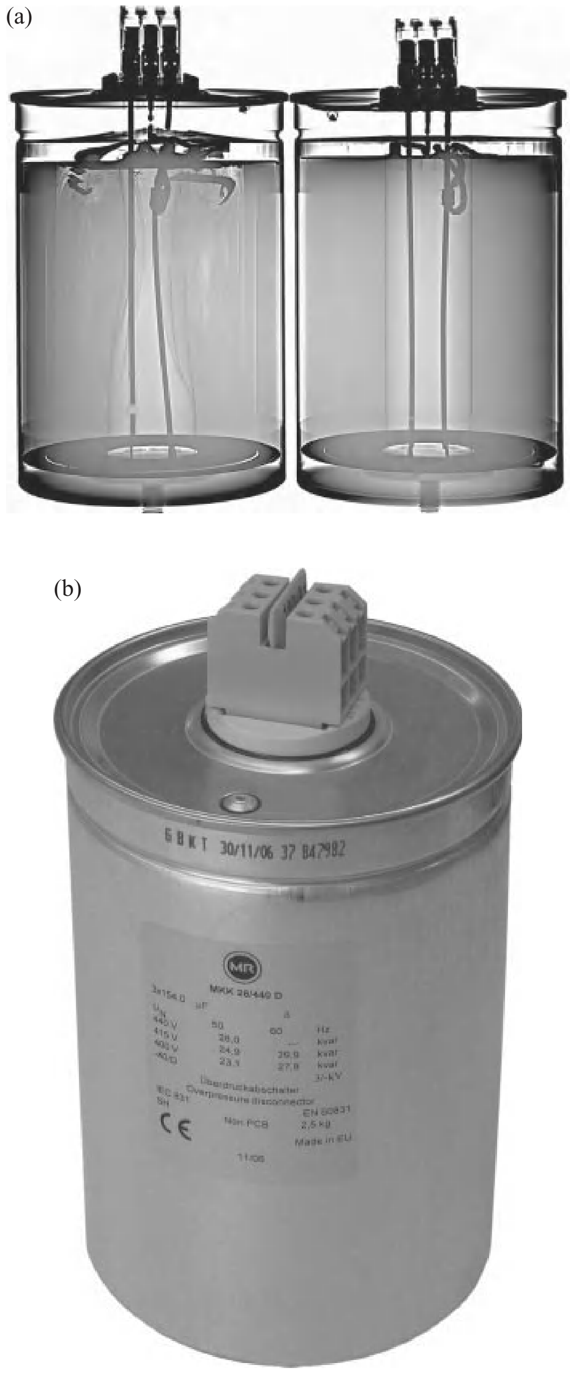


Figure 13.2 (a) Capacitor protection, technology of overpressure disconnection: X-ray pictures of a disconnected (left) and a fully operative (right) capacitor; (b) Power capacitor provided with overpressure disconnector. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

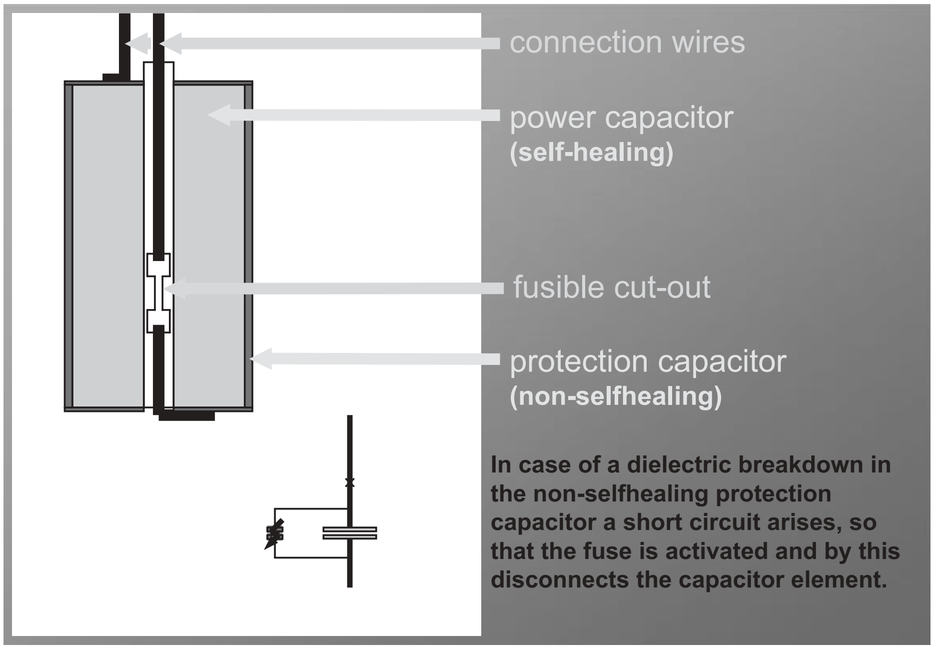


Figure 13.3 IPE (Internally Protected Element) protection concept. Reproduced by permission of Condensator Dominit GmbH (The IPE Concept), Germany.

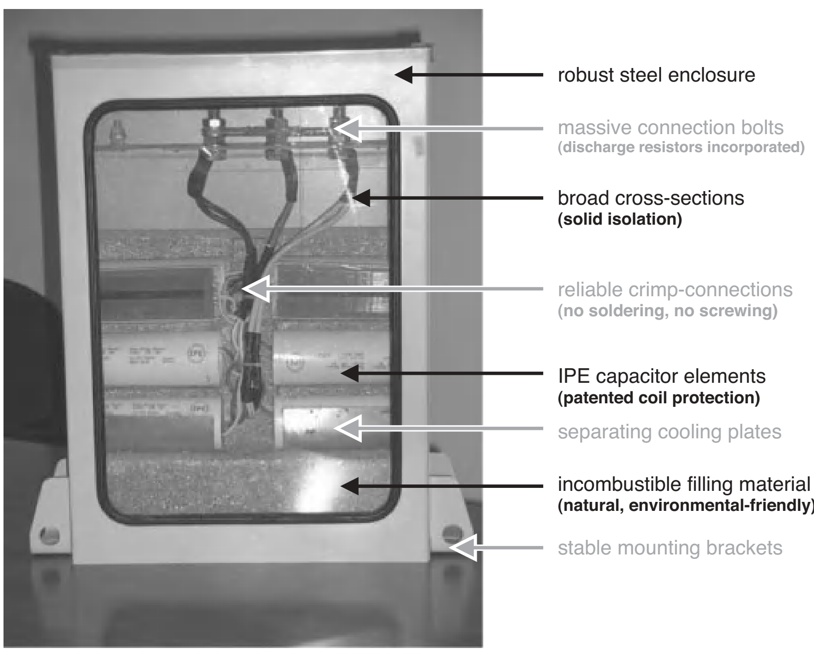


Figure 13.4 Construction of a CLMD (Condensator Low-voltage Metallic-film – version D) capacitor. Reproduced by permission of Condensator Dominit GmbH, Germany.

internal mechanical protection. The tube is designed with a crumple fold on the top which, when expanded by the internal pressure due to gas formation, tears off the internal leads to the electrodes. The capacitor then is volt-free until it is replaced.

This tear-off fuse offers sufficient protection for the capacitor and is called internal protection [1].

Figure 13.3 illustrates the patented technology of a dry capacitor to be protected.

This dry capacitor is combined with two partial capacitors connected in parallel. The main capacitor (light grey) is equipped with self-healing technology as opposed to the smaller unit (outer dark grey). For dry capacitors embedded in epoxy resin (see Figure 13.4) there is no possibility of a build-up of pressure in order to tear off one lead to the electrode (IPE protecting concept). If overheating of the main capacitor occurs it leads to a flashover in the smaller auxiliary capacitor. Due to the fact that the smaller unit is not equipped with the self-healing technology, it shorts the circuit and the fuse(s) will be blown. The entire capacitor unit is then volt-free [1].

13.6 Protection by Balance Observation at Single-Phase MV Capacitors

In protecting MV capacitors a special technology has been developed, created from their construction. Due to the electrical claim of each winding element, the manufacturers of MV capacitors produce them mainly in star connection. Since each three-phase MV capacitor contains many individual winding elements (see Figures 12.5 and 12.6), it is possible to assemble it from two three-phase MV capacitors connected in star configuration. This enables

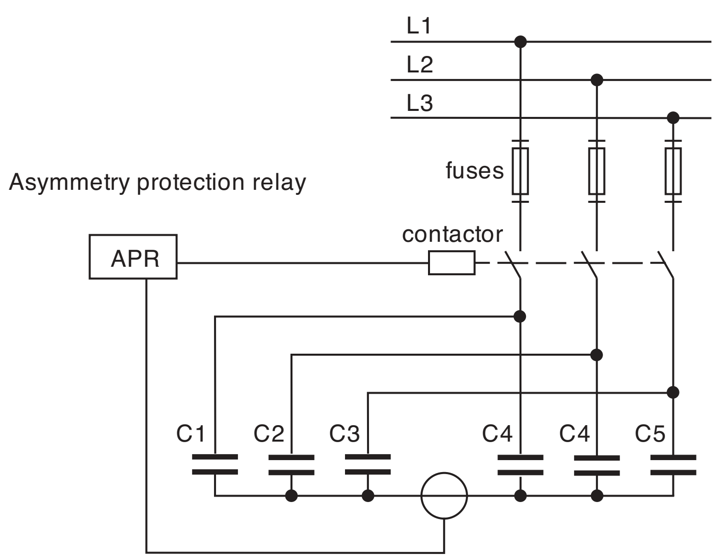


Figure 13.5 Asymmetry protection of MV capacitors with double-star connection for traditional MV capacitors in ALLFILM technology. Reproduced by permission of Electronicon Kondensatoren GmbH, Germany.

the conductor to be observed between the two star points. If both capacitors are in a 'healthy' condition, identical construction is supposed, and there is no current flowing between the two star points. Using a current transformer it is possible to observe any current flow by the so-called 'unbalance relay' or 'asymmetry protection relay' produced by several manufacturers around the world. If any fault occurs in a capacitor, an equalization current will arise. If the current exceeds a preset threshold level at the unbalance relay or asymmetry protection relay, it trips the circuit breaker to disconnect the capacitor from the grid.

Figure 13.5 shows a schematic circuit diagram for the installation of single-phase MV capacitors with asymmetry protection.

13.7 Summary

As described in this chapter, different protective technologies are available. For protecting an entire capacitor bank there are fuses with so-called 'slow blowing' characteristics in use. Using circuit breakers with the magnetic tripping feature requires higher investment costs and presetting to a much higher tripping level compared with the rated current of the capacitor(s).

Individual protection for single capacitors is given either by the so-called 'tear-off' technology or by IPE technology. Which technology is applied depends on the manufacturer.

Protection against overtemperatures is recommended for detuned capacitors primarily and is provided by the manufacturers in capacitor banks with rated reactive power of more than 200–300 kvar.

Reference

[1] Große-Gehling, M., Just, W., Reese, J. and Schlabbach, J. (2009) *Blindleistungskompensation – Netzqualität*, VDE-Verlag, Berlin and Offenbach, Germany.

14

Switching of Capacitors

14.1 Chapter Overview

This chapter assists in the selection of switching components for power capacitors. It focuses on switching operations with regard to possible inrush currents exceeding the rated current by up to 150 times or more in the worst cases. Mechanical components like air contactors never ensure a smooth energizing procedure to power capacitors. The best instantaneous moment of switching on the capacitor is if the grid voltage is identical to the stored one of the capacitor.

It may even happen by chance that, in one phase, the voltages of the remaining phases differ from the stored voltages of the capacitor if it is switched in by contactors.

Further, switching technologies by means of electronic components like thyristors are described. The diagrams presented will lead to a better understanding of switching procedures.

14.2 General

The inrush current on switching in the capacitor depends on the difference between the instantaneous voltage of the grid and the stored voltage at the capacitor. If the capacitor is connected locally much closer to the feed-in power transformer, only the very low impedance of the leads or busbars limits the inrush current as shown in Figure 14.1a. Considering a grid with a rated voltage of $U_r = 415$ V, in the worst case there could be a voltage difference of two times the peak voltage, that is $2 \cdot \sqrt{2} \cdot 415\,\mathrm{V} \approx 1475\,\mathrm{V}$! Thus the inrush current may exceed 30 times the rated current of the capacitor. It may be even worse at multi-step capacitor banks. Assuming a power factor controller with a 12-step compensation – 10 steps are already energized – is ready to switch in the 11th step, the instantaneous charge of the 10 steps plus the strong voltage impedance of the transformer may jerk up the inrush current of the 11th capacitor to 150 times the rated one or more as shown in Figure 14.1b [1].

The market offers special air contactors designed for switching power capacitors and withstanding high inrush currents. However, there are technical limits as well. In the case of very high inrush currents there may be the danger of welded contacts due to the electric arc.

Thus it is very important, in automatically controlled compensation banks especially, to ensure that any capacitor steps ready for energizing have been discharged. For this purpose the

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

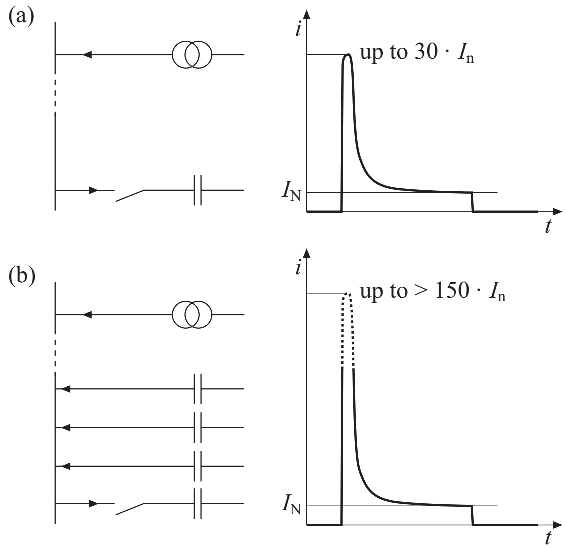


Figure 14.1 Simplified illustration of capacitors' inrush currents: (a) single-type compensation; (b) central-type compensation (capacitors operating in parallel).

market offers contactors fitted with discharging resistances of low ohmic values to be switched onto the capacitor in parallel (V connection) after the capacitor has been disconnected (see Figure 12.3). The discharging procedure then takes less than one second.

Not all compensation banks of different brands have the feature of rapid discharging as described above. Most of the capacitors only have high ohmic unloading resistances fixed or soldered in parallel. To ensure that a capacitor is discharged before energizing anew, the switching time delay preset at the power factor controller should not be below 20 seconds, approximately (see Chapters 11 and 12).

Contactors designed for power capacitors must withstand very high voltages between the contacts in the open position. During disconnection of a capacitor the electric arc should be extinguished much closer to the zero crossing of its current. The capacitor is then charged with peak voltage, about 590 V or more if one considers the additional tolerance of the grid voltage, for example 5%, or even 616 V. A half period later on, a voltage of twice the peak voltage, 1180 V or even 1230 V, will occur between the contacts. Thus the distance of the contacts has to be determined sufficiently at contactors for applications in switching power capacitors. Otherwise, there is a danger of reignition if the so-called 'ignition voltage' is exceeded.

Thus standard contactors, for example for motors, are not applicable for switching power capacitors. As mentioned above, the distance between the contacts must avoid any reignition. Further, the speed in opening the contacts is very important because the opposition voltage occurs after half a period (10 ms referred to 50 Hz, or 8.33 ms to 60 Hz). Within this time it must be ensured that the necessary air distances between the contacts have been obtained.

As one can see, contactors for capacitors must meet all requirements; last but not least, they must not make any rebounds (fluttering of contacts) because this could destroy the internal contacts. This also leads to a significant shortening of the capacitor's lifetime (see Chapter 7).

In capacitor banks designed, for example, for rated voltages of 550 V or even 660 V, there are transformers in use to feed the contactors with either 230 V, 50 Hz or 120 V, 60 Hz (in the USA, for instance). These transformers must be strong enough in power to avoid any rebounds of contactors already switched on. Any further contactor ready to be switched on generates a high inrush current due to the opened iron core. This may not reduce the control voltage to below the voltage (hold voltage) required to keep the iron cores closed for the remaining contactors to be switched on.

14.3 Selection of Switchgear

As described in Section 14.2, the requirements for contactors to switch on power capacitors are marked by the inrush current and the voltage during the switching on or off operations. To limit the inrush current there is the possibility of using contactors fitted with additional pre-loading resistances. These resistances are connected in series by leading contacts briefly before the main contacts close, as shown in Figure 14.2. The resistances thus limit the inrush current significantly and the main contacts will then be spared, as well as the capacitor with respect to its lifetime.

In reactor-protected capacitors the danger of overburdening the switchgear is much less due to limiting of the inrush current by the series reactors.

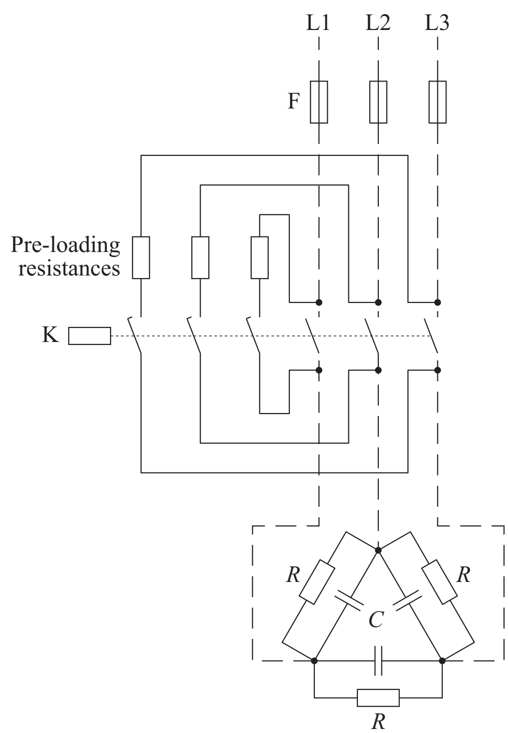


Figure 14.2 Circuit diagram of a contactor fitted with pre-loading resistances to be switched in series by means of auxiliary leading contacts.

Some manufacturers provide smaller capacitors with integrated attenuation reactors in order to limit the inrush current. However, this technology is used very rarely, though one can still find it in small capacitors, for example for the compensation of current-limiting reactors in fluorescent lamps. This enables standard switchgear to be used; however, the rated current should be 1.5 times the capacitor's rated current, referring to DIN VDE 0560. In today's industrial plants it is the existence of harmonics which increase the nominal current of the capacitor additionally.

In general the following switchgears are in use for power capacitors.

14.3.1 Air Contactors

Automatically controlled capacitor banks work with air contactors suitable for switching power capacitors (see Figure 14.3). They regularly have a long lifetime and save space as well. If

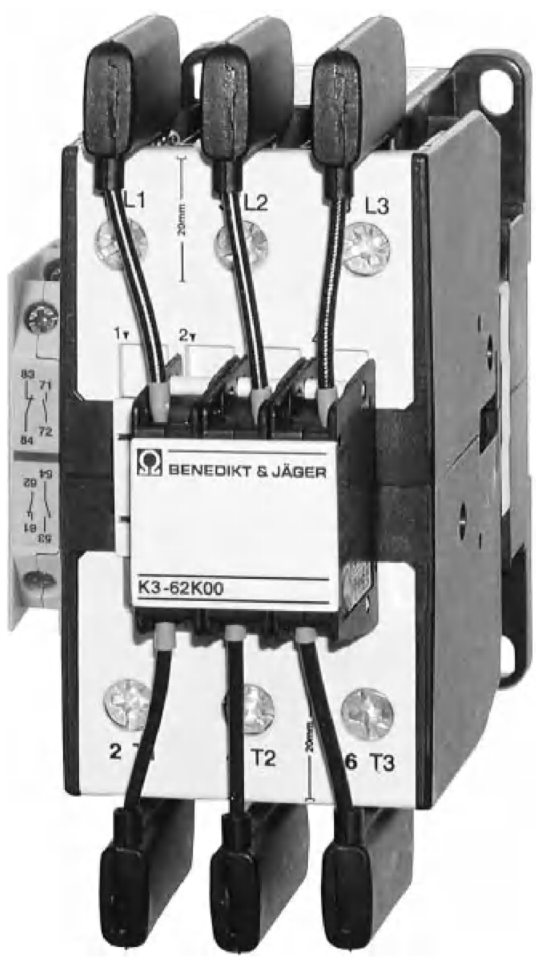


Figure 14.3 Air contactor with pre-loading resistances for power capacitors up to 50 kvar. Reproduced by permission of Benedikt & Jäger GmbH, Austria.

the capacitors are fitted with unloading resistances, rapid control is possible, though technical limits must be taken into account (see Chapter 12 on preset switching time delay at the power factor controller).

14.3.2 Circuit Breakers

To switch capacitors on or off with high reactive power there are circuit breakers in LV and MV capacitor banks which also can be recommended. An integrated spring actuator ensures rapid switching procedures and avoids any reignitions as described above. Slow-moving contacts would be dangerous and are impossible in circuit breakers.

With respect to discharging large amounts of energy in the case of de-energized capacitors, switching operations should be limited to approximately 30 times per day (see section 12.3.1).

14.3.3 Switch Fuses and Magnetic Trips

Fuses are not suitable as overcurrent protection for power capacitors. They just offer protection against short circuits. Fuses for these applications must possess a slow-blowing characteristic because of the high inrush currents as mentioned previously. Steady overcharging caused by overvoltages, resonances and harmonics increases the capacitors' rated current additionally. Thus fuses determined up to 1.6 to 1.8 times the rated current should be used.

In compensation plants there are high-break capacity fuses exclusively in use because the breaking power is much higher compared with fuses just protecting leads, cables or busbars.

Besides fuses as described above, magnetic trips are also in use. As mentioned in Section 13.2, however, they may not be triggered by the high inrush current of the capacitor. This is why they have to be preset to a level of 9 to 12 times the capacitor's rated current. Although much higher inrush currents may occur (see Figure 14.1a,b) besides the peak value of the inrush current, the duration ($i \cdot t$) becomes decisive for finally triggering the magnetic trip.

Magnetic trips protecting entire compensation banks are allowed to be preset to a lower triggering level, some about six times the nominal current of the bank, because the capacitors will be energized stepwise, which means that never more than one capacitor is to be switched in at once.

14.4 Switching by Semiconductors (Thyristor Modules)

14.4.1 General

The increasing developments in the field of electronic components within the last few years has enabled the rapid control of power capacitors free of wear and tear. There are many compensation tasks that last just for seconds, for example in cranes, elevators and welding machines (primary pulsed, exclusively). Classical compensation banks with switching time delays of 20 to 40 s per step are too slow for these applications. Even in reducing the switching time delay to, for example, 10 s or less would lead to higher numbers of switching operations followed by increasing wear and tear and significantly shortened lifetimes of the capacitors (see Chapter 7).

With the help of thyristor modules it has become possible to switch in capacitors exactly at the moment when the grid's instantaneous voltage is identical to the one stored on the capacitor. This avoids any inrush current (see Figure 14.4). Switching off the capacitor is

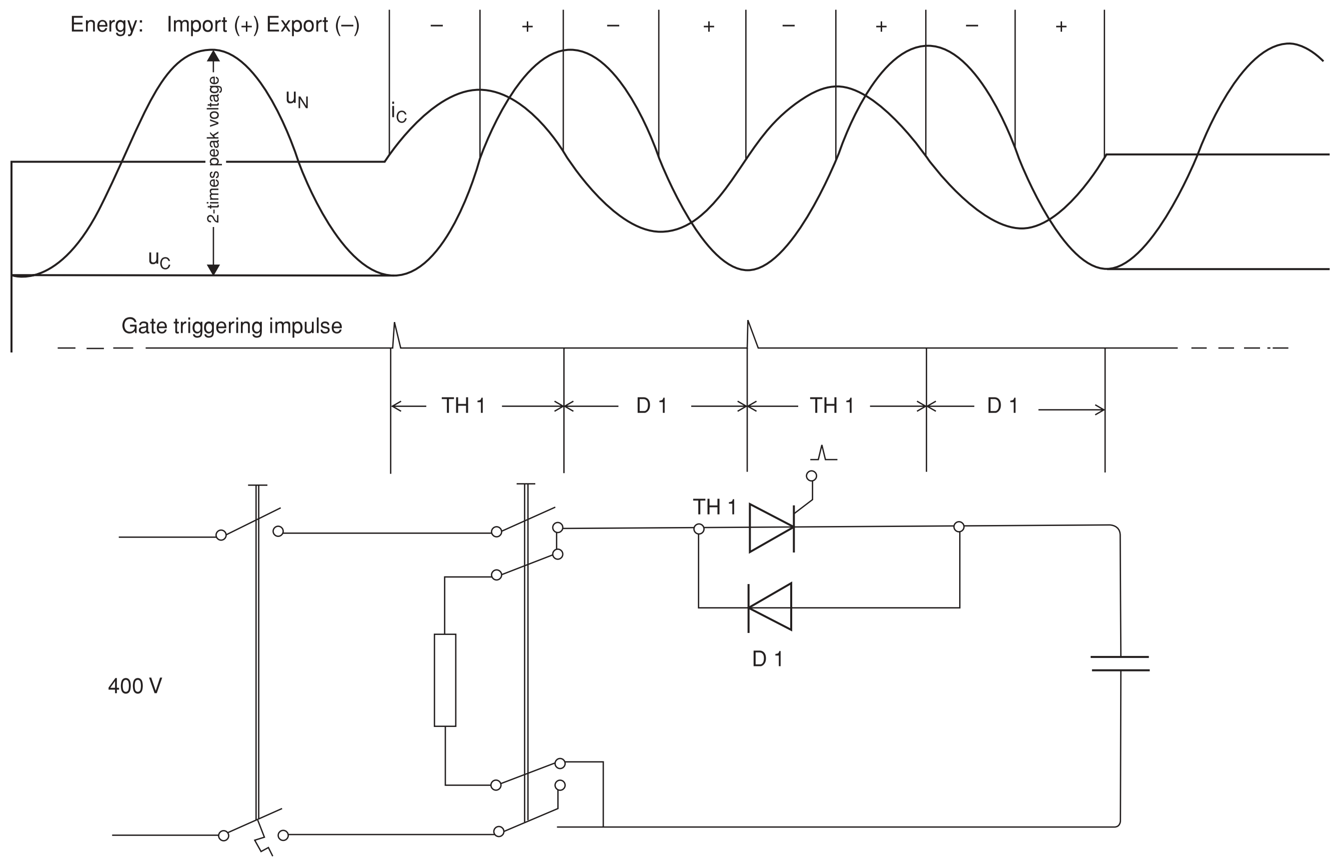


Figure 14.4 Simplified circuit diagram of a thyristor-controlled capacitor, illustrated for single-phase operation, including time courses of voltage and current while switching a power capacitor on and off.

done by the natural zero crossing of the capacitor's current if the gate trigger impulses to the thyristor have been stopped. At this time the voltage on the capacitor is identical to the grid's peak voltage, either positive or negative, depending on the polarity of how the thyristor is to be installed. An anti-parallel diode keeps this voltage at the capacitor upright until the thyristor gets new gate trigger impulses. It is a matter of course that both the thyristor and the diode have to be determined at 1.5 times the double peak voltage of the grid, at least with regard to its dielectric strength; tolerances of the grid and a safety field of 20 to 30% are also to be taken into account. This guarantees a smooth increase in the capacitor's current beginning from the zero point of the sinusoidal waveform.

This technology is suitable for different applications as there are rapid compensations of reactive power or support of voltage due to the switching-in procedures of heavy machines if the grid voltage decreases. The last application is to avoid voltage fluctuations in the grid, called flickering (see chapters 17,19,20). However, this chapter deals with the rapid compensation of reactive power exclusively. As mentioned above, such compensation in welding plants is required only if the welding transformers are pulsed primary ones. Many specialists mistakenly believe that welding procedures with pulsed secondary transformers generate fluctuations of reactive power in parallel with active power due to the fact that the power factor is changing steadily. Although this is correct, the reactive power does not change (see Figure 9.13a,b). This is the reason why welding plants with pulsed secondary transformers are compensated by classical compensation banks as quite sufficient. The same situation is to be found in, for example, punching machines. Most of the time the motor is running in idle condition. After a punching procedure the first task of the motor is to bring the flywheel up to its initial revolutions per minute, which means that the motor has to feed back the lost kinetic energy for the next punching procedure. This results briefly in a better power factor while the demand of reactive power remains constant.

14.4.2 Static Contactors for Switching Capacitors up to 415 V

In using static contactors for switching three-phase power capacitors, the thyristor modules contain one thyristor combined with an anti-parallel diode for each phase, see Figure 14.5a. As mentioned above, all three elements of the three-phase capacitor are charged to the peak voltage of the grid in case the gate trigger impulses have been stopped and the capacitor is out of operation. Thus there is a need for additional mechanical switchgear in series, for example a load breaker including fuses, to set the unit volt-free in the case of maintenance, for instance.

For economic reasons most notable manufacturers produce thyristor modules for switching three-phase capacitors (delta connected) by using just two thyristors with two diodes connected in anti-parallel fashion (see Figure 14.5a and Figure 14.5b). One phase is connected directly to the capacitor. To set the unit volt-free for the purpose of maintenance, an additional mechanical circuit breaker is necessary as well. However, this technology 'claims' the electronic components with a higher 'standby' voltage in case the capacitor is out of operation. As is well known, the switching-off procedure with thyristors is by the natural zero crossing of the current. Because of the phase shift between the two thyristor modules, this leads to a voltage shift within the capacitor elements to be connected in delta configuration. This results in 'standby' voltages in the elements of 30 to 45% higher than the peak voltage. However, this fact must be considered by the manufacturer in determining the electronic components. Figures 14.5b and 20.2 show an image of what a static contactor in this technology looks like.

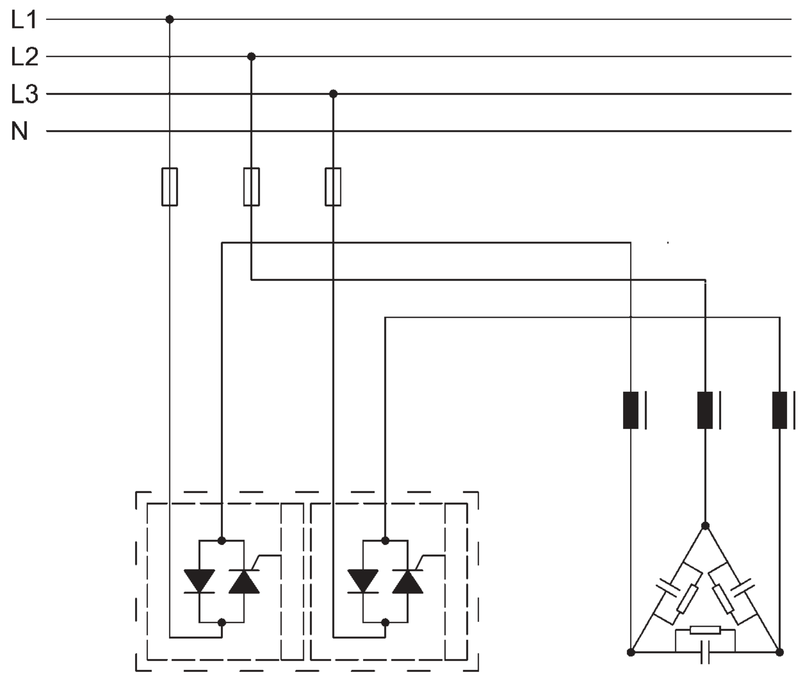


Figure 14.5a Schematic circuit diagram with two thyristor-modules controlling the three-phase capacitor. *Source*: Maschinenfabrik Reinhausen GmbH, Germany.

Figure 14.5b Static contactor (thyristor module fitted with two thyristors and two anti-parallel diodes) for contactless switching of three-phase power capacitors up to 100 kvar, 400 V, type TSCM-LC. Reproduced by permission of Janitza Electronics GmbH, Germany.

With regard to the higher 'standby' voltage above grid's peak voltage in the range from 30 up to 45% re-energizing the capacitor is only possible with a time-delay. Capacitor's stored voltage has to be decreased down to grid's peak voltage level by the discharging resistances only. This is a small disadvantage if very rapid control within periods is of need. For this purpose it is to recommend to install modules consisting in three thyristors as shown in Figure 14.7. The 'standby' voltage then is limited to grid's peak voltage, exclusively.

14.4.3 Static Contactors for Switching Capacitors of Rated Voltage Higher than 500 V

Capacitors for applications in grids with nominal voltage higher than 500 V, for example 660 V, are assembled with foil windings in star connection, usually due to the lower voltage claim of each element. For reasons of safety and limiting the 'standby' voltage to the grid's peak voltage, there are static contactors containing one thyristor combined with an anti-parallel diode for each phase in use, see Figures 14.6a and 14.6b. This technology is sometimes used in MV capacitors as well, if rapid control is required. Smooth switching operations without transients are guaranteed, see Figures 14.4 and 20.1.

14.4.4 Power Factor Relays for Static Contactors

In general all manufacturers of static contactors include in their units the electronic components that already generate the triggering impulses to the thyristors. There is a need for an input signal in the range of 10 to 30 V DC onto the terminal to be provided for. Many manufacturers

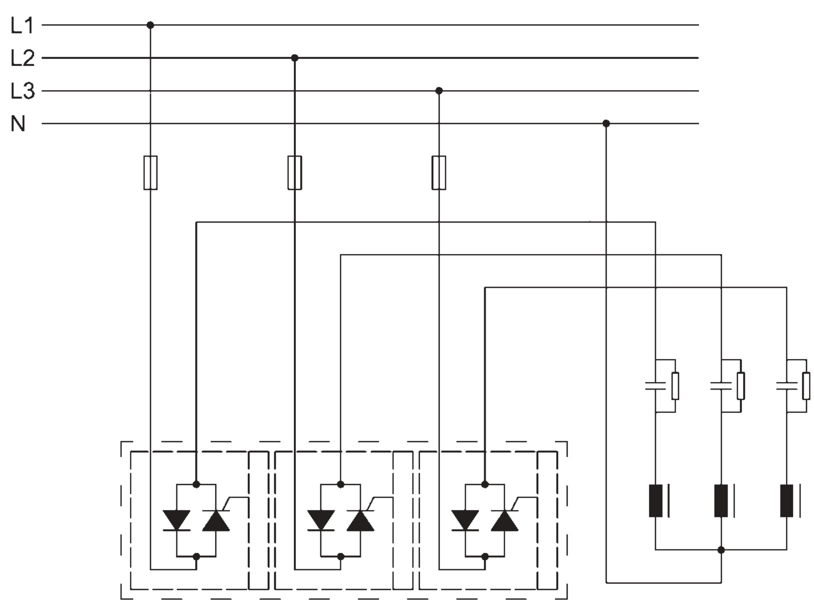


Figure 14.6a Schematic circuit diagram with three thyristor modules per phase; for example, controlling power capacitors in star connection for grids with 660 V. *Source*: Maschinenfabrik Reinhausen GmbH, Germany.

Figure 14.6b Static contactor (thyristor module fitted with three thyristors and three anti-parallel diodes) suitable for the control of capacitors with rated voltage higher than 500 V. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

are producing power factor regulators fitted with DC outputs for controlling static contactors. These power factor regulators are already installed in so-called ‘dynamic reactive power control’ units (see Section 14.4.5) and are able to control reactive power within less than 100 ms, depending on the brand.

14.4.5 Dynamic Reactive Power Compensation (Ready to Install)

Several manufacturers offer dynamic reactive power compensation units for different applications where rapid control is required, as in the one mentioned for welding plants with primary pulsed transformers (see Section 9.2.3). Switching on a capacitor then runs automatically if the

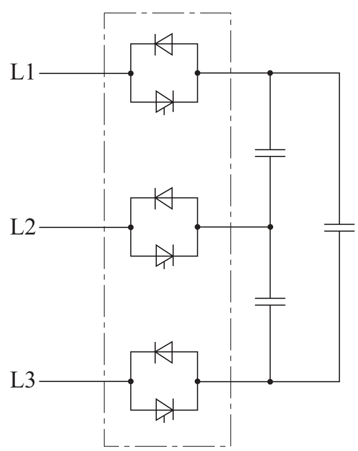


Figure 14.7 Schematic circuit diagram of static contactor fitted with three thyristor modules controlling the three-phase capacitor connected in delta.

grid's instantaneous voltage is identical to the capacitor's voltage. Switching off a capacitor is done if the thyristor does not receive any further gate triggering impulses and the instantaneous current comes down to zero. At this time the capacitor is charged with the grid's peak voltage, for example $415\ \mathrm{V} \cdot \sqrt{2} = 583\ \mathrm{V}$. Further switching on procedures will be ensured at this voltage level exclusively (see Figures 14.4 and 20.1).

14.5 Summary

Besides approved classical compensation banks, the continuing development of electronic components enables the assembly of compensation units controlled by thyristors for rapid and wear-free operations. The main field of applications is reserved for the classical compensation banks controlled by air contactors, insofar as they are quite sufficient for obtaining the desired power factor $\cos\varphi_d$ on average per billing period. This must be evaluated either by the customer or by specialists using technology that is more advantageous to install. Finally, the investment costs of dynamic compensation units are much higher compared with classical compensation banks. This is an essential aspect for choosing between the described technologies as well.

The fact that industrial electrical plants cause increasing levels of harmonics requires the installation of reactor-protected capacitor banks. Besides the advantage that these reactors protect the capacitors against harmonics, depending on the choking rate any inrush currents are now limited noticeably. Several countries around the world have installed reactor-protected compensation banks exclusively, such as Switzerland, to mention but one.

Reference

[1] Esser, W. (1991) 'Der Blindleistung geht es an den Kragen': Schütze für die Blindleistungs-Kompenation. *Konstruktion & Elektronik*, H.**6**, S.10 ('Reactive Power to be Collared': Air contactors for compensation banks. *Construction & Electronics*, **6**, 10.

15

Installation, Disturbances and Maintenance

15.1 Chapter Overview

It is very important to pay attention to the national rules of the electricity utility company regarding capacitor banks before installation. Manufacturers' instructions must be taken into consideration as well. Advice with respect to the security and location of installation of capacitor banks should be followed.

Regular registered maintenance of compensation plants is also recommended.

Several examples of disturbances, and how to solve them, are described in order to give the best possible assistance, overall.

15.2 Installation of Automatically Controlled Compensation Banks

First of all, national directions regarding the installation of electrical power plants up to 1000 V rated voltage must be checked. European standards, described in EN 60931-1 and 3 for instance, prescribe rules for the installation of capacitor banks valid for many countries around the world. Correct selection and installation of electrical components are the responsibility of the customer, assisted by technical specialists.

Before installing a new automatically controlled compensation bank the technical data have to be checked to see whether the bank complies with the requirements listed in the individual orders, such as:

- Is the rated voltage identical to or higher compared with the nominal voltage of the grid?
- Is the rated reactive power sufficient for the application, and even extendable if required?
- Does the admissible ambient temperature compare with the real one?
- If reactor protected, is the reactor rate identical to the ordered one?
- Does the integrated power factor controller fulfil the input data with reference to the external current transformer? Are free steps available for extension?
- Is the space for locating the bank sufficient, dry and not too close to heat-emitting devices?

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

- Is the location free of vibrations (if not, the bank is to be set on gum buffers)?
- Are the technical data of the compensation bank always visible?

In determining the power cables to the compensation bank, their cross-section must not depend on the nominal current but on a higher value. According to the European standards EN 60831-1 for LV capacitors and EN 60871-1 for MV capacitors, they must be constructed to lead the nominal current steadily by 1.3 times. Further, an additional plus tolerance of the capacitor's capacitance must be considered in the range of up to 10%. These factors (1.3×1.1) result in an overcurrent of $I_o = 1.43 \cdot I_n$ [1]. Roughly determined, the cross-section of cables and conductors should be selected according to 1.5 times the nominal current. This overload capability together with the high inrush current to the capacitors must be taken into account when designing protective devices and cable cross-sections [2]. Table 15.1 lists nominal currents, cable cross-sections and fuses belonging to capacitors or banks of different nominal reactive power applicable for grids' nominal voltage levels of 230, 400 and 525 V.

Thus a compensation bank with a rated reactive power of 100 kvar at a nominal voltage of 400 V, for instance, has a 144 A nominal current, which, when multiplied by 1.43, results in 200 A approximately. According to Table 15.1, a cross-section of $3 \times 95/50\,\text{mm}^2$ is then necessary.

Technical data on this listed in manufacturers' instructions are recommended. According to VDE 0100, additional points are to be noted, for example about the way the cables are laid parallel to others. In this case a cable of $120\,\text{mm}^2$ should be preferred. The type of cable may play an essential role as well. National rules may differ, so one must become informed.

15.3 Automatic Compensation Banks: Setting into Operation

Figure 15.1 shows the principal circuit diagram of an automatic compensation bank. The bank itself delivered by the manufacturer is entirely wired up and ready to connect. The main work for the electricians is to connect the bank with the selected power cables to the distribution plant. The provided fuses or load circuit breaker must comply with the specifications described in Section 15.2. Further, a cable with a cross-section of at least $2 \times 2.5\,\text{mm}^2$ is to be laid from the measuring current transformer to the power factor controller in the automatic compensation bank. The cross-section depends on the distance between them of course and is illustrated graphically in Figure 15.2a,b for current transformers both with nominal secondary outputs of either 5 A or 1 A (see the next section).

15.3.1 Selection of Current Transformer (CT) and Determination of the CT Cable

Most existing electrical distribution plants already have CTs fitted. First of all, it is necessary to check the transforming ratio and then, second, the nominal burden. These two criteria are essential for proper control of reactive power. As mentioned in Chapter 11, an admissible minimum of power factor controller sensitivity should not undersize 1% of the nominal secondary current of the CT. This results in 0.05 A or 0.01 A reactive referring to the nominal secondary current of the CT, either 5 A or 1 A, respectively. Assuming that CTs with a ratio of 1000 A/5 A, which means $k = 200$, are measuring the primary current of the incoming supply and the new compensation bank is controlling in steps of 25 kvar each, the C/k value results in

Table 15.1 Fuses and supply cable cross-sections according to VDE 0100, part 430, layout method C.

	230 V/50 Hz			400 V/50 Hz			525 V/50 Hz		
Power (kVAr)	Current (A)	Fuse (A)	Cross-section (mm^2)	Current (A)	Fuse (A)	Cross-section (mm^2)	Current (A)	Fuse (A)	Cross-section (mm^2)
2.5	6.3	10	4 × 1.5	3.6	10	4 × 1.5	2.7	10	4 × 1.5
5	12.6	20	4 × 2.5	7.2	10	4 × 1.5	5.5	10	4 × 1.5
6.25	15.7	25	4 × 4	9.0	16	4 × 2.5	6.9	10	4 × 1.5
7.5	18.8	35	4 × 6	10.8	16	4 × 2.5	8.2	16	4 × 2.5
10	25.1	35	4 × 6	14.4	20	4 × 2.5	11.0	16	4 × 2.5
12.5	31.4	50	4 × 10	18.0	25	4 × 4	13.7	20	4 × 2.5
15	37.7	63	4 × 16	21.7	35	4 × 6	16.5	25	4 × 4
17.5	43.9	63	4 × 16	25.3	35	4 × 6	19.2	35	4 × 6
20	50.2	80	3 × 25/16	28.9	50	4 × 10	22.0	35	4 × 6
25	62.8	100	3 × 35/16	36.1	50	4 × 10	27.5	50	4 × 10
27.5	69.0	100	3 × 35/16	39.7	63	4 × 16	30.2	50	4 × 10
30	75.3	125	3 × 50/25	43.3	63	4 × 16	33.0	50	4 × 10
31.25	78.4	125	3 × 50/25	45.1	63	4 × 16	34.4	50	4 × 10
37.5	94.1	160	3 × 70/35	54.1	80	3 × 25/16	41.2	63	4 × 16
40	100.4	160	3 × 70/35	57.7	80	3 × 25/16	44.0	63	4 × 16
43.75	109.8	160	3 × 70/35	63.1	100	3 × 35/16	48.1	80	3 × 25/16
45	113.0	160	3 × 70/35	65.0	100	3 × 35/16	49.5	80	3 × 25/16
50	125.5	200	3 × 95/50	72.2	100	3 × 35/16	55.0	80	3 × 25/16
52.5	131.8	200	3 × 95/50	75.8	125	3 × 50/25	57.7	80	3 × 25/16
60	150.6	250	3 × 1 20/70	86.6	125	3 × 50/25	66.0	100	3 × 35/16
62.5	156.9	250	3 × 1 20/70	90.2	125	3 × 50/25	68.7	100	3 × 35/16
67.5	169.4	250	3 × 1 20/70	97.4	160	3 × 70/35	74.2	125	3 × 50/25
68.75	172.6	250	3 × 1 20/70	99.2	160	3 × 70/35	75.6	125	3 × 50/25
75	188.3	315	3 × 185/95	108.3	160	3 × 70/35	82.5	125	3 × 50/25
87.5	219.6	315	3 × 185/95	126.3	200	3 × 95/50	96.2	160	3 × 70/35
93.75	235.3	400	2 × 3 × 95/50	135.3	200	3 × 95/50	103.1	160	3 × 70/35
100	251.0	400	2 × 3 × 95/50	144.3	200	3 × 95/50	110.0	160	3 × 70/35
112.5	282.4	400	2 × 3 × 95/50	162.4	250	3 × 120/70	123.7	200	3 × 95/50
120	301.2	500	2 × 3 × 120/70	173.2	250	3 × 1 20/70	132.0	200	3 × 95/50
125	313.8	500	2 × 3 × 1 20/70	180.4	250	3 × 1 20/70	137.5	200	3 × 95/50
150	376.5	630	2 × 3 × 185/95	216.5	315	3 × 1 85/95	165.0	250	3 × 120/70
175	439.3	630	2 × 3 × 185/95	252.6	400	2 × 3 × 95/50	192.5	315	3 × 185/95
200	502.0	800	2 × 3 × 240/120	288.7	400	2 × 3 × 95/50	219.9	315	3 × 185/95
225	—	—	—	324.8	500	2 × 3 × 120/70	247.4	400	2 × 3 × 95/50
250	—	—	—	360.8	500	2 × 3 × 120/70	274.9	400	2 × 3 × 95/50
275	—	—	—	396.9	630	2 × 3 × 1 85/95	302.4	500	2 × 3 × 120/70
300	—	—	—	433.0	630	2 × 3 × 185/95	329.9	500	2 × 3 × 120/70
350	—	—	—	505.2	800	2 × 3 × 240/120	384.9	630	2 × 3 × 185/95
375	—	—	—	541.3	800	2 × 3 × 240/120	412.4	630	2 × 3 × 185/95
400	—	—	—	577.4	800	2 × 3 × 240/120	439.9	630	2 × 3 × 185/95

Source: Frako Kondensatoren- und Anlagenbau, GmbH, Germany, Handbook, page 25.

0.083 A reactive when the grid's nominal voltage is 400 V. This is tightly above the required minimum of the sensitivity level and ensures proper control. Incidentally, if the step size is, for example, 10 kvar, proper control by the power factor controller is no longer possible.

In this case a separate CT with lower transforming ratio is to be installed. Referring to a step size of 10 kvar, a maximal ratio of $k = 120$ is allowed, which means installing a CT of 600 A/5 A. However, it should be checked that apparent currents of higher than approximately

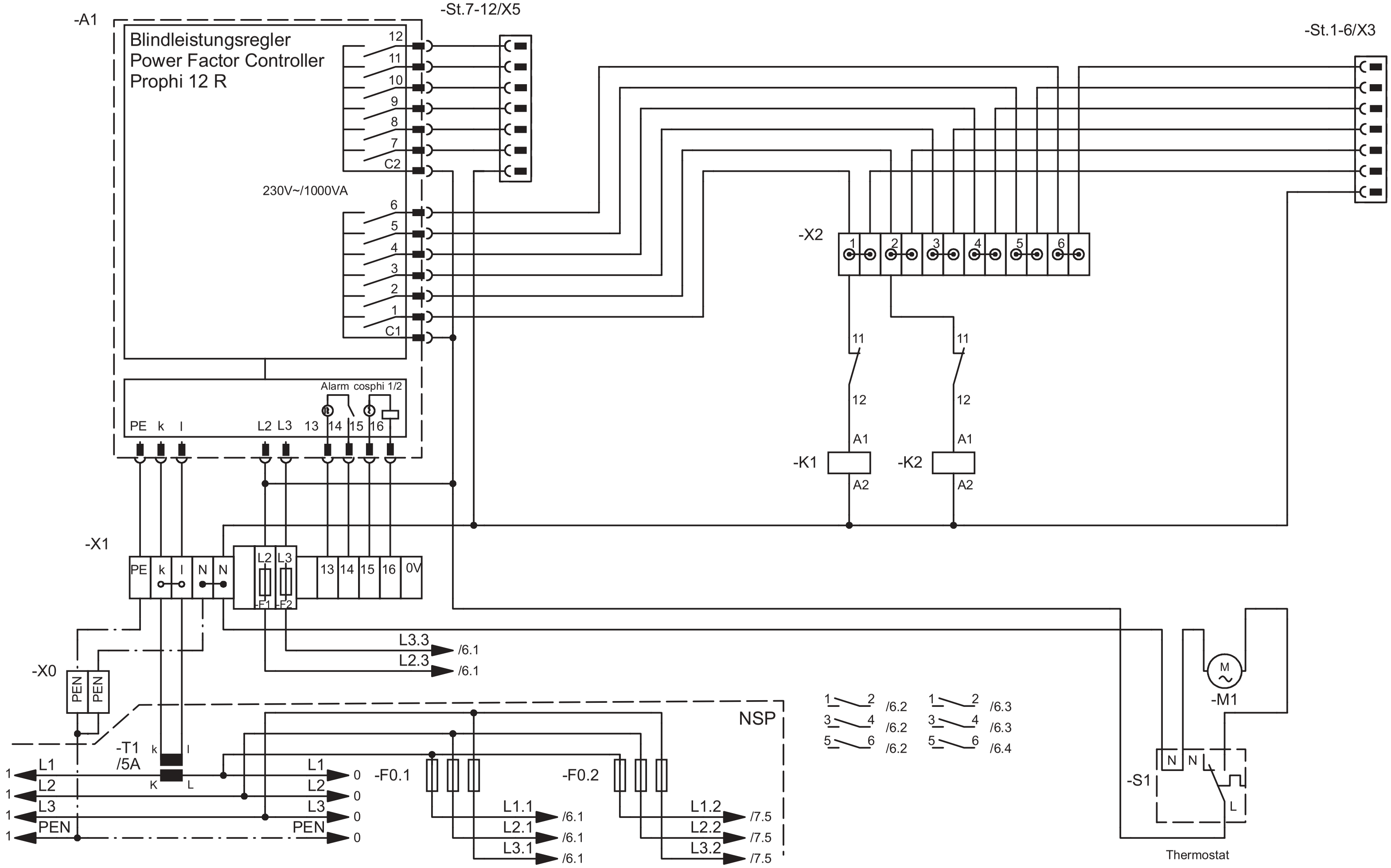


Figure 15.1 Principal circuit diagram of an automatically controlled compensation bank (NSP = Low-voltage distribution panel). *Source*: Janitza Electronics GmbH, Germany.

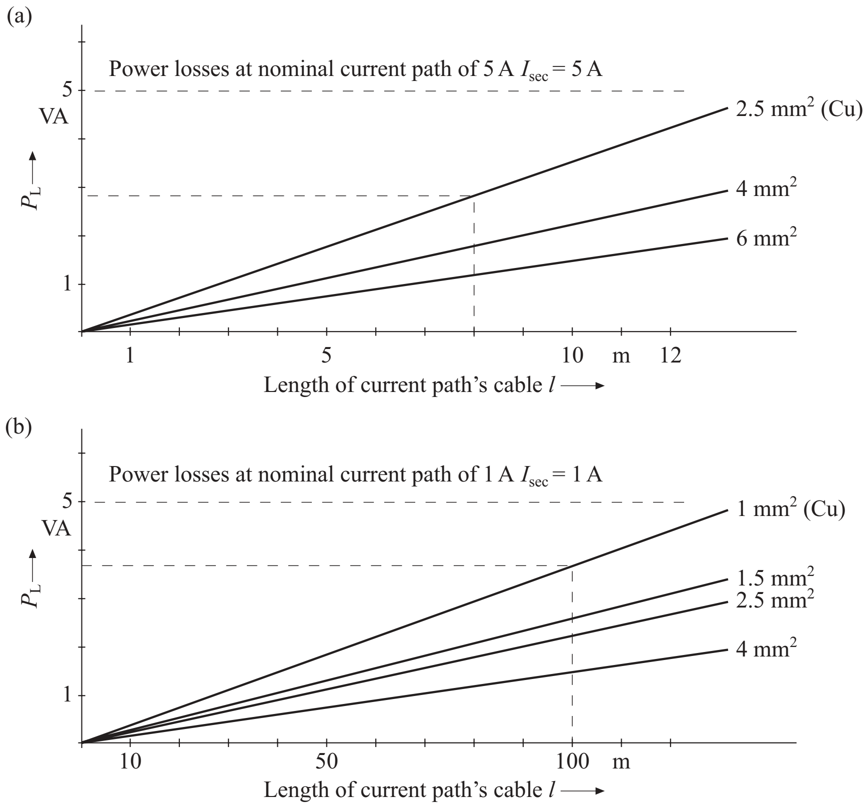


Figure 15.2 Power losses along CT cables (a) for secondary current path 5 A and (b) for 1 A.

700 A may not occur because CTs are determined to be 1.2 times the nominal current steadily without running into magnetic saturation. When ordering a new CT the following technical data are required:

1. Type of CT for installing either on cable or at busbar.
2. Dielectric strength, standardized to either $U_r = 0.66$ kV or 0.8 kV.
3. Nominal transforming ratio (e.g. 600 A/5 A).
4. Rated apparent power (10 VA usually).
5. Accuracy (Class 1–3).

Regarding the rated power, for example 10 VA, it is essential to ensure that the CT will never be overburdened. The power consumption of the current path at power factor controllers lies in the range of 0.5 to 1.0 VA. If an additional ammeter is installed, a further 1.5 VA is taken into account. Table 15.2 outlines typical consumptions of some measuring devices which must be taken into account for the selection of the CT.

However, the highest consumption of power is given by the leads as detailed in the following calculation.

Table 15.2 Some typical values of apparent power referring to different measuring devices burdening the CT (5 A secondary). Detailed values are available from the individual manufacturers.

Electrical devices	Consumption per current path	
Ammeter		
Moving-iron ammeter	(0.7–1.5)	VA
Moving-coil ammeter with rectifier	(0.001–0.25)	VA
Bimetallic ammeter	(2.5–3.0)	VA
Power meter	(0.2–5)	VA
Power factor meter	(2–6)	VA
Energy meter		
AC single phase	(1.1–2.5)	VA
AC three phases	(0.4–1.0)	VA
Relay		
Reactive current relay	0.5	VA
Overcurrent relay	(0.2–6.0)	VA
Bimetallic relay	(7.0–11)	VA
Power factor controller, electronic	(1.5–3.5)	VA

Example:

Length of cable $l = 20\,\text{m}$ (PFC to CT)

Cross-section $4\,\text{mm}^2$ (copper)

Resistance of the controller's current path $0.2\,\Omega$

$$R = \frac{2 \cdot l}{\kappa \cdot A} \tag{15.1}$$

where

$l =$ length of the cable (PFC to CT)
$\kappa =$ reciprocal specific resistance (copper)
$A =$ cross-section

$$R = \frac{2 \cdot 20\,\text{m} \cdot \text{mm}^2 \cdot \text{V}}{4\,\text{mm}^2 \cdot 56\,\text{A} \times \text{m}} = 0.178\,\Omega$$

The burden of the ammeter is calculated from the formula

$$P = I^2 \cdot R \tag{15.2}$$

$$R = \frac{P}{I^2} = \frac{1.5\,\text{VA}}{(5\,\text{A})^2} = 0.06\,\Omega$$

Thus the total burden of CT cable plus the controller's burden plus the ammeter's burden amounts to

$$R_t = 0.178\,\Omega + 0.2\,\Omega + 0.06\,\Omega = 0.438\,\Omega$$

At a nominal secondary current of 5 A the CT would be burdened with

$$S = I^2 \cdot R = 5^2\,\text{A}^2 \cdot 0.438\,\Omega = 10.95 \approx 11\,\text{VA}$$

The CT with a rated power of 10 VA would then be overburdened. It is necessary either to select a CT with higher nominal power or to increase the cross-section of the CT cable up to 6 mm^2, or even to remove the ammeter. Then it must be checked in the same way as described above whether the ammeter could be connected in series to the current path of one of the main CTs with the ratio of 1000 A/5 A.

Figure 15.2a,b outlines the power losses along the CT cables depending on their selected cross-sections. Figure 15.2a represents losses according to CTs with a nominal output current of 5 A and Figure 15.2b refers to 1 A of nominal secondary current. CTs with a nominal output of 1 A enable longer transmission distances with relatively low cross-sections and power losses, as can be seen.

All CTs are marked with capital letters ‘K’ and ‘L’ on their casing, and their output terminals with the lower case letters ‘k’ and ‘l’. Thus each CT is to be installed showing the ‘K’ side against the incoming supply (the point of common coupling (PCC)) and the ‘L’ side against the consumers.

As shown in Figure 15.1, the position of the CT should be locally close to the energy meters in order to achieve the desired power factor per month. In general most of the power factor controllers are measuring the electrical load via one CT fitted usually in phase L1. However, the voltage path for the controller is taken from the other two phases L2 and L3. Therefore the vector L1 to N is shifted 90° electrically to L2 and L3, enabling reactive power to be seized. In manufacturers’ instructions this scheme is shown as standard. If the CT in phase L1 is not available but, for example, is in L3, the voltage path must be taken from the other two phases all the time, here L1 and L2, and so on.

Note that each power factor controller is able to achieve the preset target power factor at the point where the CT is to be fitted exclusively.

Another essential point to ensure is that the CT seizes the reactive current of the compensation bank as well. If the CT had been fitted in error between the compensation bank and the consumers, any control of reactive power is impossible because the power factor controller measures in the uncompensated part of the electrical installation. It would switch in all capacitor steps without getting any compensation effects from the capacitors. Switching off the capacitors at finishing time becomes impossible and even the current goes down to zero because the CT is no longer able to measure the leading reactive current of the compensation bank (see Figure 11.10, where the capacitive vectors of the steps disappeared).

In larger electrical plants it is usual for the consumption of energy to be metered on the MV side. In this case it is very important that the target power factor at the controller be preset a little higher (e.g. instead of 0.92, up to 0.95 lagging) because its CT is sensing on the LV side and the consumption of reactive energy by the power transformer(s) is not to be seized. Detailed descriptions of ‘mixed measurement’ or measuring on the MV side can be found in Chapter 11.

15.3.2 Preset Switching Time Delay per Capacitor Step

Manufacturers deliver the compensation banks with preset switching time delays usually in the range of 20 to 30 s. It is up to the customer to change it according to the expected fluctuations of lagging reactive power demand of the consumers. If few fluctuations are expected, switching time delays between 40 and 60 s are quite sufficient. More frequent changes in reactive power require switching time delays between 20 and 40 s. The main goal of reactive power compensation is to follow the desired power factor, for example 0.95 on average within one billing period. Therefore it is recommended to check the first two or three energy invoices of the electricity distribution company. A correction may become necessary at any time in changing either the switching time delay or the preset power factor target.

Preset switching time delays shorter than 20 s are not recommended.

Note that shorter switching time delays increase the switching frequency; longer switching time delays spare both the switching devices like air contactors and the capacitors with regard to lifetime (see Section 7.7). Furthermore, this ensures that any capacitor step ready for re-energizing will be unloaded since the last operating period.

It must be underlined that the recommended switching time delays refer exclusively to LV compensation banks.

For MV compensation banks, there are totally different aspects to consider. As mentioned in Chapter 12, the MV capacitors are manufactured for a rated reactive power above 100 kvar up to several thousand kvar. The huge stored energy when de-energizing a capacitor must be converted into heat independently of which unloading technology is used. This may be done classically by resistances or more expensive reactors, and sometimes by voltage transformers. These discharging devices must be cooled down, which could take up to 15 minutes approximately. Power factor controllers for the application of MV compensations must therefore have the capability of presetting switching time delays in the range of 15 to 30 minutes or more.

15.4 Disturbances and How to Solve Them

Most of the problems one finds in cable installations are due either to twisted power cables or to errors in installing the CTs. In Europe the cables of the three phases L1, L2 and L3 are coloured black, brown and black, on the whole. Therefore it sometimes may happen that the two black-coloured cables are twisted in connection to the compensation bank. This does not matter for the power capacitors, but it does for the power factor controller wired internally (see Figure 15.1). To check the correct connection of the power cables is simple: a voltmeter is used to compare the three phases between the terminals of the distribution plant and the compensation bank step by step, that is L1 to L1, L2 to L2 and finally L3 to L3. In the correct installation no voltage can occur. However, if the voltmeter indicates a line-to-line voltage in one instance, for example 415 V, then two cables are twisted, which must be corrected.

Caution: The use of fused measuring leads is recommended, especially if multi-metre devices are employed and an error in the measuring path for currents has been detected.

After completing the check or correcting the phases, the next task is to check the current path connection to the CT and whether the cable is wired correctly to the terminals ‘k’ and ‘l’ of the controller. On the way to the CT the cable may pass several terminals provided for the purpose of additional measuring devices, like an ammeter and so on, to be connected in series. As CTs may never be in operation with opened terminals ‘k’ and ‘l’ (it would cause HV peaks), they must be linked to a short circuit if not in use. The CT must be checked for correct installation as described above (the ‘K’ of the casing to the incoming supply and the ‘L’ to the consumers) and whether it is mounted on phase L1 (see Figure 15.1). In case of a wrong mounting, for example on phase L3, the voltage path to the power factor controller must be taken from the other two phases L2 and L1 to ensure that the two paths are shifted 90° electrically against each other with regard to ohmic load. This is the basic scheme for measuring reactive power or energy referred to metering devices.

Assuming all the checked items are correct, the CT is mounted on phase L1 and the voltage path is taken from the other two phases L2 and L3, the compensation bank is then ready to be put into operation. Nevertheless it may happen that the power factor regulator controls incorrectly, which means it would like to switch off the capacitors, despite the inductive load and correct wiring; the reason lies in the anti-clockwise rotation field of the three-phase network. It is standard for all instructions to be designed for a clockwise rotation field. This problem is easily solved by just twisting either the voltage path (L2/L3) or the current path (k and l), but not both!

15.5 Working and Maintenance

Safety instructions on how to use power capacitors are settled by individual institutions worldwide and must be taken into consideration. In cases of overcharging power capacitors or at the end of their lifetime, there must not be any danger for the electrical plant or even to people. The safety instructions describe any risks in the case of disturbances with regard to power capacitors or how to minimize them by specialist maintenance.

The main rule is that power capacitors may work exclusively according to their specifications. Any manufacturers' instructions referring to applications, mounting and maintenance are to be followed strictly, as are national standards.

The following items, among others, with regard to the safety instructions are issued by ZVEI (Zentralverband der Elektro- und Elektronik Industrie) for Germany:

- Power capacitors must never be stored or put into operation beyond the admissible temperatures.
- Power capacitors must be checked for any visible mechanical alteration within the annual maintenance.
- Regular checks and maintenance are needed at locations with deposits of dust and dirt, especially at insulators or terminal screws.

Visible checks of electrical contacts, for example at contactors, signs of smoke, blown fuses or loose contacts are the main tasks of regular checks.

The temperatures of compensation rooms should be observed steadily, especially in tropical countries if air-conditioning plants are in use to keep the temperatures within the admissible range. Filters must be checked or even replaced if necessary. Any input or output of fresh air circulation must be kept free.

Specifications for electrical plants in the European standard EN 60439-1 for instance state that a temperature of 40 °C may be exceeded briefly, but not a steady temperature of 35 °C, for example, within 24 hours, except that if in the manufacturers' instructions there are differing specifications.

Further maintenance tasks are to check and to register the capacity of the power capacitors for each phase. Annual results are very illuminating with regard to the ageing procedure of the capacitor.

Safety instruction: Before checking the capacitor, it must be ensured that it is disconnected and discharged. This is easy to check with a voltmeter. In the case of failed discharging devices, power capacitors are able to store voltages for several days due to modern dielectrics.

Table 15.3 Maintenance work [1].

Position	Kind of maintenance	Date	Signature
	Electrical plant: reactive power compensation ...V/...Hz; ...kvar; ...% detuned		
1	Replacing ventilation filters		
2			
3	Replacing blown fuses		
4			
5	Cleaning the air supply		
6			
7	Check of terminal screws		
8			
9			

An annual registered check enables the current condition of an electrical plant to be estimated and guarantees proper operation of the plant. It determines whether any repairs or replacements are needed.

Tables 15.3 and 15.4 show forms for recommendations for some working procedures within a planned or outside of an annual check.

Table 15.4 Checklist for regular maintenance [1].

Position	Items to check	Defects
1	Following manufacturer's instruction	
2	Visual check of the electrical plant	
3	Visual check of the location	
4	Visual check of air supply	
5	Visual check of cables and leads	
6	Visual check regarding deposited dust	
7	Visual check regarding any damage	
8	Visual check regarding oxidation	
9	Visual check regarding humidity	
10	Visual check regarding density of capacitors	
11	Visual check regarding feedthrough bolts	
12	Visual check of switching devices' contacts	
13	Visual check of terminal screws	
14	Fuses determined correctly?	
15	C/k value preset correctly at PFC?	
16	Desired $\cos\varphi$ preset correctly?	
17	Check of correct ambient temperature	
18	Check of unloading devices at capacitors	
19	Check of operating voltage (at low load mainly)	
20	Function check of the compensation	
21	Monthly check of energy invoices	
22	Check and registration of desired $\cos\varphi$ to be achieved	
23	Final check of the compensation bank	

15.6 Summary

It is essential to follow the instructions of the manufacturers and the national specifications referring to admissible data like temperature, voltage, current, power, reactive power and frequency.

The correct preset parameters at the power factor controller ensure proper control of reactive power.

Any errors in connecting are to be discussed and their solutions explained.

Switching time delay that is too short harms air contactors and the capacitors in relation to their lifetimes. Finally it is important that the desired average power factor is achieved within one billing period.

Regular or, if necessary, irregular checks of compensation banks guarantee a long lifetime. They are indispensable for detecting any disturbances in time and for repairing or replacing electrical components before they eventually destroy further components.

References

[1] Große-Gehling, M., Just, W., Reese, J. and Schlabbach, J. (2009) *Blindleistungskompensation – Netzqualität* (Reactive Power Compensation – Network Quality), VDE-Verlag, Berlin and Offenbach.
[2] Frako Kondensatoren- und Anlagenbau GmbH, Teningen, Germany. Handbook (2000), 25.

16

Reactive Power Compensation in Electrical Plants with Generators

16.1 Chapter Overview

Up to now the compensation of reactive power has been discussed while operating in the first and second quadrants of the coordinate system. Increasingly, industrial plants, for example plants burning wood dust, are using generators driven by steam engines running parallel to the main supply.

This chapter explains the technical and economic aspects regarding the desired power factor or reactive energy to be charged. If generators are feeding back active energy to the distribution company, one speaks of four-quadrant operation. The tariff situation then has new aspects with regard to the reactive energy consumption to be charged. The tariff requiring an average power factor of $\cos\varphi = 0.9$ lagging (see Chapter 4) becomes invalid as explained in the following sections.

Furthermore, it renders prominent the meanings of power factor $\cos\varphi$ and reactive power Q as totally different electrophysical quantities. One could describe them in an inequality like

$$\cos\varphi \neq Q \neq \cos\varphi$$

Thus power factor is not identical to reactive power and vice versa.

16.2 General

Any plan for putting generator(s) into action must be declared to the electricity supplier and registered in a specially negotiated contract. It determines to which incoming supply (if more than one) the generator should be connected. Specifications issued by national or international institutions should be strictly followed [1, 2].

First of all, power generator units running steadily in parallel to the main supply must be distinguished from emergency power generator units at hospitals that are activated in case of any fault or collapse in the main supply. Emergency power generator units are in use for a

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

short time, mainly until the grid is active again. This situation may be excluded by referring to four-quadrant operation.

Power generator units may be driven by primary energy sources like water or wind power, solar cell plants, cogeneration district heating plants or fuel cells.

The electrical energy may be generated by synchronous or asynchronous generators as well as by DC generators with DC/AC converters.

The following criteria on driving generators in parallel to the grid are to be noted: voltage stability, quality of the voltage and synchronized frequency. It must further be taken into consideration whether an autarchic operation will be intended. However, this is possible mainly with synchronous generators.

16.3 Automatic Control of Reactive Power within Four Quadrants

16.3.1 Technical Considerations

Figure 16.1 illustrates the four quadrants of a coordinate system. If generators are in operation four different load situations may occur:

Quadrant I: Consumers import (+) active and reactive energy.

Quadrant II: Consumers import (+) active energy and export (−) reactive energy.

Quadrant III: Consumers export (−) active and reactive energy.

Quadrant IV: Consumers export (−) active energy but import (+) reactive energy.

In quadrants III and IV the generators are feeding back active energy to the electricity supplier to be measured by a separate kWh-meter. Most attention is paid to the situation within quadrant IV. Asynchronous generators especially are able to feed back active energy to the grid, but they import reactive energy for magnetizing!

The situation in quadrants I and II is well known as illustrated in Figures 11.7 and 11.10. There the control of reactive power is explained by means of an automatic controller. One can recognize the insensitive bandwidth limited by the so-called *C/k* threshold lines and the turning around of the zero point of the coordinate system depending on the selected power factor target.

Figure 16.1 indicates two selected power factor targets: 0.85 lagging and preset to unity. Regarding load vector 3, one capacitor step is sufficient to achieve the power factor of approximately 0.85 lagging and the controller ‘stands by’. In order to achieve the desired power factor of $\cos\varphi = 1$, the reactive power controller switches in three further capacitors.

Even though a generator is running in parallel just to reduce the consumption of the active energy from the main supply, the vectors are still moving within the first or second quadrant only (see Figure 16.2b). However, if the generator takes over the complete active power consumption and even feeds back active energy into the electricity supplier’s grid, then the vectors change into the third or fourth quadrant (see Figure 16.2c). Most electronic reactive power controllers have a digital display indicating the actual power factor. For control of reactive power operating within all four quadrants, confusing power factors may be indicated, as shown in Figure 16.2c, if the generator is feeding back. Controlling within all four quadrants,

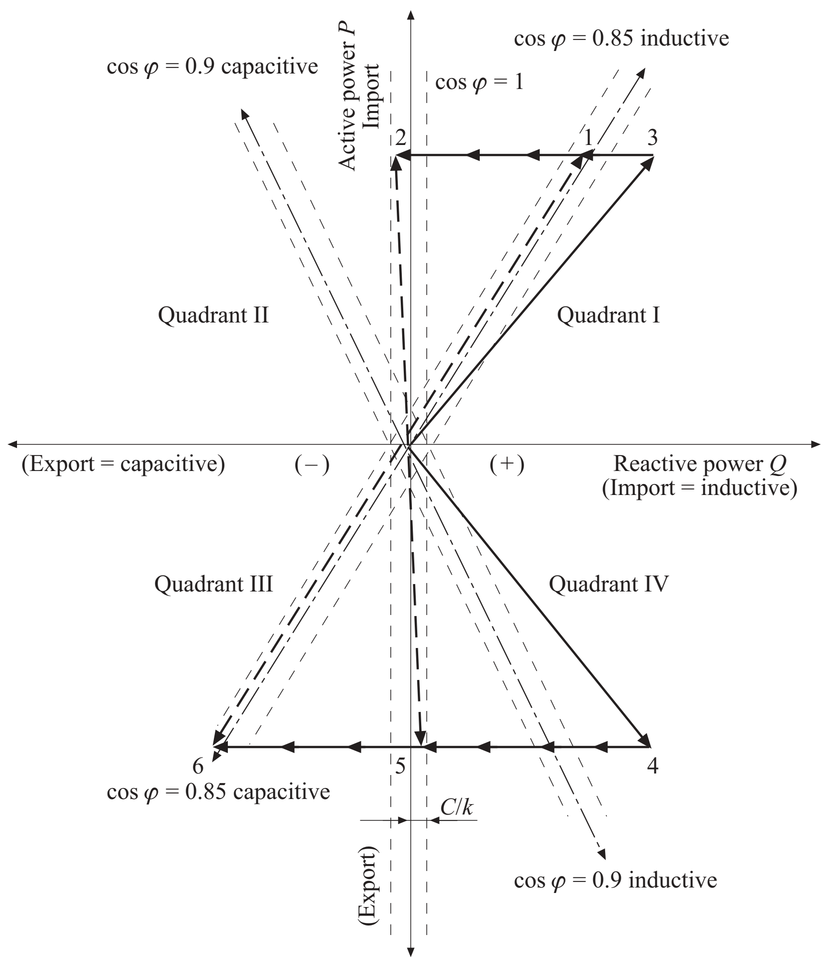


Figure 16.1 Reactive power control within all four quadrants.

any value of the power factor may be indicated from 0 to 1 in either the first or third quadrant and from 1 to 0 in the second and fourth quadrants. Thus the controller indicates any possible value within 360° of the coordinate system, provided that it is suitable for four-quadrant operation.

This is the presupposition that the reactive power controller is applicable for operation within all four quadrants. It must be underlined again that the actual power factor cos φ_a does not say anything about the actual amount of reactive power Q.

Vector 4 in quadrant IV in Figure 16.1 symbolizes the load situation where the generator is covering the consumption of active power totally and is feeding back an identical amount to the grid in addition. If the target power factor had been preset to 0.85 lagging, the controller would suddenly intend to compensate to the 0.85 leading side! The C/k bandwidth is extended from the first quadrant via zero into the third quadrant. This is called the mirror-imaging behaviour of the controller. It does not ensure that the compensation bank will be sufficient

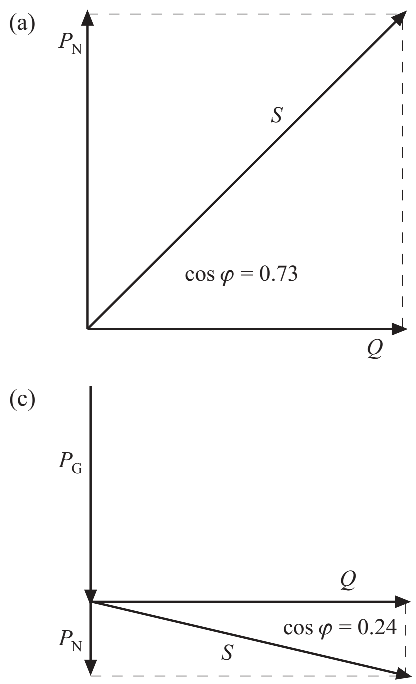


Figure 16.2 (a)–(c) 'Confusing power factors' in four-quadrant operation (current transformer fitted at incoming supply point).

to compensate according to the 0.85 leading side (see vector 6). Seven capacitor steps would become necessary in order to achieve this power factor target. As is well known, there is the disadvantage of a voltage increase when compensating into the capacitive area. If the compensation bank was not able to achieve this high power factor due to insufficient steps, many modern reactive power controllers would trigger an alarm. To get proper control of reactive power does not mean presetting the power factor target into the second quadrant, for example the 0.9 leading side in order to achieve the 0.9 lagging side when controlling in the fourth quadrant (see Figure 16.1). The simplest way to solve this problem is to preset the power factor target to unity, $\cos \varphi_d = 1$. With this power factor target, symmetrical control of reactive power is ensured within all four quadrants (see vectors 5 and 2). Thus if the reactive power compensation is working within all four quadrants the capacitors' capacitance is determined sufficiently in order to achieve an average power factor of unity, $\cos \varphi = 1$. Remember that the total compensation of reactive power saves active energy (kWh) due to power losses along the leads. This solution is indispensible not only from a technical viewpoint, but also from the economical side as well, as described in the next section.

16.3.2 Bargaining Considerations

As mentioned above, customers with their own generator(s) are obliged to compensate reactive power to a desired power factor much closer to unity, $\cos \varphi_d = 1$.

Any standard tariff agreement on achieving an average power factor of 0.9 for instance (see Section 4.2.1) becomes invalid. This standardized contract agrees that 48.5% of the consumption of active energy is free of charge with respect to the amount of reactive energy (see the example calculation in Chapter 4). In simple terms, if the consumption of active energy amounts to, for example, 1000 kWh per billing period, then 485 kvarh of reactive energy is free of charge.

The very human behaviour of customers with generators ensures that they will pay attention to bringing down the consumption of active energy to zero. Then, at the end of a billing period, the electricity invoice may indicate 0 kWh of active energy but, for example, 17 000 kvarh consumption of reactive energy! As a matter of course the electricity company will not grant any kvarh without charging. Many electrical plants with generators are using asynchronous generators, that is asynchronous motors running with so-called negative 'slip'. Independent of whether the engine is running in motor or generator mode, it consumes reactive energy for magnetizing the iron core steadily.

Thus each customer intending to reduce the consumption of active energy particularly or even totally by the generator(s) is obliged to compensate any reactive energy totally as well, except if the customer has negotiated a special contract with the electricity utility company. The following example underlines the facts described above.

Example: An asynchronous motor of 100 kVA rated power is to be driven in generator mode. Its nominal power factor is 0.82 inductive. Although it is feeding back active energy into the grid, the consumption of reactive power amounts to

$$\cos\varphi = 0.82 \Rightarrow \varphi = 34.9^\circ \Rightarrow \sin\varphi = 0.572$$

The reactive power of the generator is to be calculated by

$$Q = S \cdot \sin\varphi \tag{16.1}$$

$$Q = 100\,\text{kVA} \cdot 0.572 = 57.2\,\text{kvar}$$

Within one day, or 24 hours, the varmeter will count up to 1373 kvarh or 41 200 kvarh approximately per month if the generator is running steadily, for example at water power stations.

In operating with synchronous generators the consumption of reactive energy depends on the preset exciting rate. They are preset to a power factor referring regularly to the lagging side. Then the reactive power of the generator is calculated in the same way as described above for the asynchronous one.

16.4 Summary

Compensating reactive power within all four quadrants of the coordinate system due to generators running in parallel requires consideration of technical and economic facts in totally another way to that known from classical two-quadrant operation.

In general the aim is to compensate in achieving unity, cos $\varphi = 1$, as close as possible. The compensation bank has to be determined accordingly and the reactive power controller must be suitable for control within all four quadrants.

It is a matter of course that the controller's current transformer must 'seize' the reactive current of the generator(s) as well. Thus the feed-in point of the generator(s) always has to 'look' to the L side of the current transformer's casing.

Individual, national or international instructions are to be followed. In Germany the rules are issued by the BDEW (formerly VDEW) [1].

References

[1] BDEW (German Association of Energy and Water Suppliers) (2001) Instructions for generators running in parallel to the main supply in LV-plants. Generation Systems on MV-Networks, Technical Regulations 2008. Energieverlag, Frankfurt and Heidelberg, Germany.

[2] E-VDE-AR-N 4105 (2010) *Generation Systems on LV-Networks*. Technical Regulations, Germany.

17

Effects of Perturbation Considering Especially the Impact of Harmonics on Power Factor Correction Capacitors

17.1 Chapter Overview

A reliable electrical power supply with a high-level power quality is an absolute necessity for stable processes in any kind of enterprise. In other words, high-quality power networks and electricity are particularly indispensable for the economic sectors of industry, commerce and trade.

During the distribution of electrical energy, physical ‘phenomena’ occur which affect the power quality. As already mentioned, reactive power is not economical and consequently should be avoided as much as possible.

In addition, there has been an increase in nonlinear loads and the generation of harmonics, interharmonic components, voltage fluctuations, network unbalance, voltage drops, commutation effects and flicker (and certain audio frequency control signals) which also affect the smoothly functioning transmission and distribution of electrical power.

To be able to better understand the problem of harmonic-distorted networks in the operation of parallel capacitors, the question must be clarified as to what current stresses occur within a capacitor due to existing harmonic levels after installation.

Measurements to obtain a detailed evaluation of the on site-situation are frequently part of the preliminary planning of remedial measures for the reduction of perturbations (power quality distortions).

Use of this methodical procedure makes it possible to compile a database required for the often complex job of designing power factor correction systems or harmonic filters.

Furthermore, it is strongly recommended that the technical regulations of the local distribution system operator (power utility) be adhered to, so that other consumers are not disturbed by harmonic distortions.

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

It should be noted that, due to limited space, this chapter does not deal with the pros and cons of fixed and portable power quality analysers.

17.2 Perturbations and Improved Power Quality for Business Customers

A wide variety of electronic power converters is used in electrical power and customer networks (e.g. industrial networks) for the efficient use of electrical energy. Examples include switching network components, the control of speed-regulated drives via converters and inverters, the use of electrical equipment with rapid changes in load (e.g. cranes, elevators, welding robots), saturated ferrous cores with inductances and an uninterruptible power supply (UPS) [1].

For example, the rated power of converters today has already reached several megawatts. Additional powerful harmonic generators include arc furnaces and induction furnaces. This means that harmonic currents are increasingly being fed into the superimposed power network, which causes network perturbations or equipment failures. These undesired perturbations are not always found in the specific customer network (e.g. industry).

Electrical perturbations can also be caused by harmonics coming from a neighbouring plant, for example. One then says that the electrical network is ‘contaminated’. This increases the cost of power transmission and thus also electrical transmission losses. In addition, the power factor correction system also contributes to the reduction of CO_2 emissions.

The following can be drawn from the previous explanations for the primary types of perturbation:

- Harmonics, interharmonics.
- Voltage fluctuations, sags, swells and outages.
- Flicker.
- Voltage unbalance.
- Transients.

These types of perturbation occur in the customer’s system and possibly at the network distribution level too. Capacitors in particular react very sensitively to harmonics.

Excessive harmonic distortion causes harmonic currents to flow into the capacitors in addition to the fundamental current which is often the root cause of high temperatures in capacitors and can lead to premature ageing and even failure of the capacitors.

Good power quality in the electrical distribution and customer network means an undistorted sinusoidal network voltage with constant amplitude, rms value and frequency. This definition also includes an insistence on the effective use of primary energy during the generation of electrical power regarding possible low-loss transmission and distribution [1]. However, good network quality of the distribution and customer networks is not the same as good power quality. Plant malfunctions, equipment failures, increased electrical losses and the resulting reduction in production quality, and high failure costs are often caused by poor power quality. A safety analysis can illustrate how investment in a perturbation-free power supply is an ‘insurance policy’ for success. In addition, it must be noted that the distribution system operator (power utility) regulates perturbation ‘emissions’ many times, for example harmonics, flicker and voltage fluctuations, or requires a customer to eliminate or reduce such perturbations caused by the customer.

Precautions must be taken to ensure malfunction-free operation of electrical equipment in the electrical distribution and customer network. In addition to the classic power factor correction systems to improve the fundamental frequency power factor, capacitor manufacturers have recently developed new technologies. These technologies supplement the power factor correction systems product to reduce reactive power. Table 17.1 gives a basic overview of the impairment of power quality and its causes and suggests suitable measures to improve network and power quality.

Audio frequency absorption by a compensation and its possible solution (e.g. by audio frequency blocking) will not be discussed here since audio frequency control is used only in a few countries (e.g. Germany, Switzerland and Austria). For a discussion of this subject, see [1].

Table 17.2 shows a selection 'diagram' for power factor correction systems which reduce or eliminate the previously mentioned perturbations and also improve the voltage's sinusoidal form. The technically useful and economic use of the modern technologies shown in Table 17.2 requires correct judgement of the local network conditions.

In addition, it is recommended that the power quality be measured, the expected network *perturbation* of the planned electrical equipment calculated and the voltage quality continuously monitored.

Measures can be taken at different points in the electrical network to counteract network perturbations and improve network and power quality. Here the discussion will take a particularly good look at the customer's system (e.g. industry, commerce).

Table 17.1 Impairment of the power quality and suitable measures [1].

Problems		Cause
Reactive power	→	Inductive consumers (line-commutated rectifiers)
Harmonics, interharmonics	→	Power electronics
Commutations	→	Inverters (line controlled)
Voltage peaks	→	Switching procedures
Voltage fluctuations	→	Changes in load
Network unbalance	→	Single-phase and two-phase loads
Tone frequencies	→	Ripple control signals of the distribution system operator (power utility)
Power quality improvement by:		
Power factor correction system		
Harmonic filters, tuned and detuned		
Tone frequency interference suppression filters		
Motor startup aids		
Special network filters		
'Flicker compensation'		
Commutation reactors		
Network balancing		

Table 17.2 Selection 'diagram' for compensation equipment.

	Load conditions, dynamics of load changes			
	High reactive load			Low reactive power load
Harmonic load	Static load	Frequent load changes	Flicker	High neutral-conductor current
$\leq$15% power converter portion, primarily linear loads, no parallel resonance	Compensation without reactor protection	Dynamic compensation with reactor protection	Dynamic compensation with reactor protection or active harmonic filters	Active harmonic filters
$\leq$50% power converter portion, linear and nonlinear loads	Compensation with reactor protection	Dynamic compensation with reactor protection	Dynamic compensation with reactor protection or active harmonic filters	Active harmonic filters
$>$50% power converter portion primarily nonlinear loads, significant harmonic load	Tuned filter circuits	Dynamic compensation with reactor protection and tuned filter circuits	Active harmonic filters	Active harmonic filters

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17.3 Measuring and Analysis [2, 3]

Conventional capacitor banks without reactors could be a danger to a smooth production process in modern industrial facilities as well as other applications such as shopping malls, large office buildings, hospitals, and so on. The danger of resonance amplification is very high in the network due to increasing harmonic emissions resulting from nonlinear loads, such as power electronics (see Chapter 18) or arcing equipment, for example scrap melting, welding.

Measuring power quality and here especially the harmonic distortion can be considered mandatory. Of course, for the evaluation of the measurement results a solid knowledge of power quality is required.

The development of power electronics, for example current converters, frequency converters with network-side diode bridges, devices with capacitive smoothing, compact fluorescent lamps, causes more and more interference. Only solid measuring results make it possible to decide on proper remedial measures in the field of power quality.

Before beginning measurements, the task should be clearly and precisely stated and the goal of the measurements explicitly documented. Only with very clear goals can the desired results be achieved at the end of the evaluation. After the measuring task (e.g. what is the maximum fifth harmonic loading?) for designing a tuned harmonic filter has been precisely formulated, the necessary measured variables, that is transients, THD-V or THD-I, individual harmonic content or reactive power load profile, can then be selected for later evaluation.

For an harmonic analysis or power quality analysis it is important to decide on the measurement point. This point depends on the target or required information. In case a harmonic filter has to be designed and the overall THD-A level has to be reduced at the point of common coupling (PCC), or the overall power factor in an application has to be improved, it is necessary to measure at the PCC site of course. However, in order to find out if a power factor correction system or harmonic filter is overloaded the measurement point should be directly at the supply cable to the harmonic filter itself. In larger applications it is certainly necessary to have multiple power analysers across the distribution network. In practice the three-layer power quality monitoring model becomes more and more the standard [3]:

- Class A power quality monitoring.
- Mid-class power analyser with Ethernet communication and Ethernet/Modbus gateway, for connecting subordinate power analysers (main feeder from supply transformers).
- Economic meters and power quality field bus communication (large loads, critical loads).

Selecting the proper measuring equipment is of major importance for ensuring correct measurement results. Various aspects have to be considered under this topic:

- Voltage range.
- Overvoltage category.
- Sampling rate (e.g. transients in microseconds, events in milliseconds, load profile in seconds).
- Harmonics up to 40th order.
- Flicker measurement.
- Accuracy Class 0.5 or better.

Figure 17.1 shows an example of a Class A power quality monitoring device.

After the measuring equipment has been selected, the measuring interval must be determined. The interval should be one week when using a portable power quality analyser (see Figure 5.6; according to DIN EN 50160 and IEC 61000-4-30). For fixed installed power quality monitoring systems, there will be continuous monitoring, averaging times of 10 minutes, and a daily data download from the power quality monitoring devices to the central database is recommended (see also IEC 61000-4-30).

It must be ensured that all desired operating states (e.g. different load scenarios) occur at the measuring location within the intended measuring time. It may certainly be necessary to develop special scenarios, for example providing organizational measures such as switching of power inputs or commissioning of individual pieces of equipment, which can then be implemented during the measurement and recorded.

Easy-to-understand, reproducible documentation of the measurements should be supplied, complete with a detailed description of the conditions during the measurements. The following information should be documented in detail at the time of the measurement along with the measurement data:

- Voltage level.
- Installation location of the measurement.
- Measuring devices and sensors used.
- Technical data of the supply transformer.

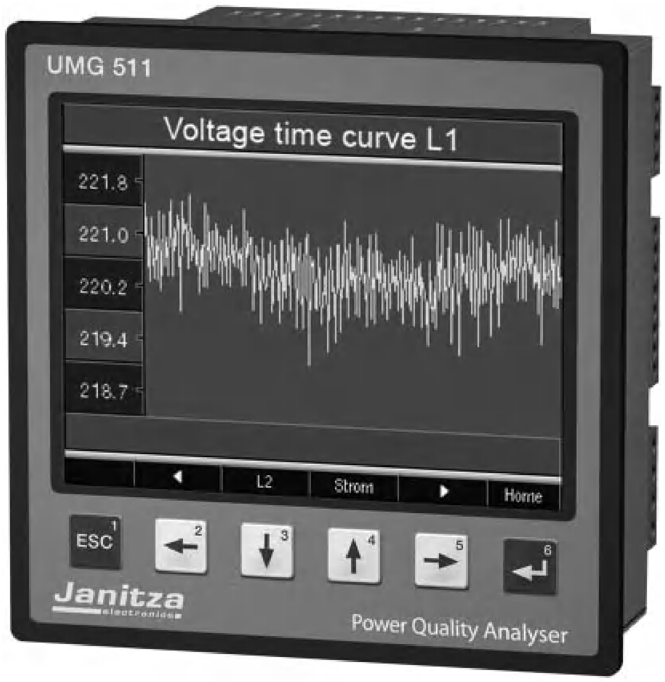

Figure 17.1 Power quality monitoring device (Class A according to IEC 61000-4-30). Reproduced by permission of Janitza Electronics GmbH, Germany.

- Short-circuit power of the superior supply network upfront.
- Cross-section, length and type of supply cables or busbars to the individual sub-distribution.
- Data of the equipment with the strongest network perturbation.
- Data of equipment sensitive against poor power quality.

It is very helpful for the documentation to develop a standard document and then have it prepared and ready on site. If operationally possible, complete documentation should include photos of the installation location and of other important locations or devices for later evaluation. If, for example, a circuit diagram of the electrical system is not available, a sketch should always be made of the most important information such as powering transformer, arrangement of the lines/wiring, sub-distribution, existing power factor correction systems, large-scale main loads, and so on.

Documentation such as the one described above ensures that the results of a measurement can still be used satisfactorily even several years later. Easy-to-understand, reproducible documentation is also a question of quality management and in many cases very helpful for documentation in various aspects.

Today's power quality analysers are typically used to perform the measurements for the evaluation of perturbations and quality distortions. These devices allow the recording of not only relevant electrical parameters such as current and voltage, but also the power quality values derived from them (e.g. harmonic level or 'total harmonic distortion').

Table 17.3 Measured and evaluation parameters (the list of measured parameters is not complete) [4, 5].

Measuring and evaluation parameter	Measuring or calculation value
The rms values of current and voltage	From actual values over half cycle
Active power, reactive power and apparent power	From rms values
Harmonic portions in current and voltage by amount and phase	Calculated by fast Fourier transformation
Harmonic active power and reactive power	From harmonics of the voltages and currents
THD-V factor	From harmonics of the voltages
Short-term flicker	From rms voltage values (10 min)
Long-term flicker	From rms voltage values (2 h)

Table 17.3 provides a rough overview of measured and evaluation parameters for perturbations. The subject of 'interharmonics'-measured variables and other measured parameters will not be covered in detail here. It should be noted that this table only presents certain parameters, which means that there may be further parameters of interest within the broader technical context.

There are often very large differences in the amount of measurement memory available for the measuring devices on the market today. However, the amount of memory is important, as is the amount of time planned for the measurement. For portable devices this topic could be even more important than for fixed installed power quality monitoring systems, which can be automatically read out into a central database.

In principle, the acquisition of the individual measured variables is also possible with simple measuring devices. However, remember that all related measuring devices should be time synchronized (e.g. Normal Time Protocol server) and have the same recording intervals. This is important to make sure that a voltage sage at one measurement point can be precisely compared with another point's current trend. For example, a current drop at the same time indicates that the voltage drop comes from the upstream supply network, otherwise a current rise indicates some switching operation or short circuit inside the application [3]. For the sake of comparability, for example in legal disputes due to production stops or defective production equipment, modern power quality analysers should comply with Class A requirements of the IEC 61000-4-30 standard, 'Testing and measurement techniques – Power quality measurement methods'. This standard describes the individual measuring procedures with regard to the acquisition of various power quality parameters, such as harmonics or flicker, and ensures that the results can be compared even when the devices of several different manufacturers are used at a specific point at the same time. Currently, the performance criteria are being specified for all measuring systems in accordance with IEC 61000-4-30 in the planned IEC 62586 standard, 'Power quality monitoring devices in power supply systems'. The use of systems which are certified in accordance with IEC 61000-4-30, Class A, is recommended. In principle, the use of Class S and Class B devices is also possible. But only the Class A devices can be used for sorting out different opinions in connection with extensive agreements or to prove adherence to standards.

When designing power factor correction systems in harmonics-polluted applications, or before commissioning power factor correction systems in networks with suspected harmonic

(a) (b)

Figure 17.2 (a) and (b) Analysis and measurement. (a) Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany; (b) Reproduced by permission of KoCos Power Grid Services GmbH, Germany.

content, it is absolutely necessary to identify the harmonic content by measurement over a longer period of time, for example one week (Figure 17.2).

The comprehensive evaluation of the electrical distribution network conditions also allows optimized solutions for complex electrical distribution systems. The following measurements should be conducted in order to get reasonable information for the evaluation of future operating behaviour of a power factor correction system to be set up with an existing electrical system:

- Measurement of the harmonic distortion without power factor correction system.
- Measurement of the load profiles of reactive and active power at the same time with harmonic measurement and without power factor correction system.
- Theoretical evaluation of the network behaviour regarding resonances that occur.
- Recording the required network data, for example network short-circuit power on the PCC of the local distribution system operator (power utility).
- Information on interference in the past which might have been caused by excessive harmonic loads.

When evaluating the recorded data, these must be examined regarding different statements. Below are a few examples:

- Voltage distribution in the network segment being discussed.
- Harmonic level in the network segment being discussed.
- Resonance behaviour under consideration of existing power factor correction systems.

Almost all manufacturers of power quality monitoring devices today offer powerful software solutions for simple data processing. These programs can be generally used to prepare graphic evaluations quickly. However, particularly when designing power factor correction systems, further processing of the data with a filter program, or the use of Excel for example, is often desired. Consequently, there should be a way to convert the data into a generally read-accessible format using the software tools.

Measurement results are also often used for documentation, that is proofing of contractually guaranteed performance, for example power quality according DIN EN 50610 at PCC, or maintaining a specified power factor in an installed power factor correction system. In many cases, it is necessary to use measuring devices and measuring sensors which are retraceable. This can be accomplished by an annual calibration performed by appropriately certified calibration labs.

In addition, it is recommended that in critical network segments or networks with more sensitive loads, for example data centres, semiconductor plants and paper plants, power quality should be permanently monitored, or at least the following parameters: active power, reactive power and apparent power, harmonic content, and THD-V and THD-I.

Many measuring devices today allow the recording of digital or analogue signals, consequently, additional parameters such as room temperature, transformer temperature, inside capacitor cabinet temperature, tripped circuit breaker, open safety gate at HV applications or relative humidity can be recorded as well [3]. These inputs can be used to record additional important information about the power factor correction systems. For example, they can include the exceeding of permissible equipment operating temperatures or digital error messages. Standard communication interfaces (RS485 or Ethernet) which many devices offer can be used to read out any widespread measuring systems from a central location (control room). With this information, early recognition of possibly impending overloads or failures is possible.

17.4 Summary

The economic benefits of power-electronics-operated equipment, which are achieved through an increase in efficiency and enhanced performance, lead to a steep rise in ‘nonlinear loads’, which causes more and more network perturbations. Measures to improve power quality ensure malfunction-free production, high product quality, reliable power supply and a reduction in energy consumption. Some advantages of enhanced power quality are listed below:

- Reduction of electrical losses, in particular due to excessive harmonic currents.
- More stable and perturbation-free operation of electronic and electrical equipment.
- Less perturbation with the upstream grid ensuring conformity with the power quality standard and power distribution regulations.
- Increased lifespan of electronic and electrical equipment.
- Reduction of investment costs for new transformers, cables and other electrical distribution and transmission equipment.

Reliable and uninterrupted operation with the electrical network requires that the network conditions are checked at regular intervals (see Chapter 15). The measuring results make it possible to provide suitable adjustments.

References

[1] Just, W. and Hofmann, W. (2003) *Blindstromkompensation in der Betriebspraxis* (Reactive Power Compensation – A Practical Guide), 4th edn, VDE-Verlag, Berlin and Offenbach.
[2] Information from KoCos Power Grid Services GmbH, Korbach, Germany.
[3] Information from Janitza Electronics GmbH, Lahnau, Germany.
[4] Blume, D., Schlabbach, J. and Stephanblome, T. (2001) *Voltage Quality in Electrical Power Systems*, IEE Power Series, No. 36, Institution of Electrical Engineers, Stevenage.
[5] Hofmann, W., Just, W. and Schlabbach, J. (2008) *Netzrückwirkungen* (Network Perturbations), 3rd edn, Medien und Kongresse, Frankfurt/Main and VDE-Verlag, Berlin and Offenbach.

18

Resonances in Electrical Power Systems

18.1 Chapter Overview

If capacitances, inductances and resistances are present in the network, the corresponding circuit represents a series or parallel resonance circuit. Such arrangements are frequently found in electrical power supply networks and it must be possible to analyse their behaviour where there are harmonics and interharmonics in the current and voltage. Examples for resonances in MV systems are given.

18.2 Parallel Resonance Circuit

A typical structure of a power system is outlined in Figure 18.1 consisting of a supply via a transformer from a network with a higher voltage level. At the connection point or point of common coupling (PCC), loads other than those generating harmonics, such as ohmic and motor consumers, are connected. A capacitor bank is often used for reactive power compensation. The aforementioned ohmic and motor consumers are sometimes connected to the PCC by cables. The cable capacitances and also the capacitors must be taken into account in the investigation. In MV systems, a similar structure can be assumed.

For a further investigation of the supply scheme with regard to harmonics, the equivalent circuit of the network in the positive phase sequence system, shown in Figure 18.2, is used.

The reactance of the feeding transformer (and the power system on the higher voltage level) and the capacitance of the compensation (and the cable capacitances) form a parallel resonance circuit seen from the PCC. The resistances of the transformer and of the load are acting as attenuators of the resonance circuit. The resonance frequency f_{res} is calculated from

$$f_{res} = \frac{1}{2\pi \cdot \sqrt{L \cdot C}} \tag{18.1a}$$

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

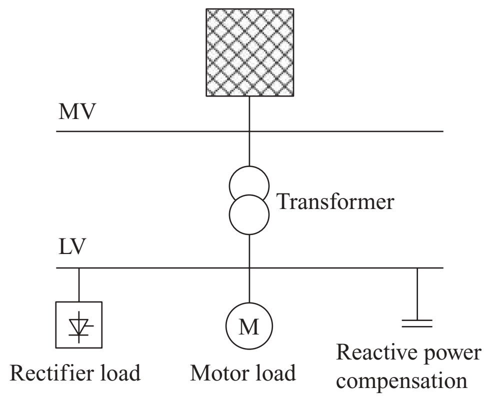

Figure 18.1 Simplified structure of power system indicating the supply of LV consumers.

$$f_{res} = f_1 \cdot \sqrt{\frac{S_k''}{Q_C}} \tag{18.1b}$$

$$f_{res} \approx f_1 \cdot \sqrt{\frac{S_r}{u_k \cdot Q_C}} \tag{18.1c}$$

where

S_k'' = short-circuit power at the PCC
Q_C = reactive power of the capacitor
S_r = apparent rated power of the transformer
u_k = impedance voltage of the transformer

The attenuation d of the resonance circuit, sometimes named A, is calculated from

$$d = \frac{1}{R} \cdot \sqrt{\frac{L}{C}} \tag{18.2a}$$

The reciprocal of the attenuation is named the resonance quality Q. Figure 18.3 shows the impedance versus frequency of a parallel resonance circuit. The impedance of the resonance circuit is increased in a typical bandwidth ($f_{res}/\sqrt{2} < f < f_{res} \cdot \sqrt{2}$) compared

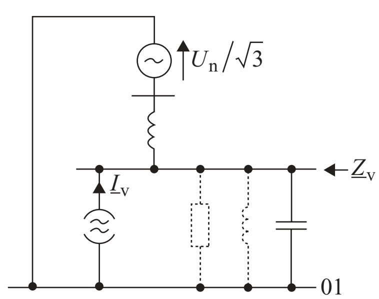

Figure 18.2 Electrical diagram of a parallel resonance circuit.

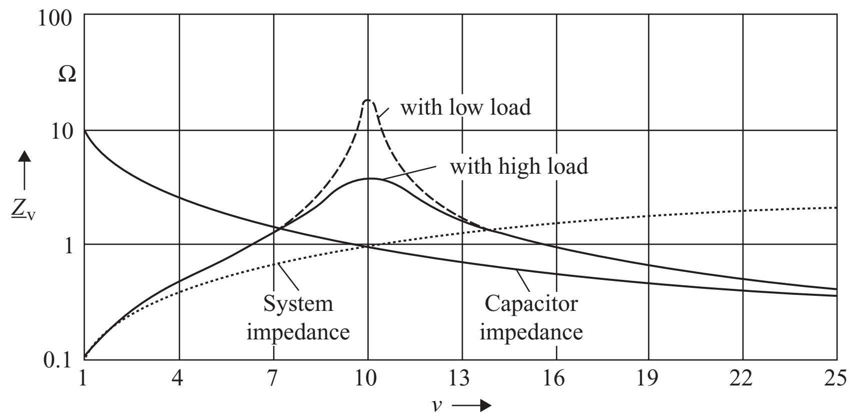

Figure 18.3 Impedance versus frequency of a parallel resonance circuit.

with the impedance at the PCC without resonance. The attenuation is higher under high-load conditions in the system.

The motor loads, represented by their inductivity, lead to a shift in the resonant frequency to lower frequencies. This effect is, however, relatively slight, taking account of the impedance values of the transformer and the motor loads. An increase of the short-circuit power S_k'', for example by reducing the impedance voltage u_k of the transformer, or an increase of the rated apparent power S_r will increase the resonance frequency.

Substantially greater effects on the impedance, however, are caused by a change in the capacitor rating, for example by the switching of capacitances. Figure 18.4 shows the change in the impedance while switching the capacitor in steps from $Q_C = 100$ kvar to $Q_C = 550$ kvar. Assuming a short-circuit power of $S_k'' = 23.8$ MVA at the PCC, the resonant frequency changes in the range of $f_{res} = 304$ to 780 Hz. Considering the impedance increase according to the typical bandwidth, the voltage increase due to resonances must be expected in the range of $f = 214$ to 1103 Hz (harmonic orders $h = 5$ to 22).

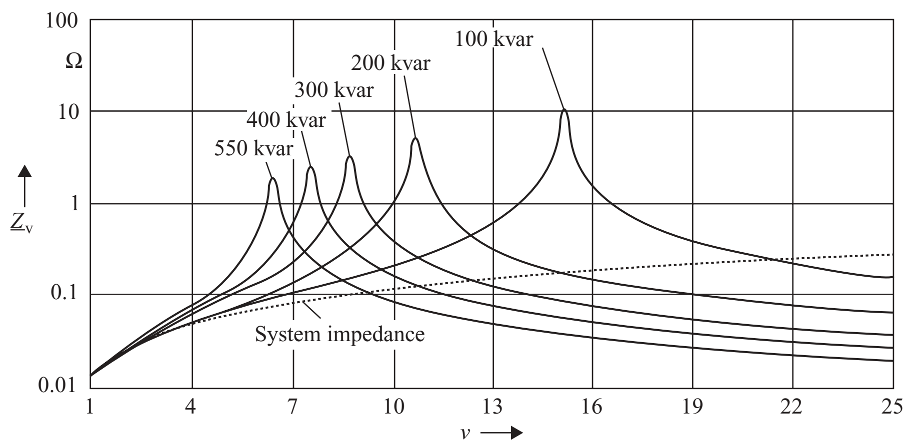

Figure 18.4 Impedance versus frequency characteristic of an industrial system ($S_k'' = 23.8$ Mvar).

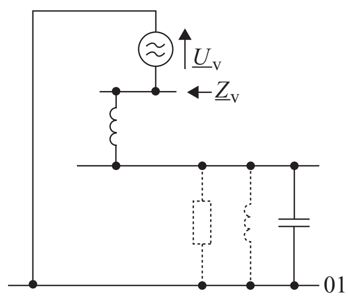

Figure 18.5 Electrical diagram of a series resonance circuit.

18.3 Series Resonance Circuit

If the system configuration is considered from the point of view of the supplying network, the inductive impedance of the transformer and capacitive impedance of the capacitor are now in series, forming a series resonance circuit which is attenuated by the ohmic part of the load; the equivalent circuit of the network in the positive phase sequence system as outlined in Figure 18.5 is used.

The resonance frequency f_{res} is calculated from

$$f_{res} = \frac{1}{2\pi \cdot \sqrt{L \cdot C}} \tag{18.3a}$$

$$f_{res} \approx f_1 \cdot \sqrt{\frac{S_r}{u_k \cdot Q_C}} \tag{18.3b}$$

where

Q_C = reactive power of the capacitor
S_r = apparent rated power of the transformer
u_k = impedance voltage of the transformer

The attenuation d of the resonant circuit is calculated from

$$d = R \cdot \sqrt{\frac{C}{L}} \tag{18.2b}$$

Figure 18.6 shows the impedance versus frequency of a series resonance circuit. The impedance of the resonance circuit is decreased in a typical bandwidth ($f_{res}/\sqrt{2} < f < f_{res} \cdot \sqrt{2}$) compared with the impedance without resonance. The attenuation is higher for high-load conditions in the system.

18.4 Typical Resonances in Power Systems

18.4.1 Resonance due to Reactive Power Compensation in 6 kV System

In an industrial network as shown in Figure 18.7, a capacitor bank Q_C is to be installed for reactive power compensation, where the desired power factor should be $\cos\varphi = 0.94$ at the 6 kV busbar. The compensation is rated with $Q_C = 3.919$ Mvar.

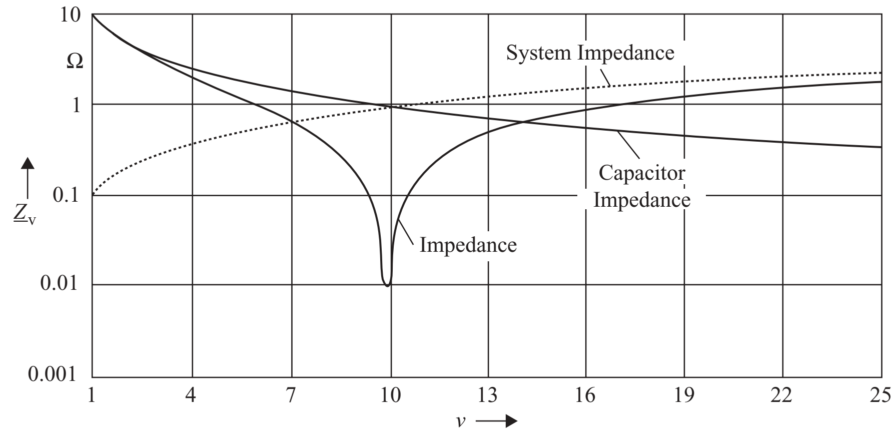

Figure 18.6 Impedance versus frequency characteristic of an industrial system from an MV system.

On the basis of the resonance condition, the capacitor ratings Q_{Cres} at which resonances $\nu = 5, 7, 11, 13$ occur are to be determined. The current harmonics fed in from the rectifier are given as follows:

ν	5	7	11	13
I_ν (A)	118.7	76.5	36.4	24.8

The short-circuit power S''_{kA} at the PCC is 204.97 MVA and the impedance of the capacitor is $X_{C1} = U_n^2/Q_C = 9.186\,\Omega$ if a 50 Hz system is considered.

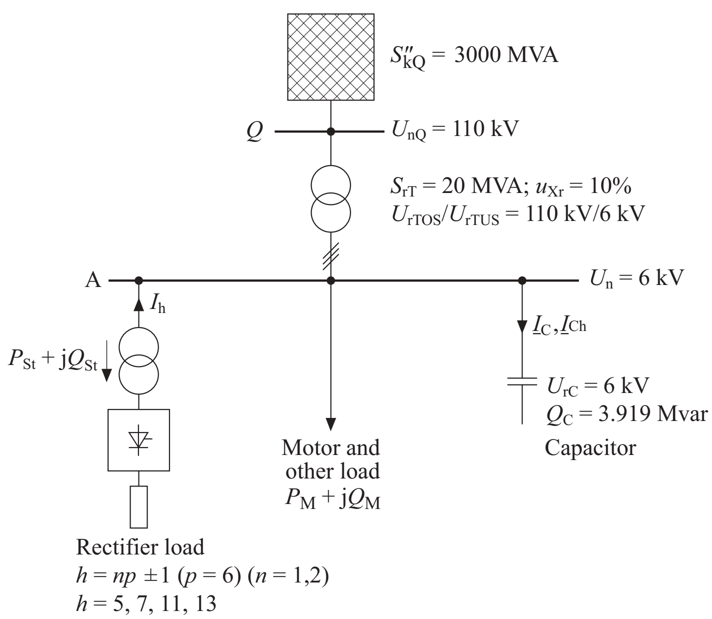

Figure 18.7 Power system diagram of a 6 kV industrial system with reactive power compensation; rectifier load $S_R = (6 + j3)$ MVA; motor load $S_M = (8 + j6)$ MVA.

The capacitor ratings Q_{Cres}, for which the resonance can occur, are as follows:

ν	5	7	11	13
Q_{Cres} (Mvar)	7.543	3.803	1.54	1.103

As can be seen, the capacitor rating to be installed ($Q_C = 3.919$ Mvar) is close to that value causing resonance for the seventh harmonic ($Q_C = 3.803$ Mvar). If the desired capacitor is installed, harmonic voltages $U_{C\nu}$ at the 6 kV busbar and the harmonic currents $I_{C\nu}$ in the capacitor will occur, calculated from $U_{c\nu} = I_\nu \cdot Z_{res\nu}$:

ν	5	7	11	13
$U_{C\nu}$ (V)	241.8	3385.5	50.1	24.2

The current harmonics $I_{C\nu}$ of the capacitor bank are thus $I_{C\nu} = U_{C\nu}/X_{C\nu} = U_{C\nu} \cdot \nu/X_{C1}$:

ν	5	7	11	13
$I_{C\nu}$ (A)	131.6	2579.8	60.1	34.5

The total rms value of capacitor current is $I_{Crms} = 2611.4$ A, which is almost seven times the rated current of the capacitor.

18.4.2 Parallel Resonance in a 30 kV Industrial System

In the 110/30 kV network shown in Figure 18.8, a 12-pulse converter to supply an industrial furnace is to be connected at node B2. The frequency-dependent impedances were calculated to estimate the expected voltage harmonics:

- Meshed network.
- The 110/30 kV transformer T124 switched off at B3.

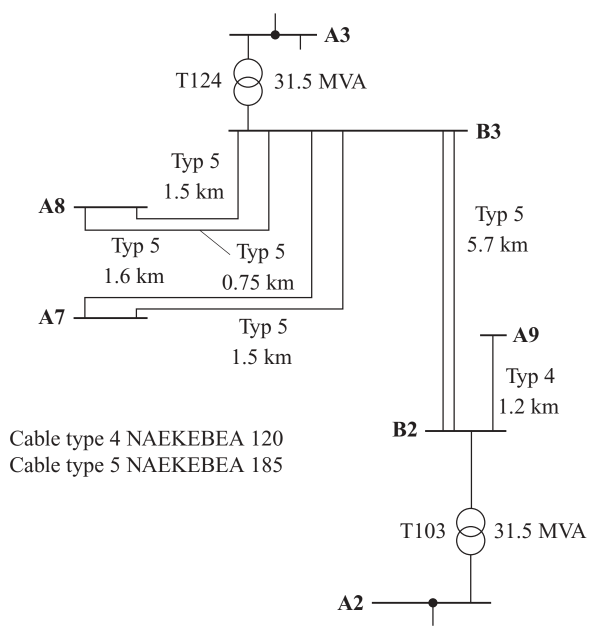

Figure 18.8 Power system diagram of 110/30 kV system.

As a significant result regarding harmonic investigations, the frequency-dependent impedances of the B2 node are shown in Figure 18.9.

A series resonance point results at $f_{resR} \approx 750$ Hz and parallel resonance points at $f_{resP1} = 650$ Hz and $f_{resP2} = 850$ Hz. These resonances occur due to the parallel circuit of the capacitance of the 30 kV cable B2–B3 with the inductances of the 110/30 kV transformers, where these in turn are to be regarded as in series with a parallel circuit of the capacitances of the 110 kV network and the inductance of the supply network. The series resonance points

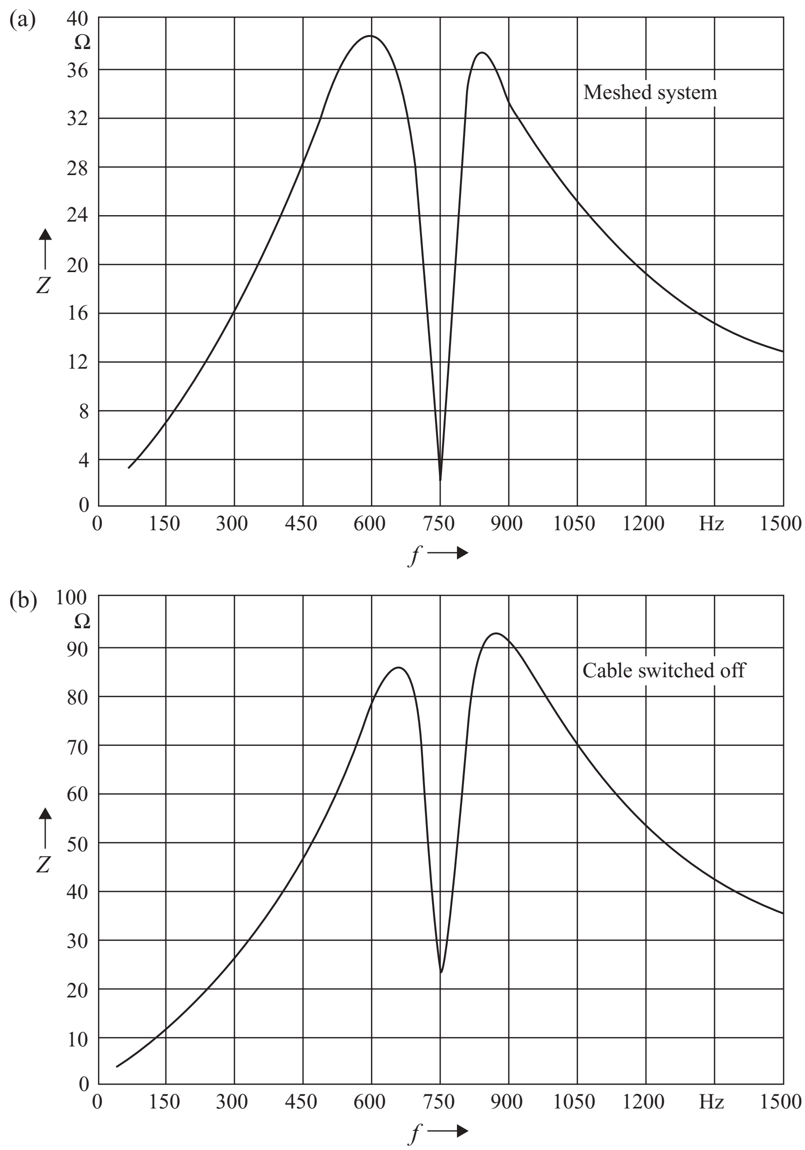

Figure 18.9 Impedance versus frequency at 30 kV busbar B2: (a) meshed system configuration; (b) 30 kV cable switched off at B3.

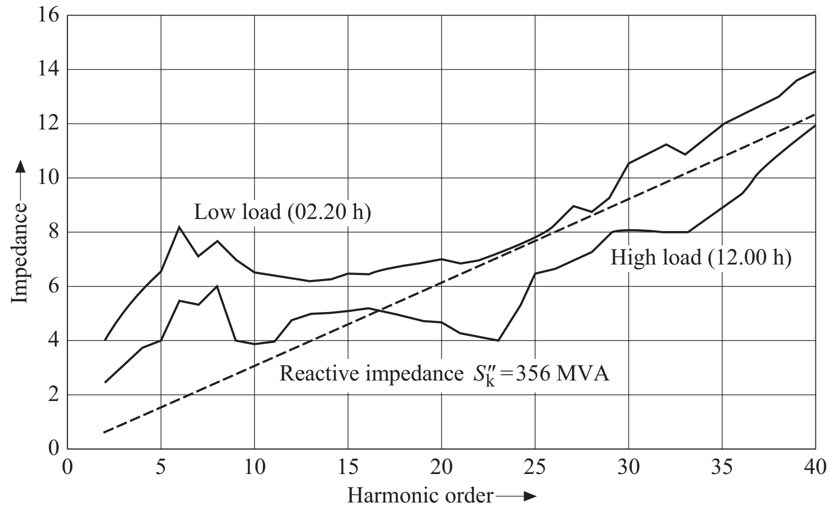

Figure 18.10 Impedance versus frequency of a 10 kV urban system at high-load and low-load conditions.

of the 30 kV network node B2 are more or less maintained for the second operational state shown (30 kV cable between B2 and B3 switched off at B3). The impedance of the parallel resonance would of course be substantially greater and would lead to a strong rise in the voltage harmonics for this operating state.

18.4.3 Impedance in Urban 10 kV System

The frequency-dependent impedances of a 10 kV urban system with short-circuit power $S''_k = 356$ MVA were measured for low-load and high-load conditions. Figure 18.10 indicates the results. A parallel resonance frequency is seen in the range of 300 to 400 Hz. The resonant frequency is more or less independent of the system load conditions. The system impedance for all frequencies is generally lower at high load compared with low load.

18.5 Summary

Parallel and series resonances occur in power system due to reactive characteristics (especially transformers) and capacitive characteristics (compensation banks and cable capacitances) of equipment. The impedance at resonant frequency is limited by the ohmic part of the equipment and load. One can observe that the impedance of a resonance circuit is increased (parallel resonance) or decreased (series resonance) in a certain bandwidth around the resonance frequency. Resonances may cause problems as harmonic and interharmonic voltages are increased, resulting in increased currents through capacitors.

Reference

[1] Blume, D., Schlabbach, J. and Stephanblome, T. (2001) *Voltage Quality in Electrical Power Systems*, IEE Power Series, No. 36, Institution of Electrical Engineers, Stevenage.

19

Reactor-Protected Capacitors and Filter Circuits

19.1 Chapter Overview

In general, capacitors without reactor protection cause resonances and are not suitable for networks. To avoid the incidents of resonance described in Chapter 18, a reactor must be added to the compensation capacitor in series. The basis of the design of reactor-protected capacitors as well as the selection of reactors and retroactive choking (series reactor) are described in the following sections. Furthermore, Section 19.4 covers the influence of the reactor rate on the lifetime of capacitors.

Filter circuits and their design are also described since filtering measures may be required (e.g. to obtain defined network conditions) for electrical systems with high harmonic levels.

Filter circuits can absorb more harmonic currents. This means that, like reactor-protected systems, they consist of one series circuit of reactance and a capacitor. The property of series resonance is used here *intentionally*. The reference variable for the design of filter circuits or their absorption capacity is the harmonic currents generated in the network by nonlinear loads. Sections 19.6.2 and 19.6.3 discuss filter circuit versions such as active and passive filters and the connection of filter circuit systems (network coupling).

Due to the many devices, for example with capacitive smoothing which generates harmonics (particularly the third, fifth and seventh harmonics), this causes undesirable network perturbations (or distortions). The installation of a neutral line harmonic filter offers a solution against third-harmonic distortions. The special features of the third harmonic also will be described in Section 19.7.

The following illustrations and explanations provide a general overview which should help to improve power quality. This means that the subject of *reactor-protected capacitors* and *filter circuits* is not dealt with in depth here. In addition, it should be noted that this chapter does not aim to cover all of the possible incidents or problems which may occur in practice.

In international usage, the following terms are used for the term ‘choked’ capacitors: reactor-protected capacitors; or, depending on the reactor rate, often ‘detuned filter

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

circuits'. Sometimes the term 'non'-tuned (without a reactor) is commonly used for the term 'unchoked'.

19.2 Effect of Reactor-Protected Systems and System Configuration

19.2.1 Effect of Reactor-Protected Systems

In order to prevent critical resonances (see Chapter 18), a reactor is connected to the capacitors. The reactor and capacitor, consisting of a series resonance circuit, is tuned to a resonant frequency which is below the lowest existing harmonic. The reactor rate is specified as a percentage of the capacitor power at fundamental frequency. The reactor rate p is calculated from

$$p = \frac{X_L}{X_C} \cdot 100\,[\%] \tag{19.1}$$

In actual practice, most reactors are selected so that their reactor rate is 6 to 7%. The series resonance frequency results in

$$f_{res} = f_1 \cdot \sqrt{\frac{1}{p}} \tag{19.2}$$

where
f_1 = network frequency (fundamental frequency)
f_{res} = series resonance frequency

If $p = 6\%$, the series resonance is $n = 4.08$ times the value of the network frequency; for example, if $f_1 = 50$ Hz, $f_{res} = 204$ Hz.

A reactor rate of $p = 7\%$ is often used (normally the most economical choice) and provides a series resonance of 189 Hz. This kind of reactor-protected capacitor absorbs a small portion of the fifth- and seventh-harmonic current, while the greater portion is supplied to the electricity utility network. It should be noted that the greater the reactor rate p, the fewer harmonics are 'absorbed away' (i.e. reduction of the absorption effect). This means that the loss of a reactor-protected capacitor with either $p = 5.67\%$ or $p = 14\%$ is greater than a reactor-protected capacitor with $p = 7\%$. In contrast to a reactor rate of $p = 14\%$, the reactor-protected capacitor with a reactor rate of $p = 5.67\%$ must be designed for a higher harmonic current. A reactor rate of $p = 14\%$ requires a great amount of reactor material, for example. Due to the greater harmonic transmission capacity, the reactor rate $p = 5.67\%$ model requires, among other things, larger line cross-sections and correspondingly greater amounts of reactor material. A reactor rate of 7% is a compromise with regard to the absorption of harmonic currents and material expense. In addition, a reactor rate of 7% provides sufficient long-term stability (see also Sections 19.4 and 19.5).

Reactor-protected capacitors can be used for both individual and central power factor correction systems (central compensation system) but mainly where resonance phenomena are expected. The capacitors are selected based on the reactive power requirements of the power consumption facilities. In addition some countries no longer allow the installation of 'non-tuned' (unchoked) capacitor banks (e.g. Switzerland).

How great the 'absorption effect' is depends on the short-circuit impedance of the electricity utility network and the residual resistance of the filter.

Regarding the filter effect on detuned filter circuits, it should be mentioned here that the lower the reactor rate, the greater the absorption; however, this also increases the load of the individual components of a power factor correction system.

It should be considered here that power factor correction equipment with reactor-protected capacitors is used for the compensation of reactive power in three-phase power supply networks with harmonic loads. The advantages of detuned filter circuits are obvious:

- Compensation of the reactive power fundamental to a specified $\cos \varphi_1$.
- Avoidance of critical resonance in the network.

In this context it should also be kept in mind that the voltage of the capacitor is increased by an inductivity connected ahead, and a capacitor with a correspondingly higher nominal voltage than the network voltage must then be selected. A useful rule of thumb is: the capacitor voltage rises by about the same percentage as the 'degree of choking'. This means, for example, that with 6% 'choking', the capacitor voltage rises by about 6% (see Equation 19.3).

With retroactive 'choking' (series reactor) the following point must be considered [1]:

- Already existing, 'non'-reactor-protected systems usually *cannot* be provided with 'choking' later on because every capacitor step requires a reactor and the capacitors must be designed for a higher rated voltage. When the reactor is retroactively switched in series to the capacitor, an increase in the voltage occurs which may be dangerously above the rated voltage of the capacitor. The capacitors must have been designed for this higher rated voltage.

The following applies:

$$U_{rC} \geq \frac{U_n}{(1-p)} \tag{19.3}$$

where

U_n = nominal voltage
U_{rC} = capacitor-rated voltage
p = reactor rate

Example: In a 400 V network, the rated voltage of the capacitors for a reactor rate of $p = 7\%$ must be at least $U_{rC} = 430.1$ V.

In addition, it should be kept in mind that the reactors for 'choking' need space to be installed and also cause a high loss in relation to the capacitor system. Retroactive 'choking' (series reactor) in a steel cabinet is only possible if the system was already prepared for it, both in design and thermally (see also Section 7.4).

Furthermore, reactor-protected capacitors also absorb harmonic currents from the higher level voltage in the customer network and thus – even if not intended – contribute to the improvement of the power quality in the distribution network. This additional current load

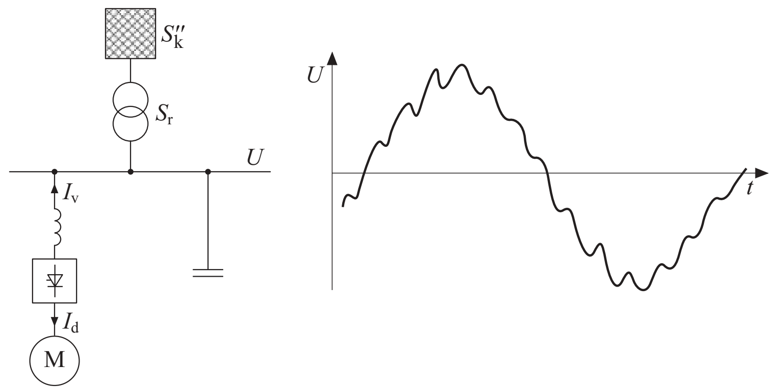

Figure 19.1 Network voltage for power factor correction with 'non'-tuned capacitors (without reactors) [2].

can take on sizeable values, however. With insufficient dimensioning, there is a danger of overloading the system.

One can see from the preceding discussions that the installation of a reactor-protected power factor correction system requires careful planning. Other *dangerous* operating conditions can occur, for example when the reactive power (Q_c) is increased by installing additional capacitors without reactors parallel to the reactor-protected capacitors. Several figures illustrate this problem.

First, Figure 19.1 shows, in very simple terms (without showing the harmonic spectrum), the time course of the network voltage for a power converter load with 'non-tuned' capacitors.

The shape of the network voltage is adjusted to almost a sinusoidal progression by 'choking', based on a series resonance frequency of 250 Hz, for example (Figure 19.2). If a 'non'-tuned capacitor is added in parallel, resonance phenomena will recur in the network voltage (Figure 19.3).

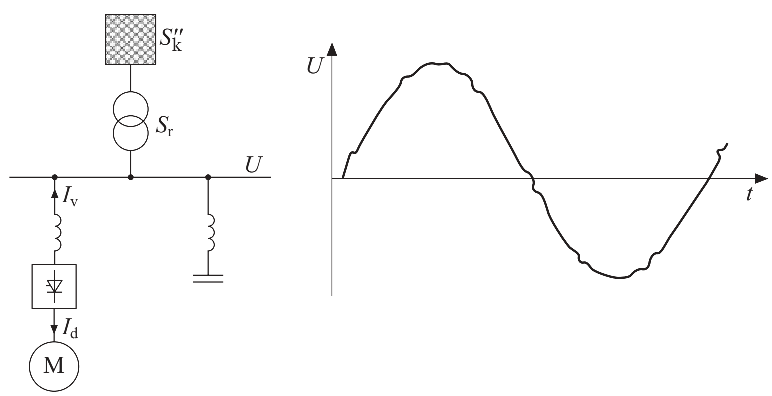

Figure 19.2 Network voltage with power factor correction with reactor-protected capacitors [2].

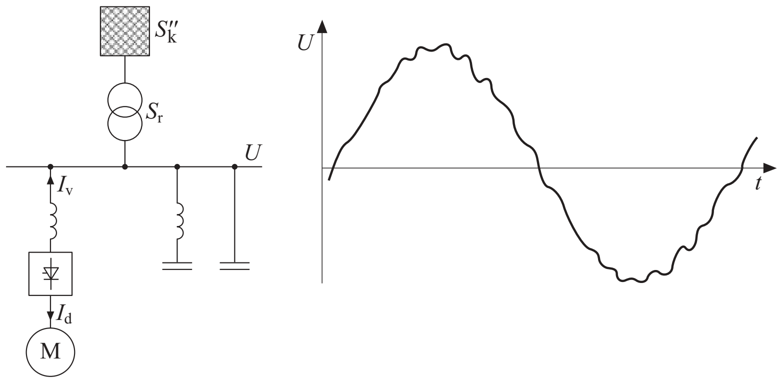

Figure 19.3 Network voltage with power factor correction with reactor-protected and 'non'-tuned capacitors [2].

The following conclusions can be drawn from the previous explanations:

- If suitably designed, reactor-protected capacitors prevent critical resonances.
- 'Non-tuned' and reactor-protected capacitors may not be operated in parallel.

19.2.2 System Configuration of Reactor-Protected Capacitor Banks

Systems with *reactor-protected* capacitors usually consist of:

- Capacitor modules, each consisting of three LV fuses with capacitor contactors, low-loss power capacitors and discharge devices (see Chapter 12).
- Three-phase reactors for each capacitor module (sub-assembly).
- Power factor controller with display and integrated manual/automatic mode selector.
- Steel plate cabinet/steel sheet cubicle with power factor controller.
- Connection (terminal) for the PE and N conductors.

The unit and the power factor correction equipment can be expanded by the parallel connection of extension units, taking account of the size of the steel cabinet and the temperatures there. The extension units are connected to the unit with control circuits. Automatic power factor correction equipment and extension modules are designed for indoor installation. It is recommended to contact the manufacturer for systems suitable for outdoor installation.

The following notes apply to the *thermal* design of reactor-protected capacitor systems in switching cabinets. For maximum capacitor life, effective dissipation of loss should be provided. Also, remember that continuous operation with 10% overvoltage, for example, can drastically shorten the useful life of the capacitors. Further details on the subjects of long-term stability, capacitor ageing, the effect of the reactor rate and the switching frequency which affect the capacitor's lifetime will not be discussed further here (but see Sections 7.6 and 19.4).

Figures 19.4 and 19.5 show examples of power factor correction equipment with reactor-protected capacitors.

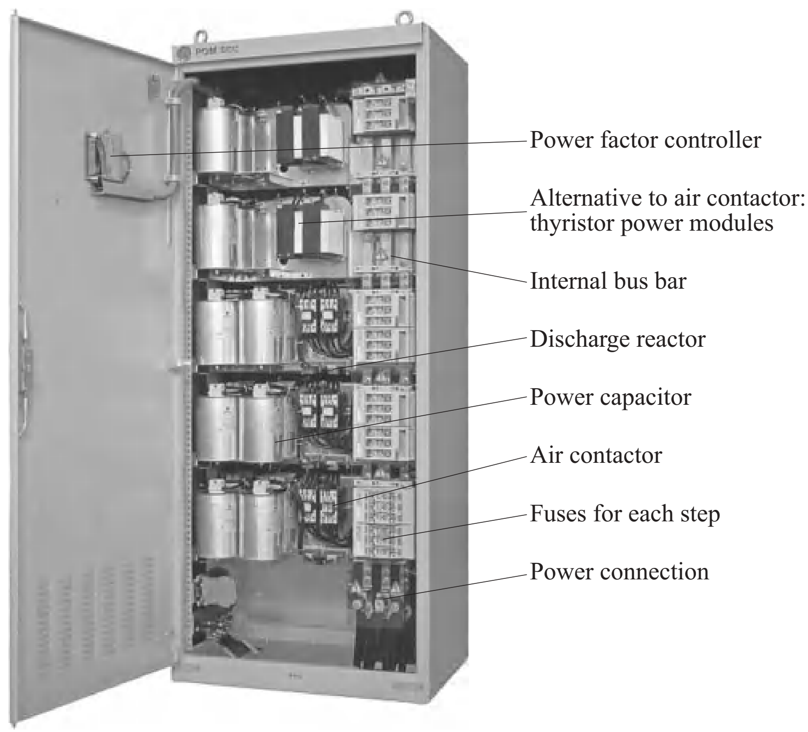

Figure 19.4a Free-standing power factor correction system in steel plate cabinet/steel sheet cubicle with reactor-protected capacitors, low voltage. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

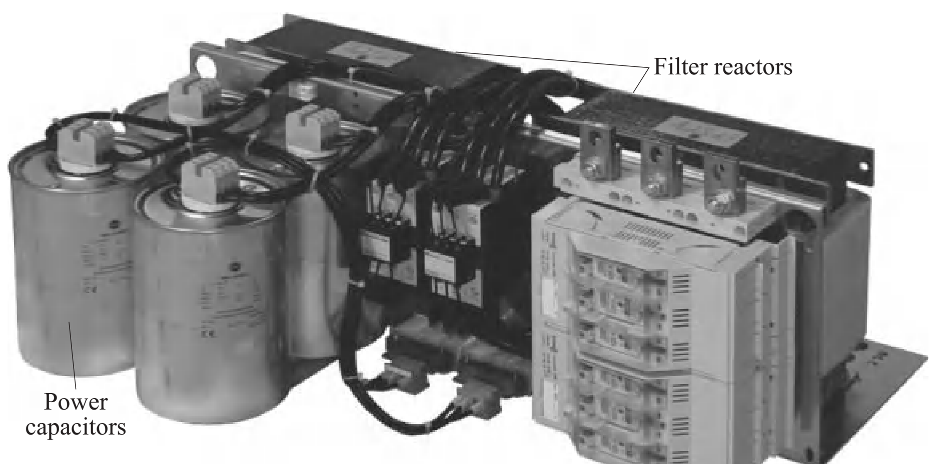

Figure 19.4b Assemblies (modular packaging systems), 400 V, 50 Hz. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

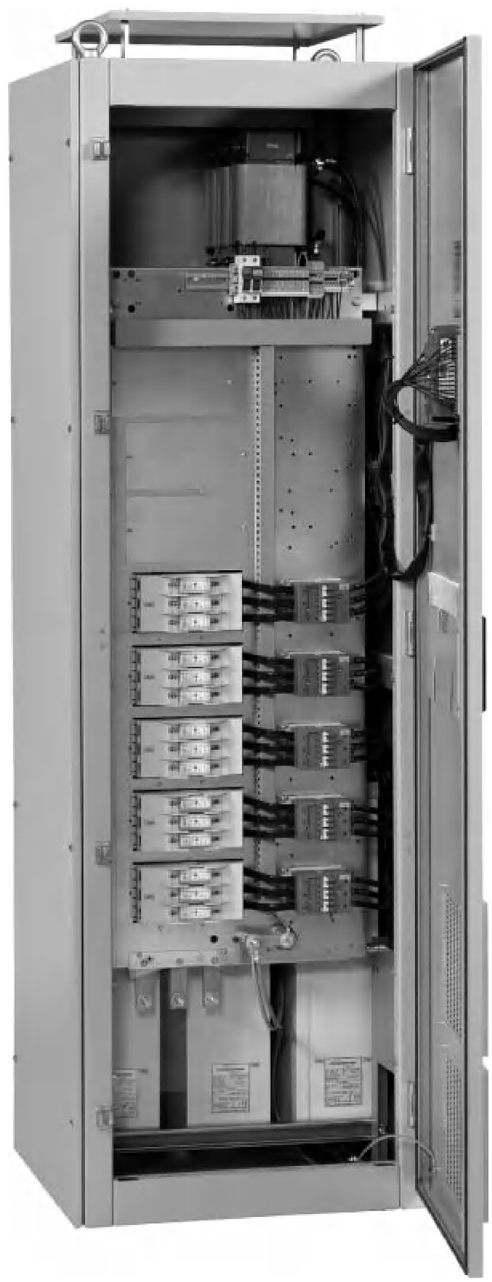

Figure 19.5 Example of an LV detuned capacitor bank. Reproduced by permission of Condensator Dominit GmbH, Germany.

19.2.2.1 Necessary Information on the Design of Reactor-Protected Capacitor Banks

To design a reactor-protected capacitor bank, the following information is generally required for the manufacturer:

- Network voltage of the customer system.
- Network frequency.
- Ambient temperature of the installation location.
- Plans to expand the customer system in the future.
- Nominal power of any existing power factor correction systems divided up into fixed and/or regulated central automatic power factor correction equipment.
- Existing power factor correction system (if present) to be expanded.
- Reactive power (Q_c) to be compensated for.
- Harmonic voltages at the place of installation.
- Known perturbations during operation (e.g. trouble with computerized numerical control (CNC) machine programs, triggering of overcurrent protecting devices).
- Tone frequency (audio frequency) – if used – of the local distribution system operator (power utility).

In addition, the following must also be kept in mind when selecting reactor-protected power factor correction systems:

- Reactor-protected and 'non'-tuned capacitors may not be operated in parallel.
- Parallel operation of reactor-protected capacitor banks with different reactor rates is possible.
- The planned or selected compensation system must fulfil the technical requirements based on the regulations of the local distribution system operator.

Additional details on the configuration of reactor-protected capacitor banks are available from the manufacturer.

19.3 Notes on the Selection of Reactors [3]

As already discussed, reactors are required to protect capacitors from harmonics or for specific filtering. These reactors have an iron core and limited linearity. In particular with inrush currents but also due to harmonics, the inductivity may drop sharply. When reactors are dimensioned incorrectly, there is a great risk of overloading and damage. This is important enough to be discussed briefly here.

It is the harmonic level at the point of common coupling (PCC) of capacitor banks which primarily determines the design of filter circuit reactors. The reactors must be capable of continuously carrying and discharging the current load; in other words, the core, winding and extra losses caused by fundamental and harmonic loads without exceeding the permissible temperatures of the insulating system being used. They must also have enough linearity so that they do not remain in the saturation range after being turned on.

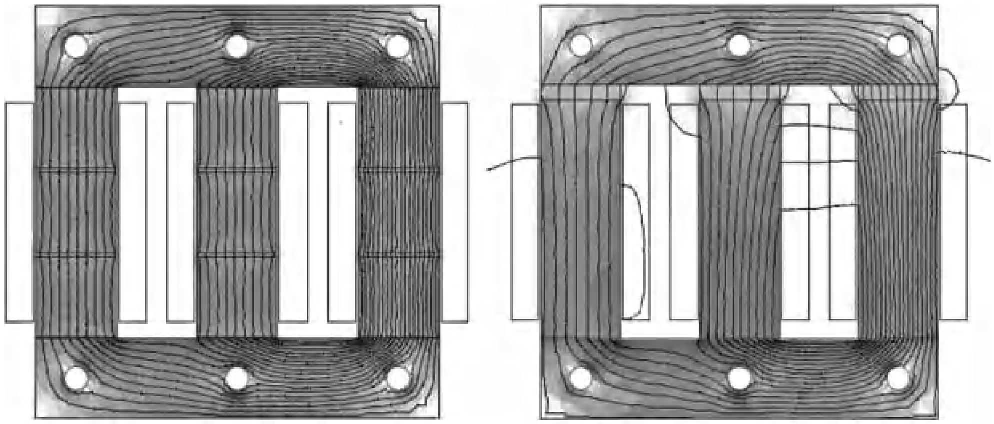

Figure 19.6 Magnetic field linear progressions with distributed air gaps (PolyGap®, left) and with one air gap (right). Reproduced by permission of Hans von Mangoldt GmbH & Co. KG, Germany.

High-quality reactors offer the following features: innovative winding technology (tape winding), optimal core selection, precise definition and arrangement of air gaps, reduction of the magnetic interference fields (with resulting decrease in losses; Figure 19.6) and vacuum pressure impregnation.

Today's technique of winding with tape foil made of copper or aluminium has prevailed for the most popular power classes since this method offers optimal heat distribution within the coil and minimizes extra winding losses.

The following should be kept in mind when selecting reactors:

Losses and loss factor of reactors: The amount of loss and the loss factor $d = R/X_L$ of reactors are dependent on frequency and temperature. Note that this part does not analyse physical properties and facts.

The fundamental frequency current flowing through the reactors is impressed with the capacitor connected behind and causes unavoidable fundamental frequency losses.

The harmonic losses vary with the degree of network contamination. This is why it is necessary and useful to divide the losses into fundamental and harmonic losses and relate the losses or loss factors to a useful reference temperature.

Heat class (isolation material class): The heat class of a reactor gives information on the permissible temperatures of the isolation system being used. It may not exceed its nominal value. The heat classes A, E, B, F and H with their related maximum continuous temperatures (105, 120, 130, 155 and 180 °C) are known from the standards (e.g. IEC 60076). The higher the heat class a reactor has, the higher the temperature that the reactor may reach.

Temperature monitoring for reactors: Temperature monitoring installed as an option will protect the reactors in case of overload. The operational switch-off of the compensation step by the temperature monitor shows that the reactor is not designed for continuous operation (reduced switch-on period), or the harmonic load on which the design was based is continuously exceeded.

The objectives when selecting the reactor should be:

- To aim for low loss and high linearity.
- The highest protection against harmonic load.
- Sufficient thermal capacity for the greatest harmonic load that can occur.

19.4 Influence of the Reactor Rate on the Capacitor's Lifetime [4]

With reactor-protected power factor correction systems, the reactor rate also affects the ageing of capacitors (see also Section 7.6). A simulation with a harmonics spectrum with $U_1 = U_r$, $U_5 = 5\%$ of U_r and $U_7 = 3\%$ of U_r will now be described to give a better understanding of the physical relationships.

Figures 19.7a to 19.7c show separately the basic current, the harmonic currents ($\upsilon = 5; 7$) and the rms current for various reactor rates. The inductive loss during correction is disregarded. As can be seen in these figures, ageing of the capacitors means a loss in capacity and thus also a change in the tuned frequency.

As a result of this, the harmonic currents increase, although the basic current decreases. In other words, at a reactor rate of 5.67%, the rms current increases as capacity decreases. This means that the power loss and thus the temperatures inside the capacitor increase. This accelerates capacitor ageing.

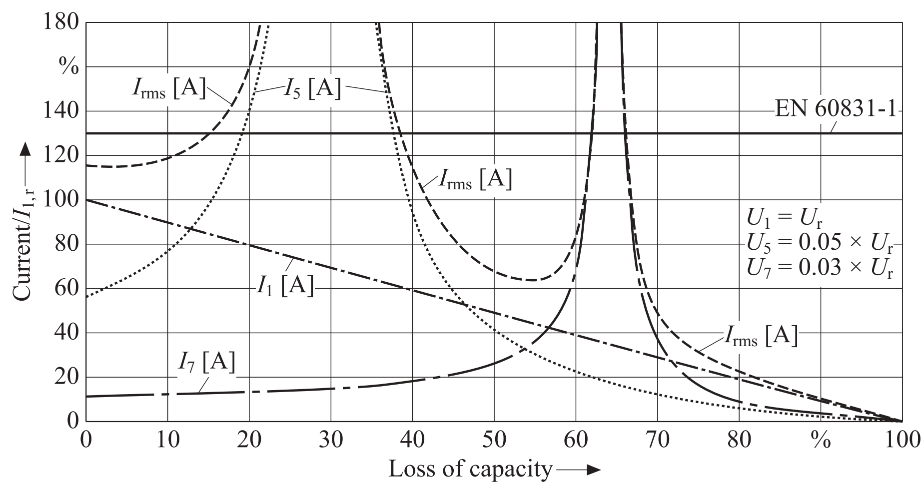

Figure 19.7a Influence of the capacity loss at $p = 5.67\%$. Reproduced by permission of Condensator Dominit GmbH, Germany.

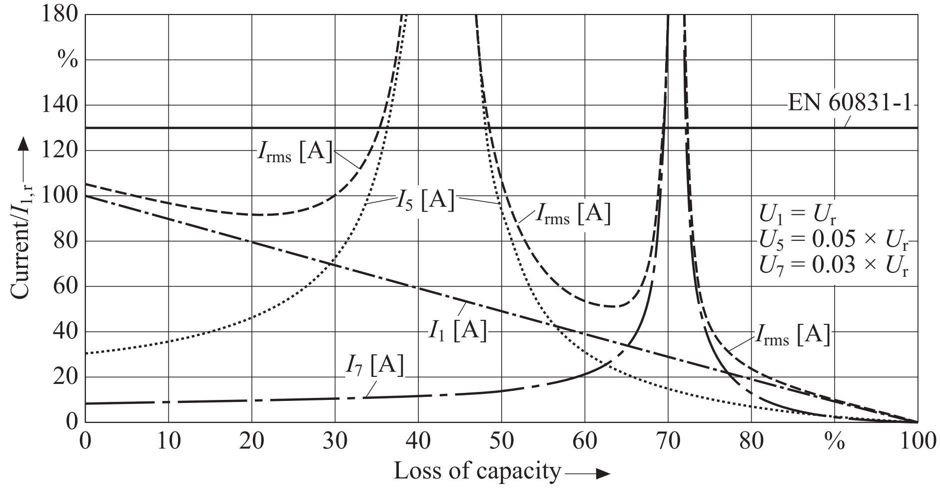

Figure 19.7b Influence of the capacity loss at $p = 7\%$. Reproduced by permission of Condensator Dominit GmbH, Germany.

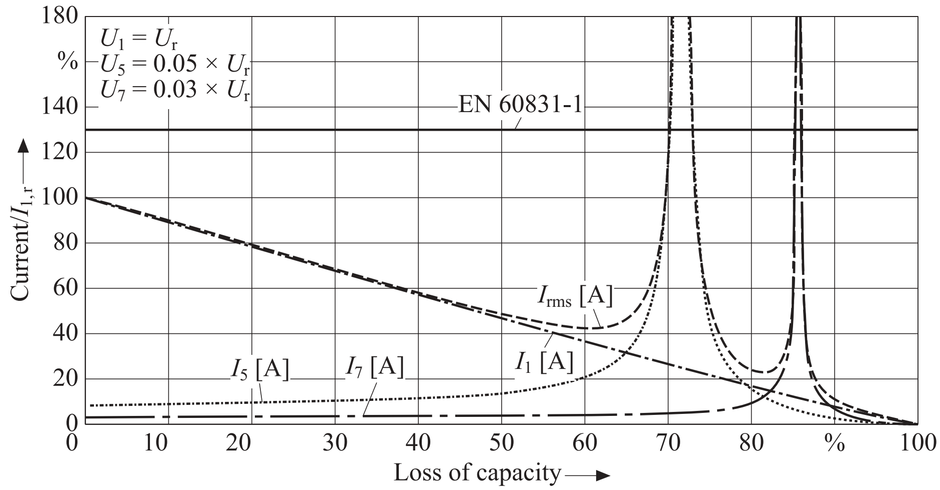

Figure 19.7c Influence of the capacity loss at $p = 14\%$. Reproduced by permission of Condensator Dominit GmbH, Germany.

19.5 Filter Effect with Detuned Filters [4]

The absorption effect will now be briefly described for various reactor rates. Figure 19.8a shows the impedance characteristic for various reactor rates.

As can be seen from Figure 19.8b, the absorption effect increases as the reactor rate decreases. However, this also means an increase in the load of the individual components of a

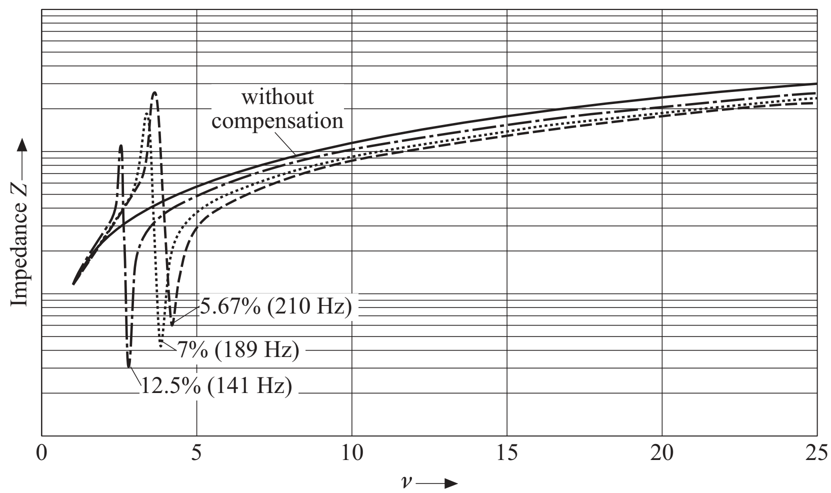

Figure 19.8a Impedance progressions for various reactor rates. Reproduced by permission of Condensator Dominit GmbH, Germany.

power factor correction system. A reduction in the system's lifespan must be expected if the load values specified by the manufacturer are exceeded.

The characteristic values which are decisive in actual practice are the permissible harmonic levels for which the power factor correction system is designed. In actual practice, a reactor rate of $p = 7\%$ is a very frequent choice. Specific filtering measures are necessary when the harmonic load is high.

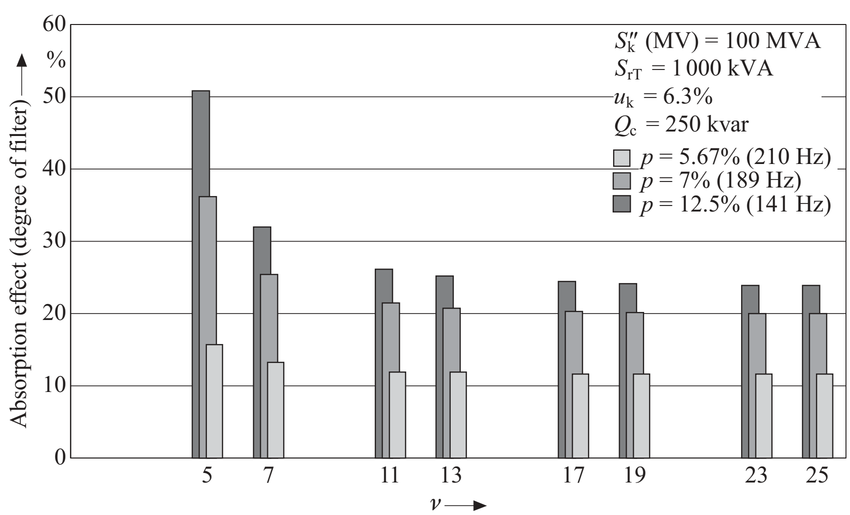

Figure 19.8b Absorption effect for various reactor rates. Reproduced by permission of Condensator Dominit GmbH, Germany.

19.6 Filter Circuits

19.6.1 General

As described in Section 19.2, a reactor-protected capacitor system not only supplies compensation power, but also reduces the harmonic voltage level. This means that a reactor-protected system creates an absorbing effect.

Figure 19.9 shows, for example, that the resulting resistance X_S of a filter circuit ($f_{res} = 250$ Hz) is 'zero' and for all practical purposes represents a 'short circuit' for the related harmonics (here 250 Hz). The load attenuation can be disregarded here. This means that the harmonic current is absorbed and cannot flow into the network.

Filter circuits have a capacitive character below the resonant frequency. This means that, on the one hand, the system gives up a capacitive reactive current for the fundamental frequency and thus compensates inductive reactive power, but, on the other hand, the system creates a parallel resonance circuit for frequencies below the tuning frequency with the network inductivity and any other parallel filter circuits located in the parallel resonance circuit. Since a parallel resonance can occur here, the filter circuits are always designed for the lowest existing harmonic frequency.

As can be seen from Figure 19.9, the filter circuit becomes inductive above the resonant frequency. The influence of the capacitors decreases as the frequency increases so that only the reactors are active at high frequencies. However, the installation of several filter circuits means that new resonances are created.

Figures 19.10a, 19.10b and 19.11 provide a simplified illustration of the way a tuned filter circuit works. First, Figure 19.10a, which has been simplified, shows the presentation of a tuned filter circuit for the reduction of the harmonics. This means that it is often desirable or necessary to reduce *further* the harmonic load of the electrical network.

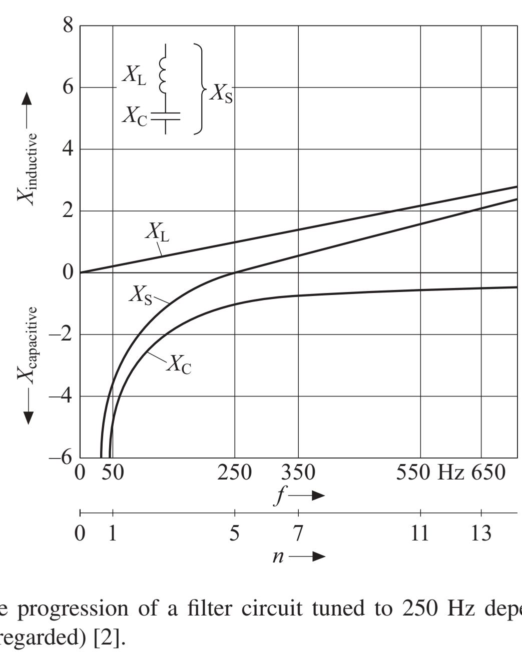

Figure 19.9 Reactance progression of a filter circuit tuned to 250 Hz depending on the frequency (effective resistance disregarded) [2].

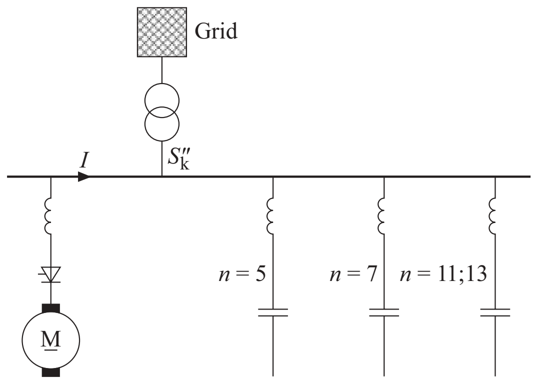

Figure 19.10a Simplified presentation of a tuned filter circuit for the reduction of the harmonics [2].

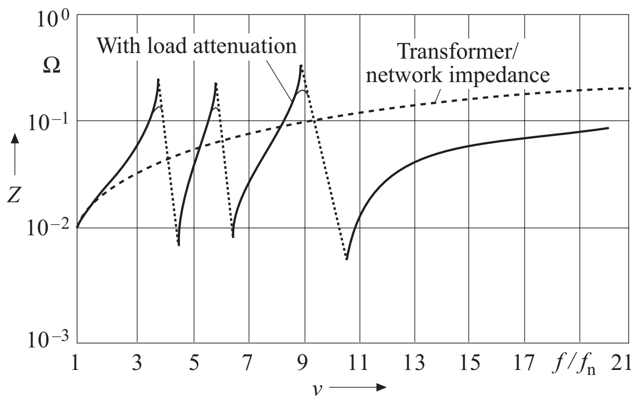

Figure 19.10b Example of the impedance progression of filter circuit compensation (as seen by the harmonic generator) [2].

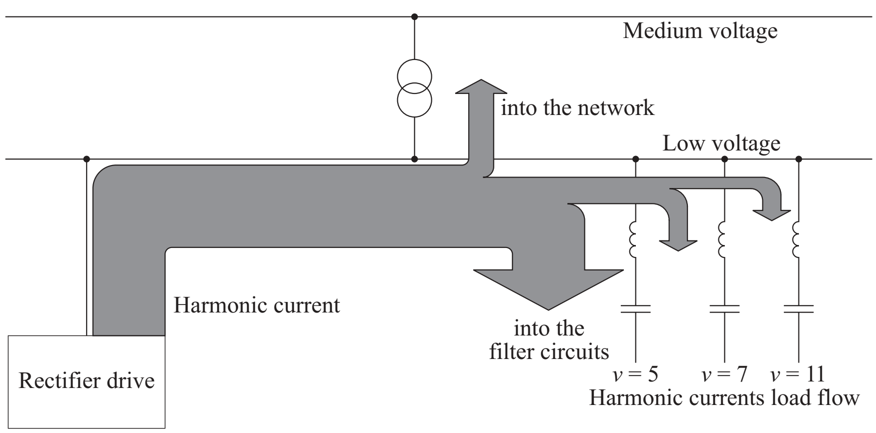

Figure 19.11 Principle of a tuned filter circuit – flow of the harmonic currents. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

In such cases, the installation of a *filter circuit system* may be a sensible measure. Instead of power factor correction equipment with reactor-protected capacitors, *a filter circuit system* is installed here which generally consists of up to three reactor-protected capacitors, for instance. Filter circuits are tuned respectively to a typical harmonic frequency. The property of series resonance is intentionally used here to increase absorption of the harmonic currents [5].

A filter circuit system as shown in Figure 19.10a must always be set up for the typical harmonic frequencies in sequential order without gaps. The filter circuits are switched on in order of the rising ordinal numbers and switched off in reverse order to reinforce critical resonance and thus avoid system overload.

Figure 19.10b shows the impedance characteristic of the filter circuit system.

The low impedances of the individual adsorption circuits for the harmonic frequencies of the fifth, seventh and eleventh harmonics are clear to see. Due to the parallel resonances with the feeder network, there will be an increase in parallel resonance between these absorption circuit frequencies. Thus it is clear that a typical harmonic frequency may not be left out between two tuning frequencies – even when only low harmonic voltage levels were measured.

As already discussed, filter circuits are put together from modules/assemblies (similar to reactor-protected capacitors). The number and power of the individual modules (assemblies) depend on both the demand of the compensation power and, even more important, on the amount of the individual harmonic currents.

Selection of resonant frequencies plays an important role concerning the effect of the filter circuit system to improve power quality, but only a subordinate role regarding the power factor correction systems. This is the great advantage of systems with tuned filter circuits in comparison with systems with reactor-protected capacitors.

Filter circuits are made up of modules (assemblies) whose resonance frequencies correspond to the frequencies of the power converter network perturbations (or distortions). The calculation of the harmonic currents to be expected must be based on the worst case.

An optimal tuning of the filter circuits to the existing power and load conditions can be achieved with a harmonic analysis.

The following designs have frequently been found to be economically reasonable in terms of actual effort in planning filter circuit systems for power factor correction of controlled power converter drives:

- Power factor correction system with tuned filter circuit capacitor banks as fixed capacitors.
- Power factor correction system with automatically controlled capacitor systems, built from detuned filter circuit capacitors.
- Active harmonic filters.

The dimensioning of the filter reactors should be based on the recommendation for permissible limits of harmonic voltages in public and industrial networks according to DIN EN 50160 (parameters similar to IEC 61000-2-4). In the case of higher harmonic loads in networks, specially designed filter reactors have to be used. The actual loads can be detected by means of a harmonic analysis (see also Section 17.3) [6].

19.6.2 Active Filters

In general, active filters are special harmonic filters. The active filter is usually utilized in the form of a parallel filter. Note that this part does not analyse the differences between parallel

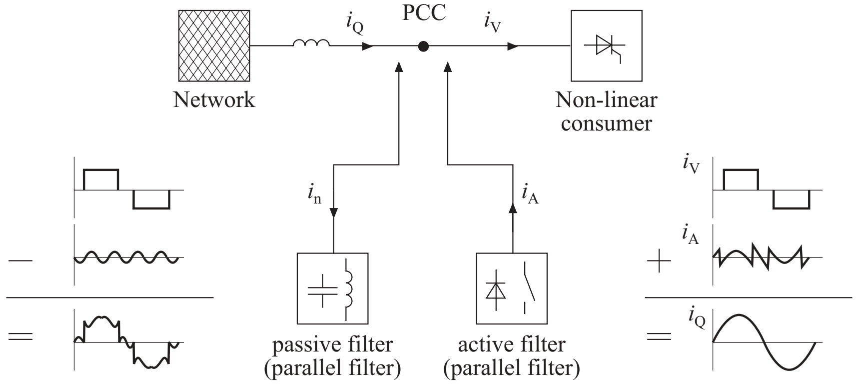

Figure 19.12 Function principle of active and passive filters [5].

filters and serial filters. Sometimes, for the term 'active filter', the term 'active harmonic filter' is more common. In contrast to the passive filter described in Section 19.6.3, this filter improves everything right down to the sinusoidal shape of currents or voltages at the connection point.

Active filters supply harmonic currents used by the consumer so that, under ideal conditions, only the fundamental frequency current is still obtained from the distribution network of the local distribution system operator (power utility).

Most active filters are digital (i.e. the harmonic spectrum is determined by amount and phase location from the current measurement and an appropriate counter-phase current spectrum is generated). Figure 19.12 illustrates the principle of active and passive filters [5] (see also Section 19.6.3).

Most of the 'active harmonic filters' on the market today are current controlled and can filter the harmonic current of a measured load. The harmonic level from the MV or the harmonic generators outside the measuring circuit are not affected by this. Active filters can filter harmonic currents up to their nominal current, whereby an individual so-called derating factor (reduction factor) must be considered for every specific frequency.

Examples of typical applications of the active filter are:

- Distribution networks in office buildings with a lot of nonlinear loads which cause a total harmonic distortion of THD-I $\cdot$ $S/S_r > 20\%$.
- Distribution networks whose voltage distortion caused by harmonic currents must be reduced to avoid malfunctions of *sensitive* loads.
- Distribution networks whose harmonic current must be reduced to avoid overloads; in particular, those of the *neutral conductor* (see Section 19.7).

Some additional typical applications are as follows:

- Power inverter load with high harmonic feedback and low reactive power requirements.
- Networks with a high share of the third harmonic due to the use of single-phase consumers.

The use of self-regulating active filters (closed-loop or open-loop regulation) is usually an economical solution. For problems with high harmonic content and low reactive power requirements, or too high levels of the third, ninth and fifteenth harmonic and the resulting high neutral conductor current (Section 19.7), *or* the need for tuned absorption circuits, the active filter is an optimal solution, especially because the compensation of network perturbations remains intact even after later system expansions.

Some important characteristics of active filters are as follows:

- Most active filters are *current controlled*.
- They can be used without any problems as distributed filters for selected system parts.
- High power density and thus low space requirements.
- Reactive power compensation is possible, but this requires expensive resources of the filter.
- Selective filtering of individual frequencies.
- Active solutions are much more flexible in their use but also more expensive.
- Active filters cannot be overloaded regarding harmonic filtering.

Some advantages of active filters are:

- Reactive power compensation.
- Dynamic compensation.
- Load balancing.
- Flicker compensation.
- Tuned filter circuits.
- Energy savings.
- Voltage stabilization.

19.6.3 Passive Filters

Figures 19.13 and 19.14 show the simplified basic principle of a passive filter and its functions. The impedance progression of the filter shows the tuning to a certain harmonic frequency and the areas where resonance reinforcement may possibly occur.

A passive filter can consist of several steps which are tuned to different frequencies. It can also consist of several steps for a certain frequency. The tuning frequency, capacity and network impedance determine the effectiveness of the filter. One step is required for each harmonic up to the desired frequency.

With passive filters, the tuning frequencies of the filter steps are not precisely tuned to the harmonic currents to be filtered so that extremely high filter currents are avoided.

In addition, passive filtering is not only possible in the range from the 3rd to the 25th harmonic, but also possible even beyond this. Filter steps for all possible harmonics of a lower order must be present for each filter circuit, namely for higher harmonics, to prevent their reinforcement.

Passive filters are frequently implemented as tuned filters [4].

In industrial networks, these filters are usually tuned to the harmonics of the order $\nu = 5, 7, 11, 13, \ldots$ which are typical for inverters. As already discussed, passive filters – and reactor-protected compensation systems – are made of a series circuit of reactor and capacitor. The characteristic of series resonance is used here intentionally to divert harmonic currents for the specific frequency by using lower impedance. This means that the network *impedance/filter*

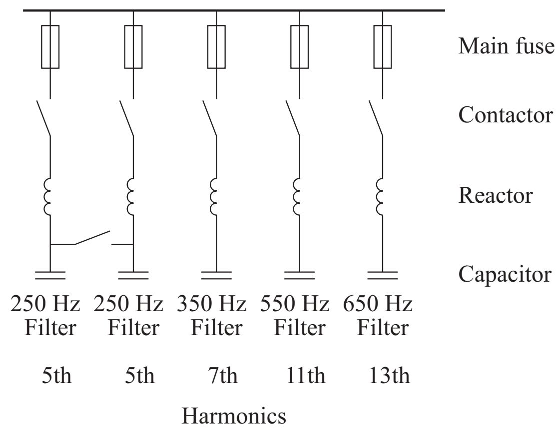

Figure 19.13 Principle of a passive filter (referred to 50 Hz networks). Reproduced by permission of Condensator Dominit GmbH, Germany.

step current divider reduces the harmonic current flowing into the network and thus also the harmonic voltage in the network impedance. In addition to the 'fundamental frequency compensation power' (basic harmonic reactive power) that is provided, the harmonic load ability thus becomes an important characteristic for passive filtering.

Due to tuning, filter circuits cannot be controlled like reactor power compensation. The generation of harmonics does not correlate with the compensation requirements. This means that the steps of the same tuning frequency can thus be overloaded if they are *only* switched on and off based on reactive power requirements. This danger exists in particular when the demand for compensation is low and the generation of harmonics is high.

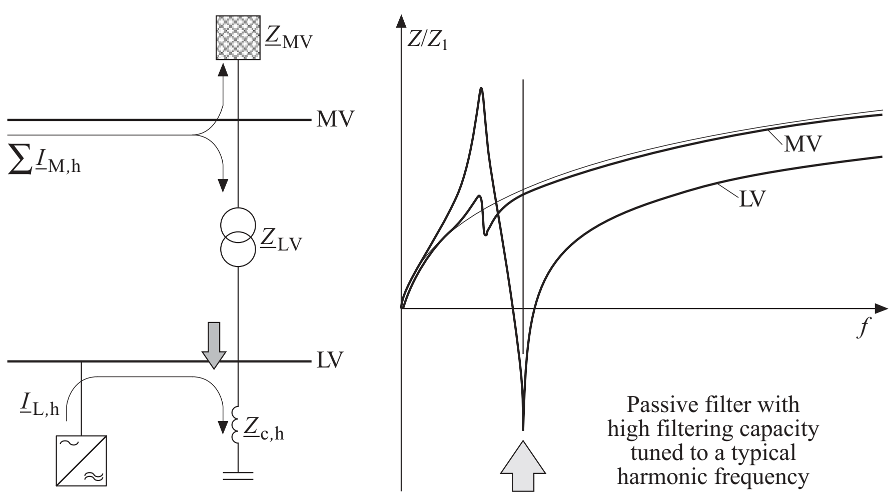

Figure 19.14a Impedance progressions of a passive filter (filter with one stage). Reproduced by permission of Condensator Dominit GmbH, Germany.

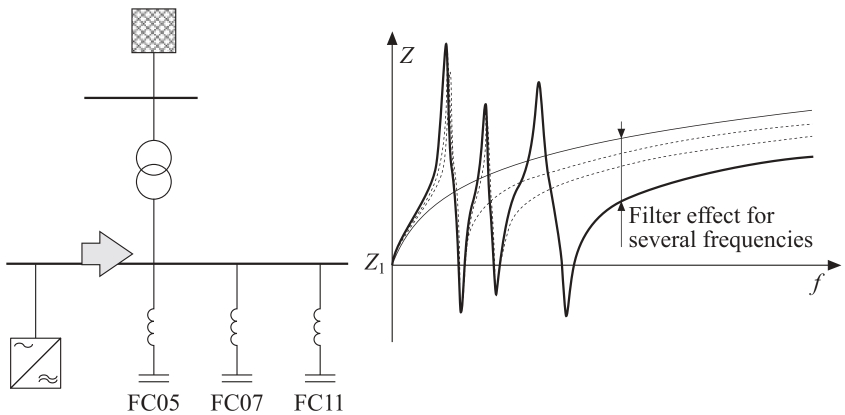

Figure 19.14b Impedance progressions of passive filters referring to the 5th, 7th and 11th harmonics (filter with three stages). Reproduced by permission of Condensator Dominit GmbH, Germany.

Technical control procedures which also consider both voltage distortion and reactive current demand can be used. In actual practice, it is usually sufficient to switch filter circuits of the same tuning frequency through in steps, since this takes place almost simultaneously [4].

If regulation (automatic equipment) is required, filter circuits are frequently designed for the fundamental load compensation and maximum occurring harmonic load. In this case, the variable reactive power requirement is compensated with conventional power factor correction equipment with reactor-protected capacitors.

Multi-step systems with filter circuits of different tuning frequencies can also be set in a limited scope by switching on and off the steps of the higher tuning frequency to the required reactive current requirements.

Filter circuits of the *same* tuning frequency which are to be operated in parallel on the network must be coupled with switchable *equalization lines* (connection lines) to avoid different harmonic loads and thus a filter overload. Without these equalization lines, a very different harmonic current load could occur [4, 5] due to tuning tolerances. This is why equalization lines are used between the filter circuits to ensure a uniform load (Figure 19.15).

The equalization lines can be omitted when the system contains decoupling elements. For example, the filter circuits can be largely decoupled from the network with commutation reactors (Figure 19.16).

The most important characteristics of passive filters will now be briefly described [4]:

- They feed capacitive reactor power to the network.
- They have a broadband effect and increase (for higher frequencies) the network's short-circuit power virtually for the 'consumer' since the network impedance is reduced. This may even mean that the 'harmonic emission' of the nonlinear loads can even increase and this must be considered during design.
- There is always the risk of their becoming overloaded since the entire available harmonic current also flows through the low impedance. Consumer structure, network topology and preliminary network load must be considered.

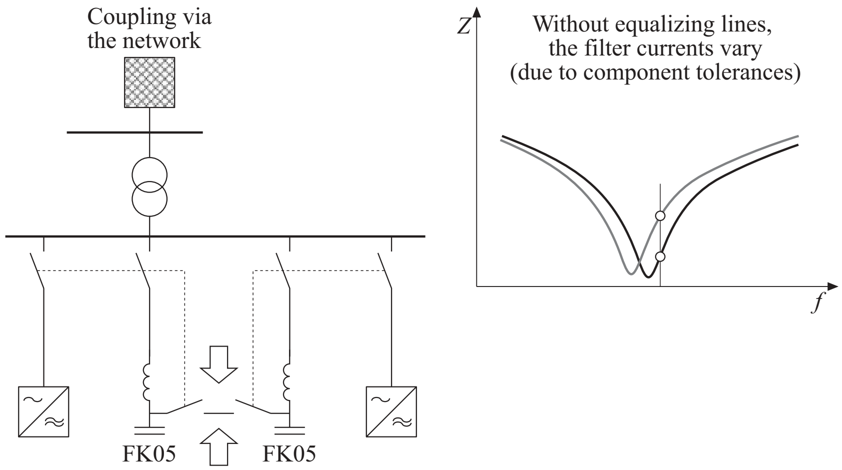

Figure 19.15 Coupling of filter circuits of the same tuning frequency. Reproduced by permission of Condensator Dominit GmbH, Germany.

- The ripple control frequency of the local distribution system operator (power utility) must be considered when the impedance progression is being configured.
- Passive solutions are usually less expensive.

The following information may not be complete:

- Precisely tuned passive filter circuits intentionally use the series resonance for the absorption of individual harmonics and thus reduce the voltage distortion.
- The impedance of the filter circuit in relation to the impedance of the network determines the effect of the filter.

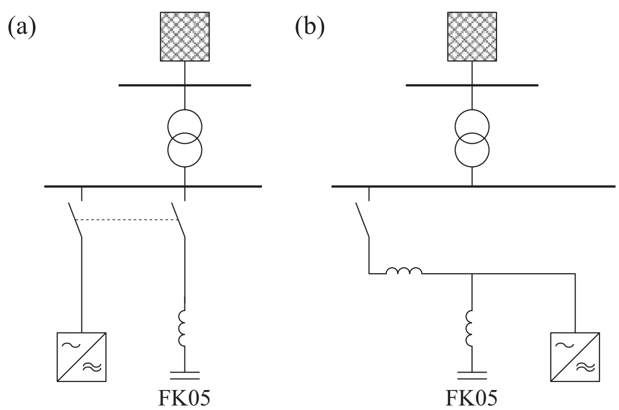

Figure 19.16 Connection of filter circuit systems [4]: (a) strong network coupling; (b) weak network coupling. Reproduced by permission of Condensator Dominit GmbH, Germany.

- The filter circuit is designed for maximum possible harmonic currents and the reactive power requirements.
- The control of filter circuits is limited.
- Filter circuits react sensitively to changes in the network structure (network impedances).
- With parallel switching of passive filters with the same tuning frequency, component tolerances can cause a very different harmonic tolerance.

These are the reasons why switched equalizing lines are used between the filter circuits.

19.6.4 Comparison of Active and Passive Filters

When the two systems are evaluated, the use and setting of goals are decisive when deciding whether the particular filter characteristic is desirable for the user [4].

Passive systems with absorption circuits have the disadvantage that they must be tuned and a separate filter circuit is required for each harmonic.

With passive filters, there is a danger of overload. Continuous monitoring and regular maintenance are urgently recommended here. In addition, the passive filters can only partially adapt to changes in load. Passive filters usually require much more space. However, they are generally much less expensive than active filters.

Active filters are currently the latest in modern technology for reactive power compensation [7]. With harmonic compensation, a certain degree of compensation can be set for each individual harmonic. Harmonics can be compensated over the entire spectrum – usually up to the 50th harmonic. This also means that active filters are not affected by other occurrences in the network. An active filter is not overloaded and instead just supplies its maximum nominal power. This offers the advantage that the maximum compensation power is available for very strong harmonic loads. In addition to the compensation (power factor correction system) of the three-phase conductors in the LV network, with active filters there is also the possibility of effectively reducing harmonics on the *neutral conductor* (Section 19.7).

In this connection, the remark also applies that – depending on local network conditions or requirements – passive systems and active filters can be combined with each other to produce a hybrid solution. In general, this inexpensive solution offers the advantages of both types of filters. This hybrid solution usually requires a precise analysis of the planned use.

19.7 Neutral Line Harmonic Filtering

19.7.1 General

Many electrical and electronic devices use power packs with capacitive smoothing or series connection units which generate harmonics – with a particularly high share of the third harmonic. The consequences are undesirable network perturbation and these frequently lead to the following observations, among others:

- The neutral conductor becomes overburdened and hot.
- The LV power switch triggers too soon.
- The power calculation appears to be too high.

Sometimes, for the term ‘neutral line harmonic filter’, the common terms ‘neutral conductor filter’ or ‘four-line active harmonic filter including neutral conductor filtering’ are used.

19.7.2 Special Features of the Third Harmonic [1, 2]

In LV networks (i.e. with a fourth conductor – TT or TN network configurations as the return conductor), the neutral conductor could carry a current of the third frequency harmonic if there were a large number of nonlinear ‘consumers’ and if a harmonic component were present in the voltage, which might cause a greater current load on the neutral conductor (N) than on the phase conductors. This unusual condition can occur for the third harmonic and its multiples. Their phase position is the same for all three-phase conductors, which means that they create a zero-sequence component and not a phase sequence.

In contrast, the currents of the zero-sequence components add up (i.e. if the load is distributed symmetrically, they do *not* cancel each other out at the star point). They flow back over the neutral conductor as a symmetrical sum. Figures 19.17a and 19.17b show the special features of the 3rd harmonic.

With transformers, operation with non-sinusoidal voltage and/or non-sinusoidal current, among others, causes excessive ohmic losses and eddy current and hysteresis losses. As can be seen from Figure 19.18, when there is an interruption of a neutral conductor, the neutral conductor potential on the load side, which has been cut off, adjusts to the load situation at that instant. The phase conductor voltage can drop significantly because of this in the individual phase conductors or also even increase. This may cause the devices to fail.

From the previous discussions, it is known that undesirable consequences (such as overload of the neutral conductor – frequently installed with a reduced neutral conductor cross-section), neutral conductor interruption and overload of the uninterruptible power supply (UPS) present a high risk of damage to the system.

In addition, it should be kept in mind in TN-C networks with PEN conductors that the harmonic currents of zero-sequence components sometimes also flow back and forth to the

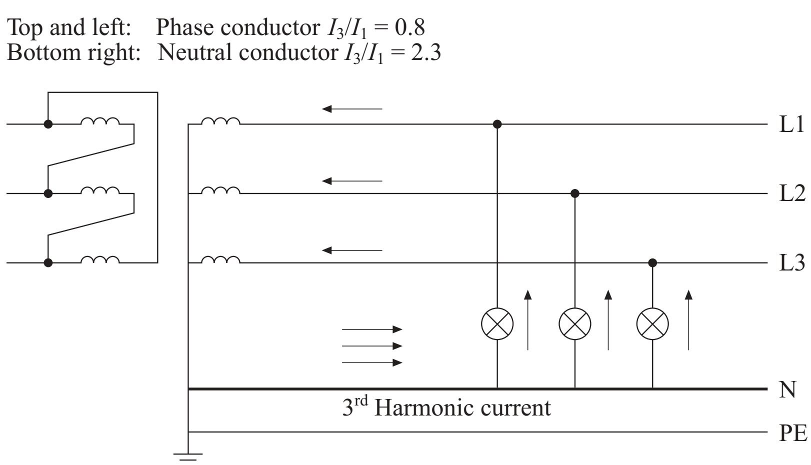

Figure 19.17a Special features of the third harmonic [2].

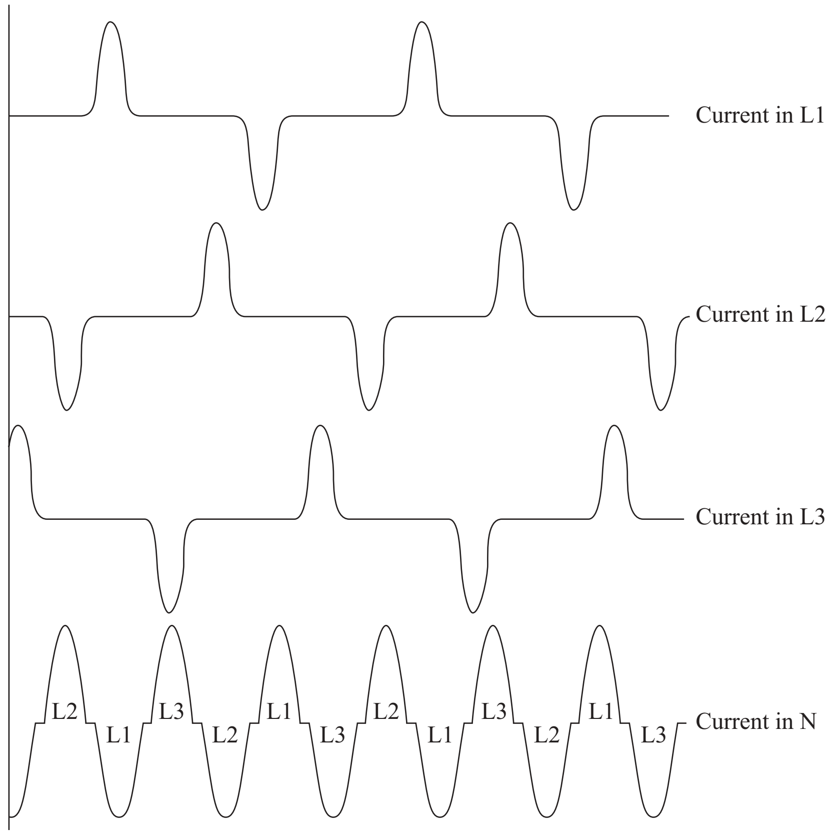

Figure 19.17b Neutral conductor overloaded by nonlinear consumers (here, compact fluorescent lamps) despite symmetrical division of all three-phase conductors [2].

transformer star point over grounded-building parts or data line shields and are the cause of many electromagnetic compatibility problems in computer centres, office buildings or other sensitive areas [4]. Older electrical systems which still do not have five-conductor networks (TN-S) installed are affected most. Upgrading a fifth conductor is frequently just as time consuming as enlarging the neutral conductor cross-section.

However, it should be pointed out here that a network problem is not always caused by the third harmonic even when the neutral conductor is clearly carrying a third-harmonic current.

19.7.3 Network Relief by the Neutral Line Harmonic Filter [2, 7]

A much more economical solution is to install a neutral line harmonic filter. This filter relieves not only the neutral conductor, but also the phase conductors. Conventional harmonic filters are usually not able to do this job since they cannot reduce harmonic currents of zero-sequence components. This means that conventional harmonic filter connections do not reduce the network load without a working neutral conductor.

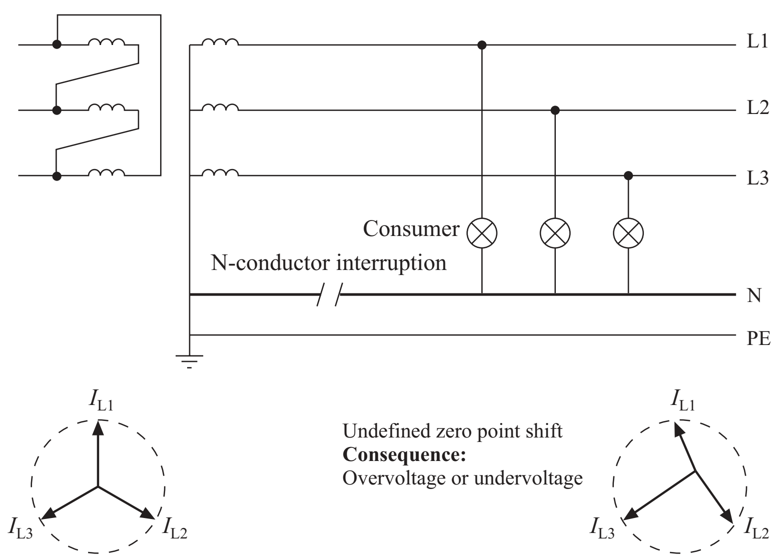

Figure 19.18 Risk of damage due to neutral conductor interruption [2].

The neutral line harmonic filter is looped through the neutral conductor of the network or in the sub-distribution, or is installed in the star point of transformers, generators or in UPS systems (Figure 19.19a and b).

Depending on the nominal current, the filter is installed in a ready-to-connect wall cabinet (e.g. steel sheet box for wall mounting) or switching cabinet (including monitoring systems).

Selection of the filter is based solely on the design capacity of the affected network range (i.e. its nominal current or nominal power). This means that high demands must be placed on a neutral line harmonic filter regarding overload capacity.

System installation is of fundamental importance (i.e. a reproducible and easy-to-understand electrical installation) since the type of system installation can affect the effectiveness of a harmonic filter and even cause the power supply to malfunction.

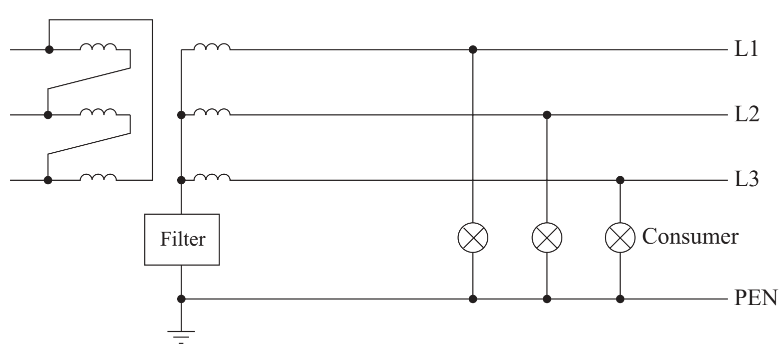

Figure 19.19a Installation of the neutral line harmonic filter in the transformer star point [2].

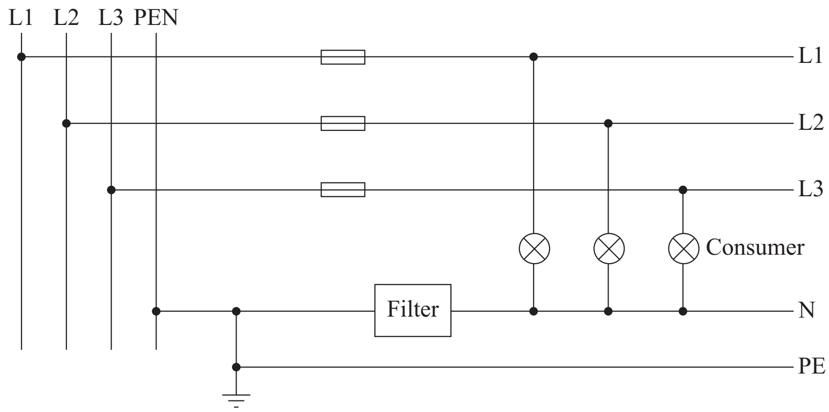

Figure 19.19b Installation of the neutral line harmonic filter in the neutral conductor (in connection with fault current monitoring) [2].

Before measures against harmonics are taken in a system, it is imperative that an optimized conductor system exists. This also means that the normal network protective systems regarding overload and short-circuiting have been installed and are in perfect working condition. This is why the installation of additional current monitoring is recommended so that a change in or overload of a system is recognized early. For example, when installing the filter in the neutral conductor (N), it must be ensured that a *fault current monitoring system* exists because of the differences in potential between the neutral conductor and the protective conductor (PE), otherwise, when a short circuit between the neutral conductor and protective conductor occurs, the third-harmonic current which is created again by this would flow over the faulty location. The filter should never be installed in the PE or PEN conductors!

In this context, note that the grounding of the power supply system must also be in good working order. If the grounding system is not functional, electromagnetic interference fields and harmonics, among others, can spread throughout the system. In other words, strict attention must always be paid to the separation of the N and PE conductors. Non-isolated installation of the N and PE conductors might sometimes even cause them to carry a large share of harmonics (in particular the third harmonic).

In practice, it is recommended to measure the currents for the N and PE conductors before installing a filter. Non-permissible currents can be determined immediately with the measurement. All kinds of measuring devices are on the market (e.g. oscillographs and current-measuring connectors with the ability to analyse individual frequencies). A rough estimate is even possible with a simple ammeter (see also Section 17.3).

The essential advantages of a neutral line harmonic filter are listed below:

- Avoidance of neutral conductor overload.
- Reduction of losses in lines and transformers.
- Reduction of electromagnetic fields.
- Reduction of network load.
- Reduction of the current pulse load of UPS systems and generators.

In this connection, remember that the possibility of installing these filters in the phase conductors also exists. However, the effect is generally not so good since, for example, a total of more than third-harmonic current could flow in the neutral conductor with the same passage of up to 12.5% of the filter current per filter. In addition, apart from the much higher investment costs, the filters would be strained in this case with the phase conductor currents.

If a filter is to be installed in an outgoing network line, the selection should be orientated on the outgoing fuse. However, when a star-point installation is used, the nominal power of the transformer or the generator or the UPS system must be considered. That is why the filter is dimensioned according to the nominal power of the network. This prevents damage with subsequent interruption of the neutral conductor or interruption of the star-point grounding due to excessive loads, for example. This means that, in conclusion, particularly high demands must be made on neutral conductor filters with regard to their current overload capacity. An additional current monitoring system is recommended.

19.8 Summary

In addition to the power factor correction system (i.e. also improvement of cos φ_1), reactor-protected power factor correction systems (detuned filters) are primarily used to avoid critical resonances. They can ‘clear the network’ of harmonics and thus increase operational security for business customers. This means, for example, malfunction-free production and high product quality. Specific filtering measures are required if the proportion of harmonics is too high. In general, compensation with reactor-protected capacitors should always be installed if the power converter share is greater than 20% of the total load. Today reactor-protected capacitors are considered the state of the art. They improve the power quality. When choosing the ‘choking or filtering’, the ripple control frequency/audio frequency of the local distribution system operator (power utility) may have to be considered to avoid impermissible manipulation of ripple control.

A present method for treating harmonic problems is the use of filter circuits. As well as an improvement of the power factor and the power quality, harmonics are also absorbed from the network. This means that they can absorb considerable amounts of harmonic current, particularly in the customer’s system, and thus keep most of it away from the higher level network. The term ‘series resonance’ is used here *intentionally* to indicate that *even more* harmonic current is absorbed. When filters are planned, it must be ensured that resonance points do not coincide with an existing harmonic frequency.

In general, it must be ensured that the switching on and off of the filter circuits is correct. To avoid resonance problems, the filter circuits with the lowest tuning frequency must always be switched on first, followed by the next highest, and so on. Switching off must then take place in reverse order. This ensures that operation of the filter circuits of the higher tuning frequencies is impossible when circuits of the lower tuning frequencies are switched off.

Active filters are electronic power systems. In general they function like a controlled current source. An active filter offers the following functions in particular:

- Harmonic compensation.
- Dynamic reactive power compensation.
- Compensation of voltage unbalances.

The increasing use of nonlinear single-phase loads results in overload of the neutral conductor and faults in electronic devices. Particularly in already existing buildings, it is usually almost impossible to upgrade the neutral conductor cross-section later on.

The use of a neutral line harmonic filter is an effective means of reducing the third harmonic and thus relieving the neutral conductor and the transformer switched in front and/or a UPS system. A reproducible and easy-to-understand electrical installation is also important.

Table 17.2 (see Section 17.2) offers assistance in selecting compensation equipment.

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20

Dynamic Reactive Power Compensation Systems

20.1 Chapter Overview

In many cases, industrial plants are characterized in particular by the use of highly dynamic drive technology. In addition to the undeniable advantages of these modern technologies, there is the disadvantage that the electrical networks are strained because of frequent changes in load and harmonics. This causes unstable voltage conditions, flickering, excessive current loads and increased loss in the electrical power distribution. This in turn not only reduces the usable network power, but also affects the functions of sensitive electronic controllers.

Conventional power factor correction systems are designed for the pure optimization of the power factor and also to reduce the harmonics level, but are not able to keep up with fast load changes and do not provide a satisfactory solution. The application area of these systems is the compensation of static or slowly changing loads with switching cycles in the range of minutes.

Dynamic (delay-free) reactive power compensation systems (i.e. with thyristor-switched capacitors) can prevent or reduce network perturbations such as brief drops in voltage and flicker.

In international technical language sometimes the following terms are commonly used: 'fast switching dynamic power factor correction', 'dynamic compensation' or 'dynamic power factor correction system'.

Another positive effect of the dynamic reactive power system is the 'soft' switching of the capacitors.

Conventional equipment with air contactors creates transient inrush currents which not only affect the compensation components, but can also lead to damage and perturbations (or distortions) of consumers.

The real-time power factor compensation equipment generally switches on and off during zero current crossing, so avoiding transient interference completely.

Furthermore, brief voltage fluctuations and the related flickering of the bulb in lamps are increasingly becoming problems for electrical power technology. In other words, voltage fluctuations can cause light current changes in an incandescent lamp. Flicker is the subjective impression of changes in lighting density.

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

Flicker compensation represents a possible or necessary measure to keep the voltage constant. Particularly networks with low short-circuit power and many powerful manufacturing facilities in operation make special demands on flicker compensation.

To avoid confusion, the principle of flicker compensation will only be discussed briefly here (without going into the subject of flicker disturbance evaluation and compatibility values).

Interesting service opportunities may develop for distribution system operators (power utilities) in the area of ‘perturbation avoidance’ to satisfy customers (business customers in this case) with regard to cost savings and power supply quality.

20.1.1 Improvement of Power Quality via Dynamic Reactive Power Compensation Systems

The demand for a dynamic reactive power compensation system today is actually the desire for high-speed control. Effective access to the power conditions within fractions of a network cycle is only possible when powerful semiconductor components are used. The fact that ‘reactions’ are possible with power semiconductors within a network cycle increases the application area of a dynamic reactive power compensation system to include also voltage stabilization or ‘power quality support’ (i.e. during strong effective power surges, the energy stored in the power capacitors can be switched through within just a few milliseconds to support the power quality).

One example of a power consumer which has strongly fluctuating effective and reactive power requirements in LV networks and also in MV networks, and can thus cause bothersome perturbations, is relatively large resistance welding machines (pulsed primary). These machines are frequently designed to use alternating current that puts a high inductive percentage of two-phase, unbalanced stress on the three-phase current network. The fundamental frequency power factor (basic harmonic reactive power factor cos φ_1) is in the middle here, at about 0.7.

With modern machines, the amount of welding current is usually set by thyristors so that the following network perturbations occur for line-commutated converters:

- Harmonic currents due to non-sinusoidal network currents.
- Network voltage drops.

Particularly in networks with relatively low short-circuit power, the network perturbations increase.

For the sake of completeness, it should be mentioned here that voltage drops are also a cause of flicker (see Section 20.4).

With dynamic real-time compensation, a combination of high-speed controller and thyristor power modules is substituted for the conventional components (reactive power controller and capacitor contactor) [1] (see also Chapter 14).

This system reacts with a minimal delay of one network cycle to a change in load and thus prevents rapid change in reactive power in the electrical network. The fundamental frequency power factor (basic harmonic reactive power factor cos φ_1) is optimized at all times and the network load is reduced to a minimum. To eliminate the reaction time totally, control

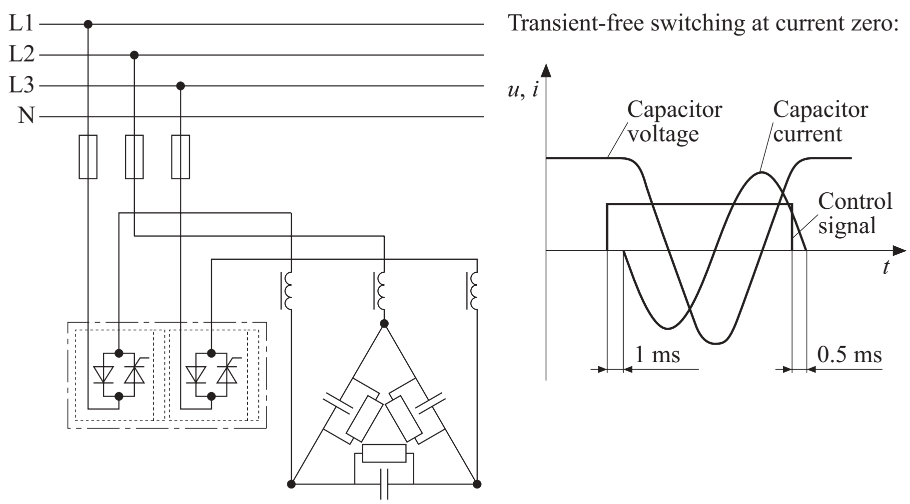

Figure 20.1 Thyristor power modules for LV power capacitors. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

of the compensation steps can be performed directly by the controller electronics of large single consumers.

Figure 20.1 shows the principle of a dynamic reactive power compensation system with thyristors. Thyristors are suitable for switching capacitive loads (i.e. reactor-protected capacitors and capacitors without reactors). Parallel operation of thyristors together with capacitor contactors on an LV distribution is only possible with reactor-protected units because of the high reloading currents.

The functioning principle, as can be seen from Figure 20.1 [1], is as follows. The device consists of two thyristor modules which switch phase conductors L1 and L3. The phase conductor L2 is not switched. Single-phase operation is also possible for the thyristor modules. If the 'ON' signal is applied to the control input of the thyristor, the integrated control electronics switches the thyristors to the next negative current zero crossing separately for each phase conductor. Switching off also takes place during current zero crossing.

This principle eliminates transient switching disturbances (transient effects) and network perturbations.

Thyristor power modules (Figure 20.2) can be used together with:

- Programmable logic controllers (PLCs).
- Reactive power controllers or process controllers.
- Computer systems or process engineering.

And particularly for:

- High-speed switching.
- Without network perturbations due to transient-free switching during current zero crossing.

Figure 20.2 Thyristor power module. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

Examples of typical applications [2, 3] are the following:

- Cranes.
- Elevators.
- Spot welding machines (primary pulsed).
- Sensitive production processes (e.g. the semiconductor industry).

In drawing conclusions from the previous explanations: the dynamic reactive power compensation system is suitable equipment for fast switching dynamic power factor correction; the capacitor contactors are replaced by thyristor modules; and the thyristor modules are suitable for a nearly unlimited number of switching operations.

Some of the advantages of dynamic reactive power compensation are listed below:

- Improvement of the power quality.
- Increase in available power (i.e. improved power network utilization).
- Decrease in transmission losses.

The advantages of switching with thyristors are:

- No high switch-on currents.
- Transient-free switching.

- Switching within one sinusoidal half cycle.
- Unlimited number of switching operations.
- Avoidance of drops in voltage.

20.2 Motor Startup Compensation

Motor startup compensation is designed especially for the application as a startup aid (i.e. everywhere where rapid changes in the load affect the voltage dynamically at the point of common coupling (PPC)). This is why large motors need a startup current (inrush current) during the startup procedure which is 4–8 times the rated current.

Depending on the network, this great power consumption causes a significant drop in voltage, in particular in networks with low short-circuit power [4].

While startup is taking place, the startup compensation is switched and coordinated time-wise with the motor. The compensation system steps the reactive power down again when the inrush current decreases.

Motor startup compensation is particularly economical for networks with a relatively low short-circuit power and large motor loads. A fixed motor compensation is also suitable for problems with motor startup such as:

- Overcurrent triggering, excitation of protective system.
- Undervoltage triggering, excitation of protective system.
- No motor startup (voltage is too low).

Thyristors with controllers (dynamic compensation) are used for somewhat smaller motors and rapid current increase. In contrast, large motors usually have a power pack with fixed motor compensation and controller (conventional compensation) for the motor startup compensation but with very high power capacity. A special controller controls the power switch of the motor and the compensation step according to the demand for reactive power [4].

The amount of compensation is determined by load-based measurement of the current.

The next two figures show the current progression (Figure 20.3) and the principle of the controller (Figure 20.4) for motor startup compensation.

The advantages of motor startup compensation are as follows:

- Reduction of the network current without limiting the motor current.
- Stabilization of the network voltage.
- Avoidance of production disturbances.
- Several motors can be started up with one startup compensation system.
- Flexible combination of startup compensation, fixed motor compensation and reactive power control system, and automatic power factor correction equipment.

20.3 Flicker Compensation

Conventional dynamic compensation is not suitable for flicker reduction. Flicker compensation has the special task of keeping the voltage constant.

As already mentioned in Section 20.2, brief changes in voltage (depending on the form and strength of the changes and their frequency) within a defined time interval will cause flicker

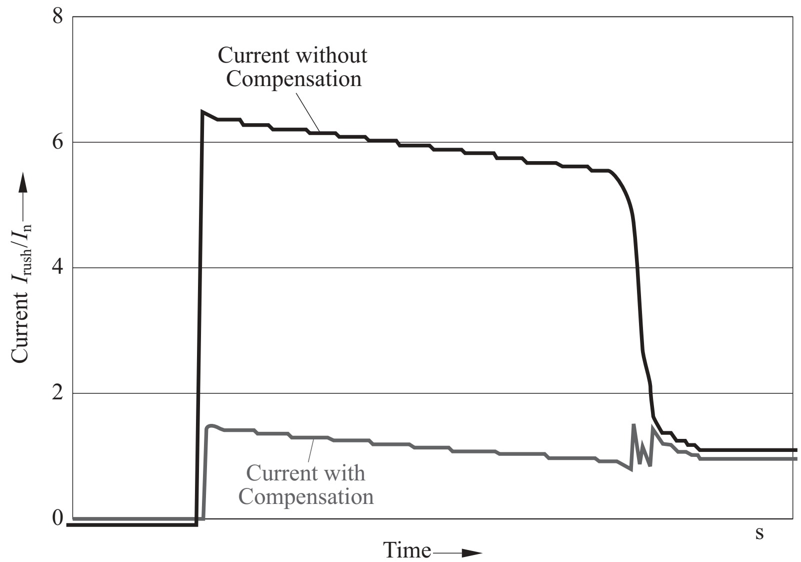

Figure 20.3 Current progressions without and with compensation. Reproduced by permission of Condensator Dominit GmbH, Germany.

which must be restricted in size. Voltage fluctuations with a frequency of approximately 0.005 to 35 Hz can generally be perceived by people as a more or less strongly flickering light, depending on the amplitude [5].

Figure 20.5 shows the flicker boundary curve ($P_{st} = 1$) that was determined during test trials. The curve indicates that 95% of the test subjects felt bothered by flicker. The threshold of perception of flicker is approximately $P_{st} = 0.8$.

To avoid confusion, some terms will not be discussed here, for example flicker disturbance factor, compatibility levels for voltage changes (e.g. as in EN 61000-4-15), calculation

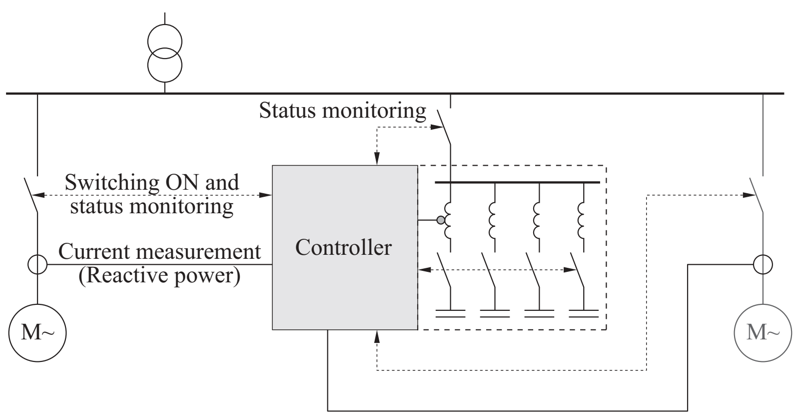

Figure 20.4 Principle of the controller. Reproduced by permission of Condensator Dominit GmbH, Germany.

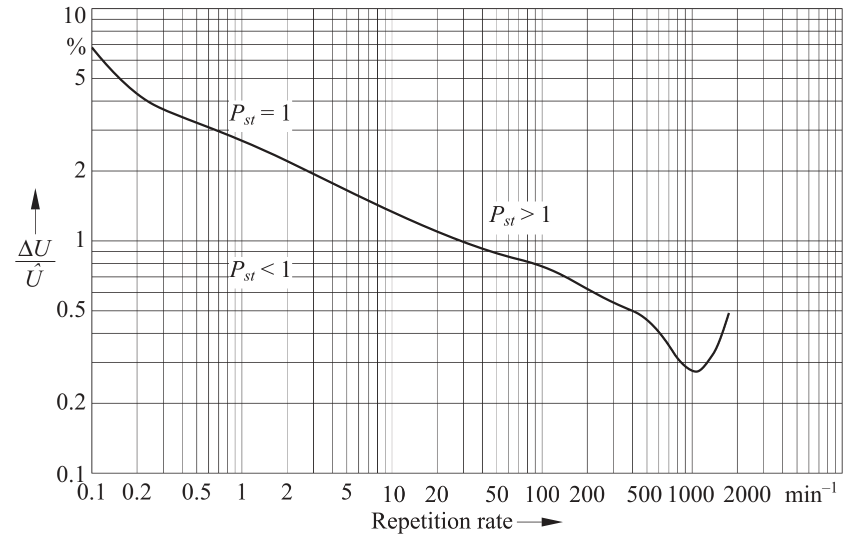

Figure 20.5 Flicker boundary curve ($P_{st} = 1$) for rectangle voltage changes as in DIN EN 61000-4-15 [6].

formulae for the elimination of flicker disturbances as well as the features of the supply voltage (e.g. as in EN 50160) and the interference evaluation procedure. A study of [5] is recommended for a better understanding of the subject of flicker compensation.

Some of the primary reasons for changes in voltage and flicker are listed below:

- Motors with high switch-on currents.
- Dynamic loads.
- Welding machines (particularly spot welding machines with high clock pulse rate during welding).
- Arc furnaces.
- Wind turbines.

The reasons for the occurrence of flicker in electrical ‘consumers’ include the following in particular:

- Drops in voltage due to the load’s demand for reactive power.
- Drops in voltage due to the load’s demand for active power.

Compensation of the active or reactive power surge as the cause of drops in voltage only reduces flicker when the compensation is switched on and off at exactly the same time as the welding current. The strongly fluctuating demand for reactive power of welding machines, in particular for primary-pulsed welding transformers, can be effectively reduced with rapidly reacting power electronics. In addition, it should be considered that, with a dynamic reactive power compensation, the demand for compensation should preferably be determined by a load-side current measurement. This reduces control delay significantly (i.e. open-loop

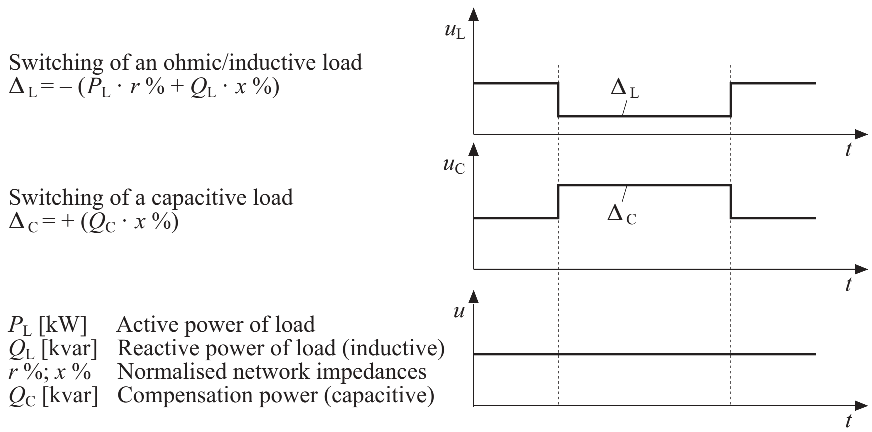

Figure 20.6a Principle of flicker compensation: ideal presentation. Reproduced by permission of Maschinenfabrik Reinhausen GmbH, Germany.

control). In addition, direct activation can also be used in special individual cases (e.g. flicker interference).

During a brief change in voltage caused by a change in load, a change in voltage is superimposed with reversed polarity as near as possible to the time of the change by flicker compensation, provided the voltage progression is known (Figure 20.6a). As this figure shows, reactive power is intentionally fed in to increase the voltage.

In reality, at many times (particularly with the passive filter) simultaneous switching procedures or compensation in a precise amount are just not possible. A time difference of several milliseconds always remains in addition to a tiny difference in the amount [4] (Figure 20.6b).

The achievement of as fast a reaction time as possible is decisive for the effectiveness of a satisfactory compensation solution. The objective is to obtain changes in voltage caused by changing loads as close to zero as possible. If, for example, one wants to achieve welding

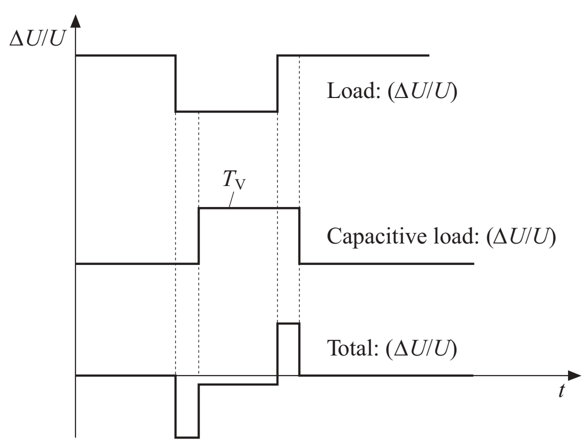

Figure 20.6b Principle of flicker compensation: actually implemented presentation [4].

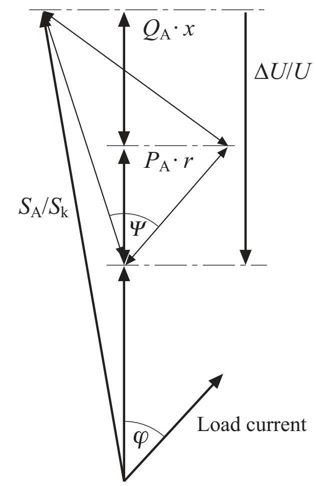

Figure 20.7 Calculation of voltage change for three-phase conductors [3].

clock pulse times of somewhere around 1 second, compensation systems used for this purpose (mostly also possible via the active filter) should be able to react very quickly to prevent the disturbance effect from being increased by the resulting double flicker.

Figure 20.7 shows that changes in both reactive and active power cause flicker-relevant changes in voltage.

Note, from the preceding explanations, that generally it is not enough just to keep the reactive power consumption of an interfering consumer constant. The active load must also be considered.

Figure 20.8 illustrates the different goals regarding reactive current compensation and flicker compensation.

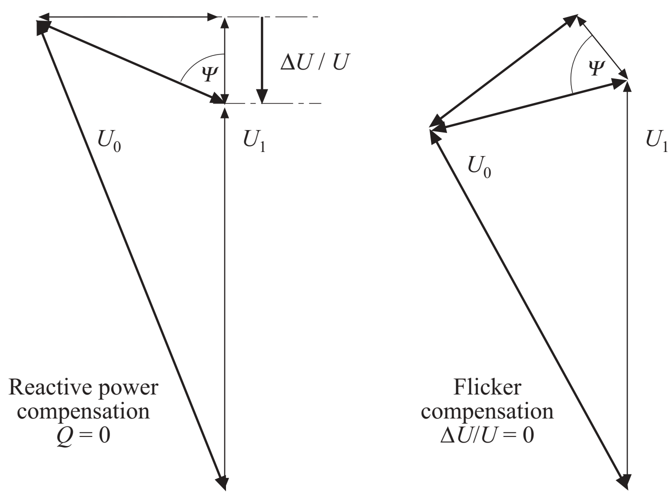

Figure 20.8 Tasks of reactive power compensation and flicker compensation [3].

Flicker compensation can be described by the following three measures:

1. Reactive power compensation.
2. Load balancing (for two-phase loads).
3. ‘Active’ flicker compensation.

To be able to handle the demands involved in voltage quality improvement, users of flicker compensation systems should ask themselves the following questions, among others:

- Will the ‘active flicker’ also be compensated in addition to the reactive compensation?
- How will the load symmetry (load balance) be represented for a two-phase load?
- Can a very fast reaction time be achieved?
- What reactive power (kvar demand) will be required?

Figure 20.9 and 20.10 show examples of the reaction time of flicker compensation as well as voltage changes with and without compensation. Figure 20.10 shows the interaction of a welding machine with a dynamic compensation system. The reaction times of 1 ms to 2 ms, which are caused by the phase position of the welding current as opposed to the compensation current, result in only a very small remaining flicker [3].

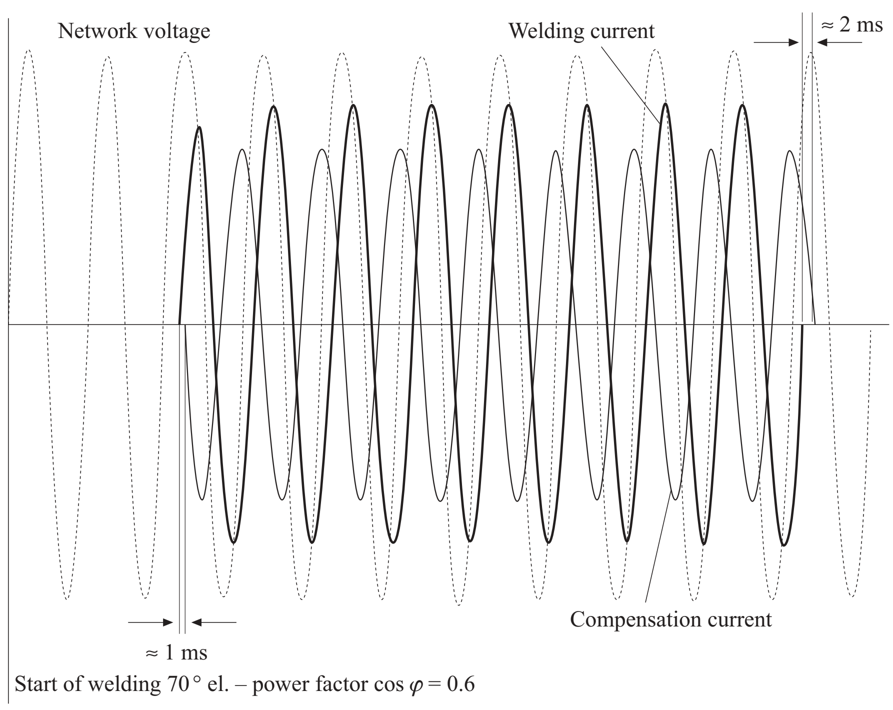

Figure 20.9 Reaction time of passive flicker compensation (here, a welding application). Reproduced by permission of Condensator Dominit GmbH, Germany.

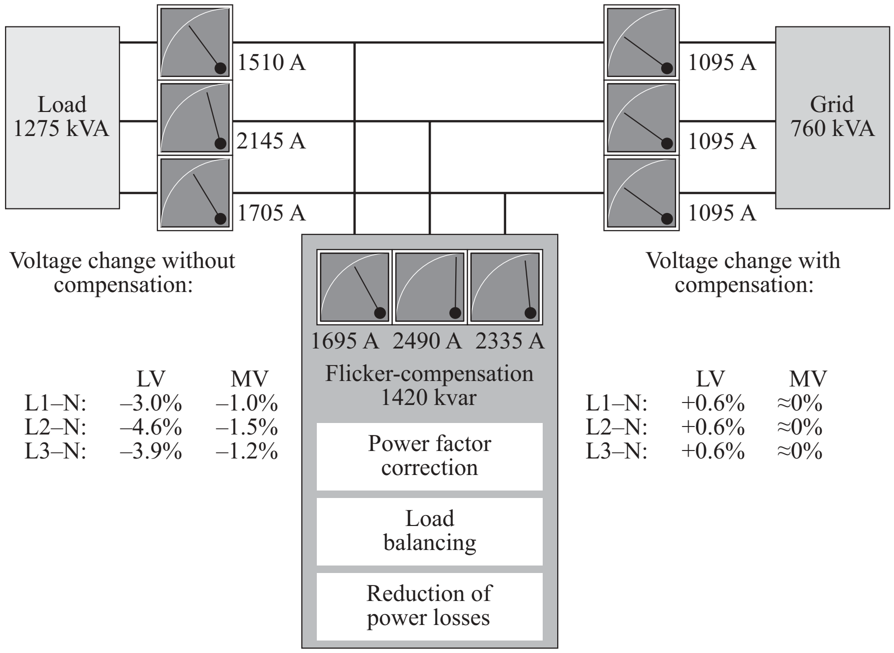

Figure 20.10 Example of flicker compensation (voltage changes with and without compensation). Reproduced by permission of Condensator Dominit GmbH, Germany.

It should be kept in mind that the flicker compensation can be used for permissible network perturbations so that the requirements of local distribution system operators (power utilities) are also met. The problem of flicker disturbances and its elimination can be described based on voltage change, reactive power demand (Q_c) and the flicker disturbing effect, among others [5].

20.4 Evaluation of Power Factor Correction Solutions as Seen by the Distribution System Operator (Power Utility) [3, 5, 7]

A high-quality network is particularly indispensable for economic areas (e.g. industry, commerce and trade). Without going into the special features of network operation and the legal requirements which apply to the operation of a public power supply (e.g. reliability of the power supply), the quality of the power supply at the PCC and the quality of the network from which the customer is supplied must be differentiated regarding the terms ‘network quality’ and ‘power quality’.

The number of possible plans and thus the flexibility of the distribution system operator (power utility) may possibly be increased with reliable and well-engineered compensation or filter circuit systems which provide additional improvement of the network quality. In addition, costly network expansions can be avoided by using local solutions.

Since demands on the transmission capability of the network will increase in the future, all possible ways to increase efficiency and thus also the described solutions for the distribution system operator should be utilized. This may result in cost savings, among other things, for customers and distribution system operators.

20.5 Summary

Repeatedly heavy load changes can cause a disturbing voltage fluctuation which often results in critical malfunctions in other electrical equipment.

In general, dynamic reactive power compensation equipment means a real-time reactive power factor compensation system. This system reacts immediately to load fluctuations and reactive power surges will be neutralized in the supply network.

Thyristor power modules are a ready-to-install solution for dynamic power factor correction equipment [1]. They are also suitable for switching power capacitors with or without filter reactors. The number of switching operations of thyristors is unlimited. They are almost wear-free.

During startup, larger motors frequently need a network with strong short-circuit power or help from motor startup compensation.

Voltage fluctuations with a high repetition rate are typical of equipment like welding machines. Such productions can cause unacceptable flicker disturbance on the grid. Flicker compensation has the task of keeping the network voltage constant during a change in voltage to avoid flickering lights. Here the reactive power compensation is just one of the necessary measures. Because of their reaction times in the millisecond range, modern flicker compensation systems are able to reduce changes in voltage and also enable interference-free operation (e.g. of cranes, welding machines, presses, rubber kneaders, mill saws and shredders) in electrical networks with low short-circuit power.

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21

Compensation Effects at Rectifiers

21.1 Chapter Overview

In the world of nonlinear consumers one finds occurrences far away from an understanding of classical compensations at linear consumers. Typical well-known laws in three-phase systems, for example to distribute single-phase consumers to the phases symmetrically in order to unburden the neutral wire, become invalid if they are nonlinear (see Figure 19.16b in Chapter 19).

Regarding the time courses of voltages and currents especially, it is usually best to convert them into fundamental waveforms thus enabling classical formula to be employed further on. Considering the real time courses in practice, one finds deviations from the theory.

This chapter therefore tries to give a better understanding of the electrophysical procedures while compensating nonlinear consumers like, for example, three-phase bridge-connected rectifiers.

21.1.1 General

> An understanding of reactive power at converters will be rendered more difficult as it is not possible to present a physical interpretation directly. Up to now, only linear consumers have been taken into consideration. At these consumers any reactive power has been described as an energy oscillating steadily between the source and consumers, which does not contain active energy for the consumer.
>
> However, if there are diodes or thyristors in the circuit, the consumers follow a nonlinear behaviour. The meaning of reactive power then has to be formed in a new way. In general one may say that, if the time courses of voltage and current are running synchronously, without any time deviation, then no reactive power exists. Temporal deviations do, however, have an effect similar to reactive power [1].

It is correct that the electrophysical facts described in Chapter 1 may not apply to the world of rectifiers either directly or indirectly. As mentioned in Chapter 1, reactive power represents an oscillating energy between the source and the consumer. The syllable 're' in

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

reactive underlines that energy is fed back [2, 3]. As is well known, reactive energy is caused by components which are able to store energy briefly, like inductances and capacitors. Inductances store energy in their magnetic field and capacitors in their electric one. Semiconductors are never able to store energy. Thus , understanding becomes more and more difficult.

There is therefore an urgent need to explain the occurrences of 'reactive power' at rectifiers and to compare the theory and electrophysical facts.

21.2 Compensation Bank at a Six-Pulse Rectifier

Although this chapter's title is 'Compensation Effects at Rectifiers', the aim is to focus on the behaviour between an automatically controlled compensation bank and a six-pulse rectifier. Any occurrences on the DC side of the rectifier do not affect the reactive power on the primary side. Even the DC voltage is to be converted into AC voltage of medium frequency afterwards, in order to feed, for example, inductive furnaces where any reactive power has to be compensated exclusively on this side. In other words, any occurrence of reactive power on the secondary side of the rectifier will not influence its primary side.

AC/DC rectifiers are of different character. For example, two-pulse single-phase bridge-connected rectifiers (Graetz) have linear characteristics; supposed linear consumers are connected on the secondary side. However, three-phase bridge-connected rectifiers have non-linear characteristics. This means that the load on the secondary side, even with a linear characteristic, takes energy alternating within the three phases of the AC network in a nonlinear manner (see Figure 21.6a below). The current does not run within the entire half period of the voltage's time course (180°) but is taken over 120° electrical before changing to the next bridge system. Thus the time course of the current is no longer linear but pulsating.

The situation becomes worse if the rectifier is to be controlled, for example, by thyristors, gate-turn-off thyristors (GTOs) or integrated bipolar transistors (IGBTs). Any application of the well-known 'power triangle' (e.g. Figure 10.1) composed of apparent, active and reactive power leads to the wrong results if the time courses of voltage and especially current are no longer sinusoidal. In distributing nonlinear consumers over all the three phases symmetrically, it was demonstrated in Figure 19.16b that the current in the neutral conductor does not become zero as in linear consumers. The pulsating currents are to be added in the neutral conductor and may overburden it. This leads to cables with a strengthened cross-section of the neutral conductor. In modern technology one can find many nonlinear consumers, such as TVs, computers and energy-saving lamps for instance. Figure 21.1 shows the time courses of voltage and current for an energy-saving lamp. The current pulsates for just a few milliseconds within one half period only.

So far there has been no definition of reactive power existing independently of the waveforms of voltage and current. The well-known definition $Q = U \cdot I \cdot \sin\varphi$ is applicable for sinusoidal procedures exclusively, as underlined by the factor sin φ. Even symmetrical vectors in the three-phase network must be ensured in order to obtain the correct results by measurement or metering devices.

In 1929 the classical definition of reactive power was somewhat dubious, since at that time no one knew about harmonics, not to mention nonlinear consumers [5]. Deviations between theory and electrophysical facts have now come to light (compare Figures 21.2 and 21.3).

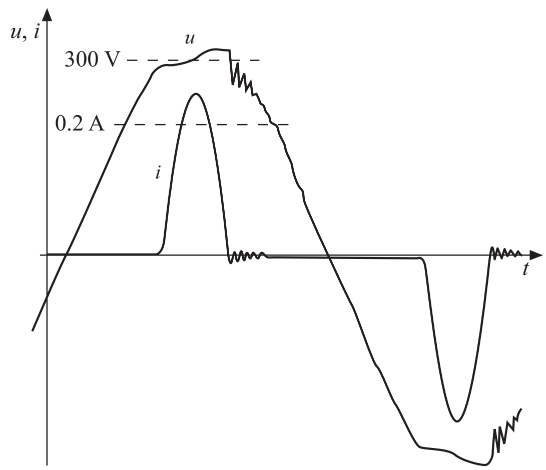

Figure 21.1 Time courses of voltage and current referring to an energy-saving lamp.

Industrial converters indicate a nominal power factor cos φ printed on their nameplate. The definition of the power factor is settled by the ratio of active power to the apparent one and does not say anything else about the amount of reactive power at nonlinear consumers. In the world of non-sinusoidal courses referring to voltages and currents this fact must be taken into account.

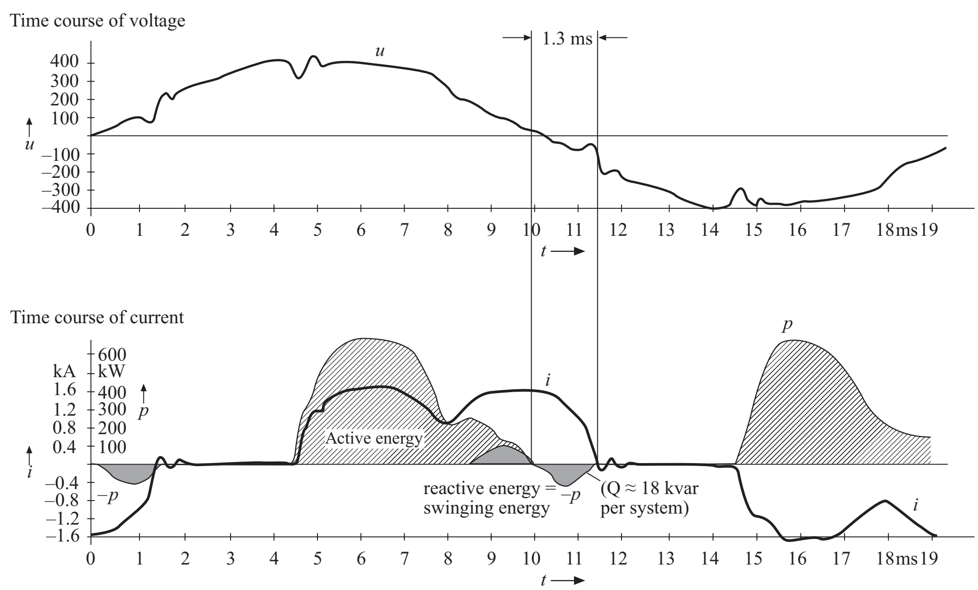

Figure 21.2 Time courses of voltage and current for a three-phase bridge-connected rectifier without phase-angle control with commutating reactor to be switched in series.

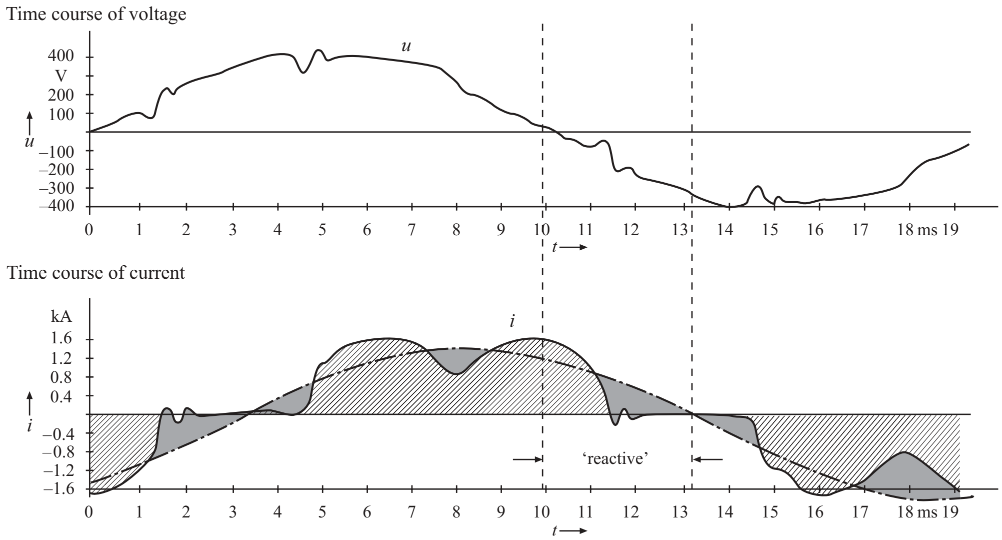

Figure 21.3 Time courses of voltage and current identical to Figure 21.2, but with the pulsating current to be converted into a sinusoidal waveform.

21.2.1 Time Courses of Voltage and Current at a Three-Phase Bridge-Connected Rectifier

Figure 21.2 shows the time courses of voltage and current to be rendered in one of the three phases. It is noteworthy that the 'blocks' of current are not symmetric to half of the voltage wave, though the rectifier is not phase angle controlled. It is easy to see that if the voltage changes its polarity to the negative side, the current still has positive polarity for a brief period. For about 1 ms the current and voltage are in opposition resulting in 're'active power (negative). This is not caused by the rectifier itself but by the commutating reactor switched in series for each phase. The negative area coloured dark grey represents the fed-back energy. Any energy to be exported to the grid first of all has to be imported as well. This is why the same amount of energy occurs at the positive side and reduces the active energy accordingly. By dividing the two dark-grey energy areas by the duration time of 2.6 ms one gets the reactive power of the commutating reactor, that is about 50 kvar.

Measuring devices indicate scattered values in the range of 800 to 1200 kvar, depending on the brand. The reason for these failing values is easily found: manufacturers of measuring or metering devices for reactive power or energy are obliged to design the units in accordance with the standard DIN 40110. These devices are therefore calibrated exclusively to sinusoidal waveforms of voltage and current. Pulsating courses of the current especially lead to incorrect values [4]. This is the reason why in theory the pulsating current blocks are to be converted into sinusoidal waveforms (see Figure 21.3). The duration of the 'reactive' period becomes much longer than in reality (see Figure 21.2). However the current blocks when converted into sinusoidal waveforms do not exist at any time.

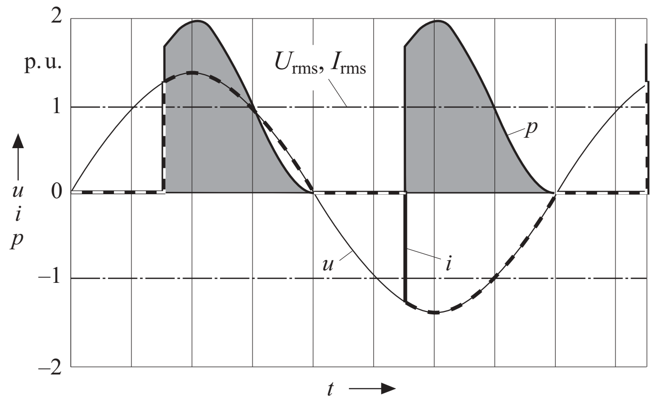

Figure 21.4 A phase-controlled ohmic load does not cause any reactive power, as signs of voltage and current will never be opposed to each other.

A much higher discrepancy is seen in Figure 21.4 which illustrates a phase-angle-controlled ohmic consumer. The time course of power never changes into negative polarity. Thus any reactive power (exported) does not exist. This does not comply with the theory of course.

Last but not least, the European standard EN 61268, point 3.1.1, issued in 1996 for electronic varmeters, underlines that correct metering is given under conditions of sinusoidal time courses of voltage and current exclusively.

21.2.2 How Compensation Banks Affect Three-Phase Bridge-Connected Rectifiers

In principle, different factors must be taken into consideration here. Practical measurements show that the input current does not change while 'compensating' – for example, in comparison with classic compensation. Furthermore, the digital power factor indication 'stands by' at the controller. These are confusing occurrences but simple to explain by the following electrophysical facts.

For a better understanding, a single phase-angle point control for an ohmic load – like a dimming circuit for an incandescent lamp – will be used as an example. The characteristic time courses of voltage and current with control angle α are shown in Figure 21.4. As is well known, such periodic processes deviating from the classical sine function are subdivided into pure sinusoidal oscillations of basic frequency and several integer multiple harmonics by means of Fourier analysis. Due to the phase-angle point control, in theory the harmonics of the current should appear shifted in phase in relation to the voltage. Although an ohmic load is regulated in this way, the literature refers to the inductive action of a control valve. Depending on the control angle, the valve causes more or less reactive power 'which is not visible' [7]. Indeed, this so-called reactive power is not visible and is under no circumstances reactive.

The time periods during which $i = 0$ represent neither reactive nor active power, since $u \cdot I = 0$. Any power is equal to zero. Thus periods of 'no-load power' can be recognized.

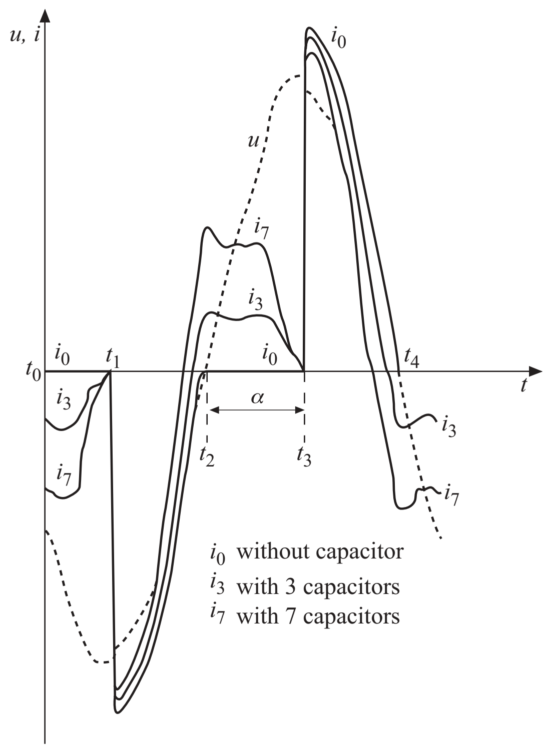

Figure 21.5 Compensation with phase-angle control (single phase) (i_0, without capacitors; i_3, with three capacitors; i_7, including seven capacitors).

Fourier analysis can be used, but it must be kept in mind that, in practice, the entire sum of the theoretical splitting always occurs.

What actually happens during the 'compensation' of control valves and rectifiers is shown – for one phase – in Figure 21.5. Without capacitors being switched in, current i_0 can be recognized. Current i_3 shows the current leading the voltage by 90° during regulated compensation in three capacitor steps. During the time period t_1 to t_0, only the capacitor current appears. In the following period, t_2 to t_1, the capacitor current which in the meantime has acquired positive polarity is subtracted from the negative load current, which commenced ignition at the moment t_1. With decreasing load current the positive capacitor current reappears, until it alone appears when the load current drops down to zero. At t_3 the positive half wave of load current, the capacitor current which in the meantime has acquired negative polarity, 'compresses' the original load amplitude i_0 down to i_3 until, also with decreasing load current, around t_4, the capacitor current is predominant again. The effect of four additional capacitor steps is reflected in the current curve i_7 and needs no further explanation. The above-mentioned point, that the effective input current to the rectifier does not change with increasing 'compensation', and is certainly not reduced, is also easily seen in the curves of the different currents. In this case, the capacitors do not compensate any reactive energy but rather 'trickle charge' the load current, as confirmed by laboratory findings and practice [6].

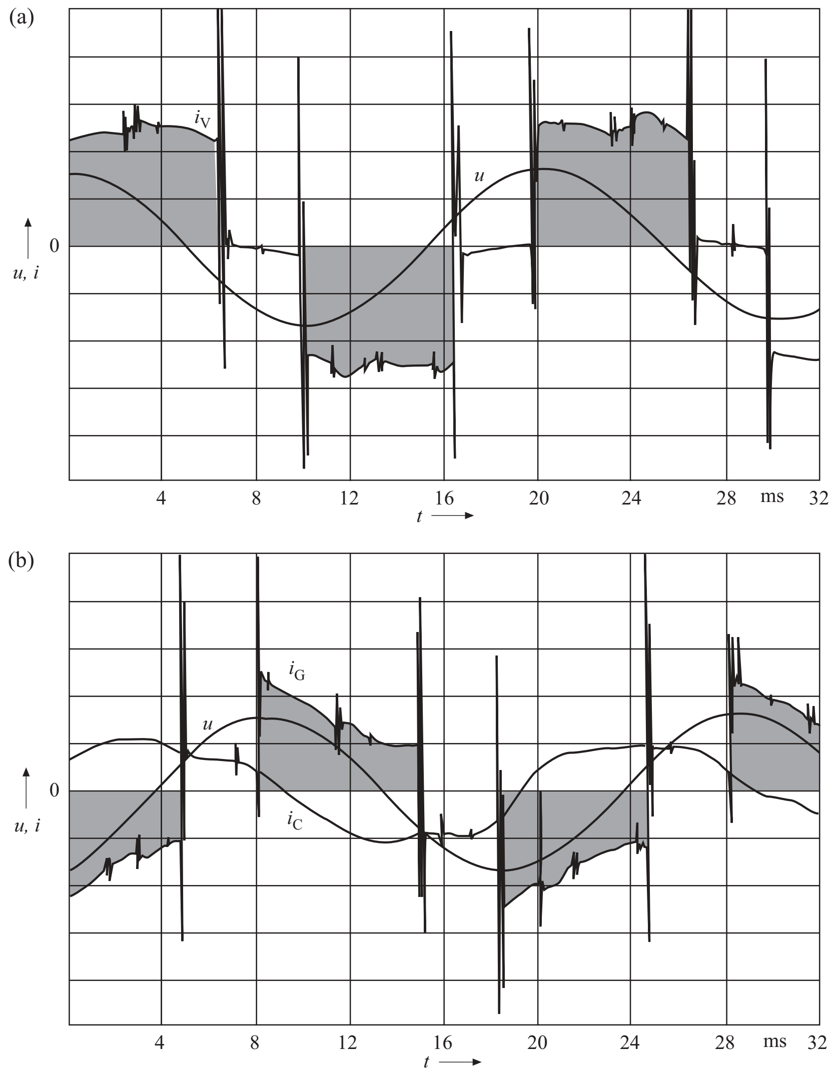

Figure 21.6 (a) and (b) Effect of capacitors at the input of a six-pulse rectifier.

With this knowledge it becomes easier to understand the procedures at a three-phase bridge-connected rectifier.

Figure 21.6a,b shows the time courses of voltage and current of a 500 kVA six-pulse rectifier without and with 'compensation'.

Similar to Figure 21.5, observations by electricians had been made as follows:

> The power factor cos φ, indicated by the controller digitally, changes over a very small range, e.g. 0.92 up to 0.94, independently of the number of energized capacitor steps, say one or eight! The most confusing fact is that the apparent input current will not be reduced by the increasing number of capacitor steps [6].

Explanations are the same as for Figure 21.5 but now with reference to Figure 21.6a,b.

Figure 21.6a shows the time course of the current pulsating to the rectifier in the described nonlinear manner and without any capacitors connected in parallel. Figure 21.6b shows the effect of the ‘compressed’ current blocks by eight capacitor steps, of 25 kvar each, with the full power of 200 kvar, similar to Figure 21.5. The assumed capacitor current is represented by curve i_c in the ‘invisible’ phases to show how the periods without load current are ‘filled up’. Furthermore, this ‘trickle charging’ supports the otherwise interrupted current curve at the input and distributes it over the whole cycle, which is essential for the accuracy of all wattmeters. Thus the rms value of the apparent input current is not reduced by the eight capacitor steps but rather ‘stands by’, independently of the number of capacitors energized. Even the deviation of the current blocks against the voltage changes over a very small range because the capacitors compensate the internal commutation reactors inside the rectifier and nothing more. This is why the indicated power factor ‘stands by’ as well. The input current blocks themselves, however, remain ‘unshiftable’.

These observations were made at compensation banks working in parallel exclusively to converters. In large electrical plants with a mix of linear (classical inductive load) and nonlinear consumers (rectifiers and converters of any kind) modern electronic power factor controllers just compensate the real reactive power, now well known as ‘feedback’ power.

The ‘behaviour’ of modern power factor controllers in relation to rectifiers is described in Section 21.3.

21.3 Characteristic Behaviour of Reactive Power Controllers at Rectifiers

The reactive power controller fitted in the 200 kvar compensation bank described in Section 21.2.2 switched in all capacitor steps and triggered an alarm if it was not able to obtain the desired power factor of cos $\varphi_d = 0.98$ lagging. Modern controllers do not recognize any compensation effect. The reason for this has already been explained.

The design of reactive power controllers with regard to seizing the actual reactive power has to meet the standard DIN 40110 in Germany. However, as mentioned previously this definition applies for sinusoidal time courses of voltage and current. All varmeters are calibrated accordingly. The principle of wiring any varmeter in taking the current path from one phase and the voltage path from the other two phases with 90° shifting between them has been adopted from the so-called Ferraris system, commonly used among varmeters. However, any control of reactive power at nonlinear consumers like rectifiers fails as described above. Formerly, electromechanical reactive power controllers working with a disc would still be driven by the torque caused by the asymmetrical current blocks compared with the voltage’s half wave, even though there was no reactive power. They would energize all capacitor steps as well as the electronic units without achieving the desired power factor.

Modern electronic reactive power controllers with the so-called *fully automatic C/k adaption* (see Section 11.3.3) either do not control due to an unregistered compensation effect (reduction of the input apparent current) or just switch in one or two capacitor steps to compensate the internal commutating reactors inside the converter.

The described observations are well known in practice. Therefore the following ‘solutions’ have been agreed:

- Fixed single-type compensation (see Chapter 9) in order to compensate the commutation reactors.
- With the agreement of the electricity supplier, not to install any capacitor bank as done in feed-in stations with AC/DC rectifiers, such as on the underground railways in Munich for instance.

21.4 Summary

As mentioned in Section 21.2, the meaning of reactive power has another view with regard to rectifiers or converters [1]. In the world of nonlinear consumers and time courses of voltages and currents far from sinusoidal functions, there is a need to reform the existing definition $Q = U \cdot I \cdot \sin\varphi$ into one valid for time courses of voltages and currents.

The definition of active power meets this requirement from the very beginning with the formula

$$p = \frac{1}{T} \cdot \int_0^T p \cdot dt \tag{21.1}$$

Also, it is not appropriate to refer here to a so-called ‘fundamental oscillating active power’. Furthermore, there is no need for complicated subdivisions into pure sinusoidal active power and its integer multiple harmonics because the formula (21.1) allows true active power to be seized independently of harmonics.

Nevertheless, a similar definition for reactive power does exist, and has even been patented. First of all, though, it must be accepted by the responsible institutions worldwide of course.

The main task of this chapter was to introduce mostly unknown facts and to explain mysterious and confusing occurrences known to specialists in the field of nonlinear consumers in modern power electronics.

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22

Environmental and Climate Protection Using Capacitors

22.1 Chapter Overview

This chapter deals with the toxic effects of capacitor fillings and their handling in case of damage or exchange of capacitor installations. A further aspect to be regarded is the savings in primary energy and the related reduction of CO_2 emissions, if coal and gas are used as primary energy.

22.2 PCB-Filled Capacitors

The following notes provide a brief insight into the overall problem occurring with capacitors filled with polychlorinated biphenyls (PCBs). PCB insulation liquids are mostly clear, yellow fluids, whose viscosity can be tuned by means of additives. PCBs are thermally and chemically very resistant, virtually non-flammable and practically insoluble in water. The biodegradability of PCBs depends mainly on the amount of chlorination, since it reduces with increasing chlorine content. PCB insulation liquids were formerly used because of their good dielectric properties and flame resistance; capacitors with PCB insulation can still be found in discharge lamps for reactive power compensation The overall problem cannot be treated comprehensively in the context of this book, however. In Germany, the relevant laws, rules, technical regulations and manufacturer's instructions are based on common practice, but can be adopted for installations in other countries as well.

From environmental and toxicological points of view, equipment containing PCBs should be treated carefully, because it may contain increased concentrations of polychlorinated dibenzodioxin (PCDD) and polychlorinated dibenzofuran (PCDF). Special protective measures when handling PCBs are to be observed. In case of fire exposure, equipment containing PCBs will emit dangerous toxic radicals, in particular PCDD and PCDF. Exchanging the PCB insulation of capacitors by decanting is both economically and technically without sense and impossible.

The normal thermal and electrical stresses of the dielectric of the capacitors may cause punctures in the capacitor films, resulting in chemical reactions producing gas and increased

Reactive Power Compensation: A Practical Guide, First Edition. Wolfgang Hofmann, Jürgen Schlabbach and Wolfgang Just.

pressure inside the capacitor can, and thus an increased risk of damage and disruption of the outer covering (of the can). PCB-filled capacitors with low rated power are installed mainly in discharge lamps with built-in magnetic ballasts, but can still be found in operation in other installations, such as in motor compensation with rated power above 1.5 kvar. If PCB-filled capacitors are installed inside the housing of lamps, temperatures at the reactor of up to 125 °C are possible. Even higher temperatures may occur in the case of high ambient temperatures, due to air-conditioning, ceiling heating and from heat accumulation due to special ceiling and lighting design or high operating voltage. In the case of abnormal operating conditions, such as multiple starting of the lamp, short circuits of windings temperatures up to 300 °C are possible. Overcurrent protective devices do not respond in this case. The capacitor installed in the vicinity of the reactor will be destroyed, rupture of the capacitor can will occur, and PCB and fractional products will be scattered outside the lamp.

The identification of PCB-filled capacitors causes problems, as some capacitors are not marked according to standards. The type of dielectric impregnation is usually encrypted on the nameplate, for example capacitors containing PCBs are marked C, CL, CD, CP, CP 30, CP 40 or with the name Clophen. If the capacitors cannot be identified as PCB-free, as is sometimes the case with capacitors in older installations, or in a non-existent nameplate, they have to be treated in the same manner as capacitors containing PCBs.

With regard to the disposal arrangements of PCB-filled capacitors, users have to decide whether to exchange them as soon as possible (precautionary method) or to exchange them in the course of the normal replacement for PCB-free capacitors (maintenance method). Leaking capacitors must be immediately replaced, dismantled and packed liquid tight, including all contaminated mounting and other materials, and be disposed of selectively. If PCB liquid is scattered inside the lamp, the complete housing should be dismantled and disposed of in the same way as for the capacitor itself. Partial cleaning of the lamp is not suitable. If PCBs have contaminated other parts of the surroundings, for example the floor covering, all contaminated parts should be cleaned thoroughly, in some cases by replacement of the sealing of the soil or floor covering. Replacement of the floor covering or of the contaminated parts should be considered. Cleaning should not be carried out using solvents but in a dry and dust-free matter. PCB-contaminated parts and PCB capacitors must be handled according to national laws (Acts for Transport of Dangerous Goods), standards and technical regulations.

22.3 Climate Change and Energy Efficiency through Power Factor Correction

In 2005 the Commission of the European Communities issued the Green Paper COM 265 (2005) [1] on energy efficiency. Millennium Development Goals are defined to improve energy efficiency in all sectors of energy consumption in the European Union. A Strategy is defined which is to be applied not only for the European Union, but also in international cooperation as well:

> The first part of increased international cooperation on this issue will consist of working with particularly the OECD countries within the International Energy Agency (IEA), to establish energy efficiency plans. As developing countries are now able to join the Implementing Agreement of IEA, they could be encouraged to participate in these fora. This international forum could for instance be the starting point for launching ideas . . .

> European environment policy should help develop the capacity to value efficient projects implemented in developing countries through climate change mechanisms such as the CDM . . .
>
> The EU and the Member States must incite the International Financing Institutions to give more attention to energy efficiency measures in their future financial and technical assistance operations to third countries.

Based on the Green Paper, the Central Association of Electrical and Electronic Manufacturers' Association (ZVEI), in Germany, published two reports on energy efficiency and CO_2 reduction through power factor correction [2, 3] in EU-25. Data included in the reports are based on the statistical year 2004.

The total demand in the European power systems was 2836 TWh, including 195 TWh losses in the transmission and distribution system (6.9% of total demand). As can be seen from Table 22.1, the main consumer of reactive power is the industrial sector accounting for more than 90% of the total reactive energy in the power system.

From the table, it seems very effective to consider first the improvement of power factor in the industrial sector and partly in the service sector as well. If the target power factor in these sectors is to be $\cos\ \varphi = 0.95$, the reactive energy consumption is reduced by 1069 Tvarh, that is by more than 60%. The drop in apparent energy is 443 TVAh or 15%, as can be seen from Table 22.2.

The reduction in apparent energy results in a reduction of the current in the power system equipment and leads to a reduction in current-dependent network losses and in the system load as well. According to [1], the total system losses are up to 10% of the consumption, that is 264 TWh, transmission system losses amount to 20% (52.8 TWh) of the total system losses, whereas distribution system losses amount to 80% (211.2 TWh). The share between current-dependent and voltage-dependent losses is estimated as 90% to 10% for the transmission system and 60% to 40% for the distribution system [2]. Table 22.3 indicates the share of losses between the different categories and system levels.

The main potential for the reduction of system losses is in the distribution system, which amount to 126.7 TWh as outlined in Table 22.3. In order to estimate the potential in energy saving, the scenario without power factor correction was compared with the scenario with target power factor $\cos\ \varphi = 0.95$, see Table 22.2. The total reactive energy consumption

Table 22.1 Electrical energy consumption in EU-25 for the statistical year 2004; estimated power factor by ZVEI [2].

Consumption sector	Active energy (TWh)	Estimated $\cos\ \varphi$	Reactive energy (Tvarh)	Apparent energy (TVAh)
Industry	1168	0.70	1192	1669
Service	620	0.80	465	775
Subtotal	1788	0.73	1657	2437
Transport	78	0.80	59	98
Domestic	717	1.00	0	717
Others	58	0.80	44	73
Subtotal	853	0.99	102	859
Total	2641	0.83	1759	3173

Table 22.2 Electrical energy consumption in EU-25 for the statistical year 2004; target power factor 0.95 in industry and services [2].

Consumption sector	Active energy (TWh)	Target $\cos\varphi$	Reactive energy (Tvarh)	Apparent energy (TVAh)
Industry	1168	0.95	384	1229
Services	620	0.95	204	653
Subtotal	1788	0.95	588	1882
Transport	78	0.80	59	98
Domestic	717	1.00	0	717
Others	58	0.80	44	73
Subtotal	853	0.99	102	859
Total	2641	0.97	690	2730

in the power system is $E_Q = 1759$ Tvarh and the total current-dependent losses are $E_{PL} = 180$ TWh. In order to compensate the system load as in Table 22.2, reactive energy of $E_Q = 1069$ Tvarh is to be supplied. Based on an estimated annual period of use of $T_{use} = 3600$ h (industrial sector, two shifts of 8 hours each, 5 days per week, 45 weeks per year), reactive power compensation equipment of $Q = 297$ Gvar is to be installed. The losses of capacitor installations including reactor and cabling are estimated as $P_{QL} = 2.4$ W/kvar resulting in losses per year of $E_{QL} = 8.6$ kWh/kvar. The current-dependent system losses are reduced by the compensation to 129 TWh and the additional losses of the compensation are 3 TWh, in total 132 TWh. The loss reduction by improvement of power factor is 48 TWh or 27% of the actual system losses, see Table 22.3. Assuming average CO_2 emissions from energy generation in power stations (in Germany in 2009: 0.575 kg/kWh), the savings on CO_2 emission are in the range of 28 Mt of CO_2 per year.

Table 22.3 Share of losses between different system levels [1, 2].

			Current dependent		Voltage dependent	
System level	Share of losses [1]	Share of losses [2]	%	TWh	%	TWh
Transmission system	20% (52.8 TWh)					
Current dependent		90%	18	47.5	2	5.3
Voltage dependent		10%				
Distribution system	80% (211.2 TWh)					
Current dependent		60%	48	126.7	32	84.5
Voltage dependent		40%				
Total system	100% (264 TWh)	—				
Current dependent			66	174.2	34	89.8
Voltage dependent						

22.4 Summary

Older capacitors, especially in consumer installations and household installations, may contain PCB filling. Special care has to be taken while exchanging these capacitors to avoid any risk of environmental contamination. The use of capacitors reduces system losses and through this the generated energy in power stations. If coal and gas are considered as primary energy sources, the installation of capacitors results in CO_2 saving as well. A study carried out some years ago for Germany indicated that a target power factor of 0.95 will result in a reduction of 28 Mt of CO_2 per year.

References

[1] Commission of the European Communities (2005) Green Paper in Energy Efficiency. COM (2005) 265 final, Brussels, November.
[2] ZVEI (2006) Position Paper on the Green Paper on Energy Efficiency. German Electrical and Electronic Manufacturers' Association, Frankfurt, March.
[3] ZVEI (2008) Energy Efficiency by Power Factor Correction. German Electrical and Electronic Manufacturers' Association, Frankfurt, April.

Symbols and Abbreviations

A	Cross-section of area (e.g. of cables)
B	Susceptance
b	Width
C	Capacitance/electrical load
C_r	Rated capacitance
c	Constant for metering devices
C/k	Threshold level for controlling power capacitors by means of reactive power controller
CO_2	Carbon dioxide
CVS	Consumer vector system
c.t. or CT	Current transformer
$\cos\varphi$	Power factor referring to sinusoidal procedures
$\cos\varphi_1$	Power factor referring to fundamental frequency
$\cos\varphi_a$	Actual power factor
$\cos\varphi_d$	Desired power factor
D	Diameter
d	Thickness of, for example, dielectric
DIN	German standards for industry
e	2.718 28; basis of natural logarithms
E	Energy
EN	European standards
F	Force
f	Frequency
f_{res}	Resonance frequency
f_1	Fundamental frequency
G	Conductance
g_i	Fundamental content (I_1/I) of current
GVS	Generation vector system
HT	High tariff
HV	High voltage
I	Current (rms value)

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I_a	Active component of current
I_{Fe}	Active current losses in iron core of, for example, transformers
I_μ	Magnetizing current
I_r	Reactive component of current
IEA	International Energy Agency
IPE	Internal protected element
i	Instantaneous value of the current
$\hat{\imath}$	Peak value of current
K	Primary terminal of current transformer
k	Ratio of current transformer (c.t.) to secondary terminal of c.t.
k_{PV}	Loss reduction factor
L	Inductance
L	Primary terminal of current transformer
L	Secondary terminal of current transformer
LT	Low tariff
LV	Low voltage
l	Length
ln	natural logarithm (base e)
MV	Medium voltage
N	Number of windings of a coil
n	Revolutions per minute
P	Power
$P_{\max}$	Maximal active power (peak value)
P_r	Rated power
P_{ST}	Threshold of perception of flicker
p	Instantaneous value of power
p	Reactor rate; detuning factor
PCB	Polychlorinated biphenyl
PCC	Point of common coupling
PFC	Power factor control
PFCR	Power factor control relay
Q	Reactive power
q	Instantaneous value of reactive power
R	Resistance (active)
RPC	Reactive power controller
r	Rate
rms	Effective value
S	Apparent power
S_r	Rated apparent power
S''_k	Short-circuit power at PCC
THD-V	Total harmonic distortion referring to the voltage
THD-I	Total harmonic distortion referring to the current
t	Time
U	(Line) voltage
UPS	Uninterruptible power supply
u	Instantaneous value of the voltage

$\hat{u}$	Peak voltage
u_k	Impedance voltage
u_r	Reactive component of the voltage
u_x	Leakage voltage
Δu	Voltage drop
V	Volume
VDE	Association for Electrical, Electronic & Information Technologies
v	Velocity
W	Energy
W_r	Reactive energy
w	Instantaneous value of energy
X	Reactance
x	Variable
Y	Apparent admittance
Z	Apparent resistance
ZVEI	Central Association of Electrical and Electronic Manufacturers
δ	Distance (e.g. in air gap)/angle of loss (capacitor)
ε	Dielectric coefficient
ε_r	Relative dielectric coefficient
ε_0	8.85 pF/m
η	Efficacy factor
κ	Electrical conductivity
λ	Displacement factor
μ_r	Relative permeability
μ_0	Permeability (magnetic field constant)
π	3.141 59
τ	Time constant
υ	Index number referring to harmonics
φ	Phase angle
ψ	Phase angle of network
ω	Equal to $2\pi f$

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