12 Transformers and other Equipment for Switchgear Installations

12.1 Transformers

12.1.1 Design, types and dimensions

The purpose of transformers is to transfer electrical energy from systems of one voltage U_1 to systems of another voltage U_2.

Transformers can be differentiated according to their manner of operation (Fig. 12-1):

1. *Power transformers,* the windings of which are in parallel with the associated systems. The systems are electrically independent. The transfer of power is solely by induction.
2. *Autotransformers,* the windings of which are connected in line (series winding RW and parallel winding PW). The throughput power S_D is transferred partly by conduction and partly by induction.
3. *Booster transformers;* their windings are electrically independent, one winding being connected in series with one system in order to alter its voltage. The other winding is connected in parallel with its associated system (excitation winding EW). The additional power S_Z is transferred purely inductively.

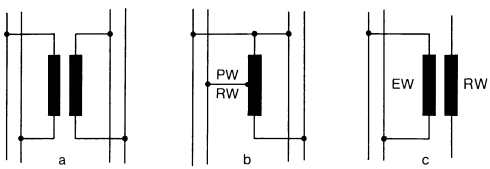


Fig. 12-1

Different types of transformers according to their manner of operation: a) Power transformer, b) Autotransformer, RW Series winding, PW Parallel winding, c) Booster transformer, EW Excitation winding, RW Series winding.

The following distinctions are made according to applications:

1. Transformers for the supply of power DIN EN 60076-1 (VDE 0532 Part 101), such as distribution or main transformers, machine transformers and system-tie transformers,
2. Industrial transformers, such as welding transformers, furnace transformers, starting transformers and converter transformers,
3. Transformers for traction systems,
4. Special transformers, e.g. for testing, protection and control purposes.

Three-phase distribution transformers are covered by standards DIN 42500 (≙ HD 428.151) and DIN 42523 (≙ HD 538.151).

Transformers are divided into the following categories:

1. *Class A:* dry-type transformers (e.g. cast-resin transformers)
   Core and windings are not contained in an insulating liquid. Heat losses are dissipated direct to the ambient air, hence large surface area and low current density.
   Up to approximately 20000 kVA and a maximum of 36 kV.
   ABB resin-encapsulated transformers of the RESIBLOC type are characterized by extremely high mechanical resistance of the windings because of fibre-glass-reinforced resin insulation and a very high resistance to fluctuations in temperature.

2. *Class 0:* oil-immersed transformers
   Core and windings are contained in mineral oil or similarly flammable synthetic liquid with a fire point ≤ 300 °C which is simultaneously a coolant and insulating medium.

3. *Class K*
   Core and windings are contained in a synthetic liquid having a fire point > 300 °C which is also a coolant and insulating medium. In construction, they are much like oil-immersed transformers.

   ABB uses silicone liquid for transformers with ratings of up to 10 000 kVA and service voltages of up to 36 kV.
   Silicone liquid is flame-retardant and non-polluting. Other synthetic liquids (ester) with a fire point > 300 °C may be encountered, besides silicone liquid.

   Askarel is no longer used as a coolant (environmental hazard).

Ratio variability

Ability to vary the ratio is important particularly with main transformers; it is used for matching the service voltage in the event of load fluctuations, for load distribution or for adjusting active and reactive current in interconnected networks, and for voltage correction with electric furnaces, rectifier stations, etc. In the simplest case, this is done with the transformer dead, by altering the connection between winding sections with the aid of extra winding terminals, so-called tappings (normally ± 4 % or ± 5 %).

For *stepwise variation under load,* the tap changer (available in oil-insulated and dry design) is preferably installed at the neutral end of the HV winding with power transformers, and at the series winding with series transformers and autotransformers.

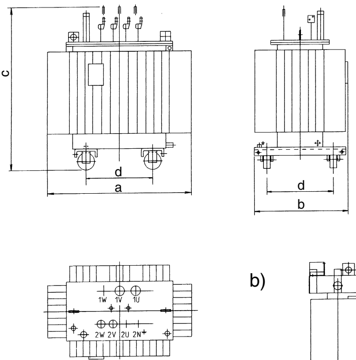
The tap changer, which connects the respective tappings while under load, consists basically of a load switch and a selector (or alternatively just a selector switch) with or without preselection.

The number of tappings and range of adjustment for power transformers of up to 40 MVA and 110 kV are standardized (DIN 42515).

Continuous variation under load can be done with moving windings in the form of a special design as a rotary transformer or moving-coil regulator.

Fig. 12-2 shows an oil-insulated transformer (a) which has the currently preferred hermetically encapsulated design without expansion tank and a resin-encapsulated transformer (b) without enclosure. There are no standards for the dimensions of distribution transformers. Table 12-1 lists the main dimensions of a number of distribution transformers as examples of practical transformer designs with varying technical data from the ABB production range.

a)



b)

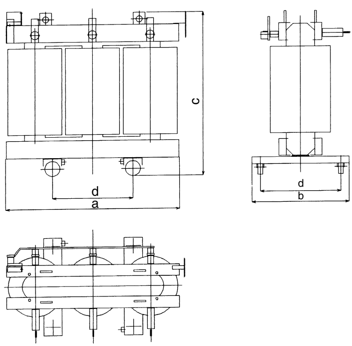


Fig. 12-2

Structural types of distribution transformers

a) hermetically encapsulated oil-insulated transformers

b) RESIBLOC resin-encapsulated transformers without enclosure

Table 12-1

Main dimensions of ABB distribution transformers, as shown in Fig. 12-2
a) Oil-insulated transformers, hermetically encapsulated
b) RESIBLOC resin-encapsulated transformers without enclosure

	Tech. data	Main dimensions in mm			
		a	b	c	d
a)	10 kV, 250 kVA, 4%	1170	740	1440	520
	20 kV, 250 kVA, 4%	1170	770	1510	520
	10 kV, 630 kVA, 6%	1420	870	1440	670
	20 kV, 630 kVA, 6%	1460	930	1525	670
b)	10 kV, 250 kVA, 4%	1110	660	1250	520
	20 kV, 250 kVA, 4%	1350	660	1560	520
	10 kV, 630 kVA, 6%	1500	810	1360	670
	20 kV, 630 kVA, 6%	1560	810	1820	670

12.1.2 Vector groups and connections

Vector groups

The vector group denotes the way in which the windings are connected and the phase position of their respective voltage vectors. It consists of letters identifying the configuration of the phase windings and a number indicating the phase angle between the voltages of the windings.

With three-phase a.c. the winding connections are categorized as follows:

a) Delta (D, d)
b) Star (Y, y)
c) Interconnected star (Z, z)
d) Open (III, iii)

Capital letters relate to the high-voltage windings, lower-case letters to the medium and low-voltage windings. The vector group begins with the capital letter. In the case of more than one winding with the same rated voltage, the capital letter is assigned to the winding with the highest rated power; if the power ratings are the same, to the winding which comes first in the order of connections listed above. If the neutral of a winding in star or interconnected star is brought out, the letter symbols are YN or ZN, or yn or zn, respectively.

To identify the phase angle, the vector of the high-voltage winding is taken as a reference. The number, multiplied by 30° denotes the angle by which the vector of the LV winding lags that of the HV winding. With multi-winding transformers, the vector of the HV winding remains the reference; the symbol for this winding comes first, the other symbols follow in descending order according to the winding's rated voltages.

Example:

For a transformer with three power windings (HV windings 220 kV in neutral connection with brought-out neutral, MV winding 110 kV in neutral connection with brought-out neutral, and LV winding 10 kV in delta connection), if the vectors of the neutral voltage of HV and MV winding are in phase and the vector of the neutral voltage of the LVwinding lags behind them by $5 \cdot 30 = 150°$, the identifying symbols are:

YN, yn 0, d 5.

Preferred connections

Yyn 0 for *distribution transformers.* The neutral point can be loaded continuously with up to 10 % of the rated current, or with up to 25 % of the rated current for a maximum of 1.5 hours. Example: for connecting arc suppression coils.

YNyn 0 with *compensating winding,* used for large system-tie transformers. The neutral point can be loaded continuously with the rated current.

YNd 5 intended for *machine and main transformers* in large power stations and transformer stations. The neutral point can be loaded with the rated current. Arc suppression coils can be connected (delta winding dimensioned for the machine voltage).

Yzn 5 for *distribution transformers,* used up to approx. 250 kVA for local distribution systems. The neutral point can be loaded with the rated current.

Dyn 5 for *distribution transformers* above approx. 315 kVA, for local and industrial distribution systems. The neutral point can be loaded with the rated current.

Ii 0 for *single-phase transformers,* intended for traction power supply or for three-phase banks with very high voltages and powers.

If single-phase transformers are combined to form three-phase banks, the switchgear, instrument transformers and conductor cross-sections must be designed for the voltage and current ratings given in Table 12-2.

Table 12-2

Values of Ur and Ir for transformers of connection III iii

Connection of windings	Rated voltage U_r	Rated current I_r
Star	$\sqrt{3}\ U_{ph}$	I_{ph}
Delta	U_{ph}	$\sqrt{3}\ I_{ph}$

U_{ph} phase (conductor/earth) voltage, I_{ph} phase (winding) current.

Identification and arrangement of terminals

Terminations of the windings (coils) brought out in the same winding sense are denoted 1U1,1V1,1W1 for the primary windings and 2U1, 2V1, 2W1 for the secondary windings. The terminations at the other ends of the windings, brought out in the inverse winding sense, are designated 1U2, 1V2, 1W2 for the primary windings and 2U2, 2V2, 2W2 for the secondary windings.

As a rule, the terminals of a transformer (1U,1V,1W for the primary side and 2U, 2V, 2W for the secondary side) are arranged from right to left as viewed from the low-voltage side, with their inscriptions visible from the low-voltage side, Fig. 12-3.

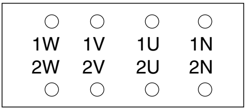


Fig. 12-3

Identification and arrangement of the terminals of a transformer (in accordance with DIN 42402)

12.1.3 Impedance voltage, voltage variation and short-circuit current withstand

Voltage drops

The *impedance voltage* U_{kr} *is* defined as that voltage having the rated frequency which must be applied to the primary side of a transformer so that the rated current I_r flows when the secondary terminals are short-circuited. Since only the short-circuit impedance is present in the circuit,

$$U_{kr} = \sqrt{3} \cdot I_r \cdot Z_k.$$

The rated impedance voltage is usually stated as a percentage of the voltage rating U_r of the winding to which the voltage is applied:

$$u_{kr} = \frac{U_{kr}}{U_r} \cdot 100\ \%.$$

The impedance voltage is composed of the ohmic voltage drop (U_R, u_R) which is in phase with the current, and the reactive voltage (U_x, u_x), which leads the current in time by 90°.

Ohmic voltage drop:

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{\text{Impedance losses at rated power}}{\text{rated power}}\ 100\ \%.$$

Reactive voltage:

$$u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2}.$$

In the case of a partial load, the short-circuit voltage U_k is proportional to the load on the transformer:

$$u_k = u_{kr} \frac{I}{I_r} = u_{kr} \frac{S}{S_r}$$

For distribution transformers, according to DIN 42500 a rated impedance voltage u_{kr} is allocated to each power rating S_r, Table 12-3.

Table 12-3

Rated impedance voltage u_{kr}

Rated output S_r in kVA[1)]										u_{kr}
50	(63)	100	160	(200)	250	(315)	400	(500)	630	4 %
630	(800)	1000	(1250)	1600	(2000)	2500				6 %

[1)] Rated outputs not in brackets are preferred.

Transformers with a rated impedance voltage u_{kr} = 4 % are used mainly in distribution networks in order to keep the voltage drop small.

Transformers with a rated impedance voltage u_{kr} = 6 % are preferably to be used in industrial networks and in high-power distribution networks in order to limit the short-circuit stress. The rated impedance voltages of medium-size and large transformers are even higher so as to achieve sufficient short-circuit strength.

Voltage variation

The voltage variation between no-load and a symmetrical load of any magnitude for any cos φ can be calculated from the rated impedance voltage and the impedance losses at rated load. It is denoted u_φ, and referred to the rated voltage.
For a given part load $a = S/S_r$ and a given power factor cos φ,

$$u_\varphi = a \cdot u'_\varphi + \frac{1}{2} \cdot \frac{(a \cdot u''_\varphi)^2}{10^2} + \frac{1}{8} \cdot \frac{(a \cdot u''_\varphi)^4}{10^6} + \ldots^{1)}$$

where

$$u'_\varphi = u_{Rr} \cdot \cos\varphi + u_{Xr} \cdot \sin\varphi$$

and

$$u''_\varphi = u_{Rr} \cdot \sin\varphi - u_{Xr} \cdot \cos\varphi$$

The actual voltage at the terminals on the output side of the loaded transformer will then be

$$U_a = U_r \left(1 - \frac{u_\varphi}{100\ \%}\right)$$

Example:

Find the full-load voltage U_a for a transformer with rated load on the output side at cos φ = 0.8 (sin φ = 0.6).

Rated output:	S_r = 2500 kVA,
Impedance losses:	P_{kr} = 24 kW,
Impedance voltage:	u_{kr} = 6 %.

$$u_{Rr} = \frac{P_{kr}}{S_r} \cdot 100\ \% = \frac{24\ \text{kW}}{2500\ \text{kVA}}\ 100\ \% = 0.96\ \%$$

$$u_{xr} = \sqrt{u_{kr}^2 - u_{Rr}^2} = \sqrt{6^2 - 0.96^2}\ \% = 5.923\ \%$$

$$u'_\varphi = u_{Rr} \cos\varphi + u_{xr} \sin\varphi = 0.96 \cdot 0.8 + 5.923 \cdot 0.6 = 4.32\ \%$$

$$u''_\varphi = u_{Rr} \sin\varphi - u_{xr} \cos\varphi = 0.96 \cdot 0.6 - 5.923 \cdot 0.8 = -4.16\ \%$$

$$u_\varphi = u'_\varphi + \frac{1}{2}\frac{(u''_\varphi)^2}{10^2} = 4.32 + \frac{1}{2} \cdot \frac{(-4.16)^2}{10^2} = 4.4\ \%.$$

$$U_a = U_r\ (1 - \frac{u_\varphi}{100\ \%}) = 0.965 \cdot U_r.$$

1) If u_{kr} < 20 % the third summand can be disregarded. The second summand may also be disregarded if u_{kr} < 4 %.

12

The criterion for the short-circuit is a reference impedance composed of the impedances of the network (Z_Q) and transformer (Z_k). This is

$$I_{k3p} = \frac{U_r}{\sqrt{3}|Z_Q + Z_k|} \approx \frac{I_k}{u_{kr}\ \%} \cdot 100\ \%.$$

With distribution transformers of ratings up to 3150 kVA and $Z_Q \leq 0.05 \cdot Z_k$, the network impedance Z_Q can usually be disregarded.

The short-circuit impedance limits the short-circuit current. Thermal stress is governed by the sustained short-circuit current I_k. The maximum permissible short-circuit duration is 2 s as per DIN 57532-5 (VDE 0532 Part 5), unless otherwise specified by the customer.

With transformers of vector groups Dy and Yd, the single-phase sustained short-circuit current is about the same as the three-phase value. At windings in interconnected star connection, the single-phase sustained short-circuit current can reach roughly 1.4 times the three-phase value, as its zero-sequence impedance is usually very small.

Table 12-4

Reference impedances for two-winding transformers (to VDE 0532 Part 5)

Rated power kVA	Typical values of z_k (or u_{kr}) %	Maximum system voltage kV	Typical values of reference system fault level S_{kQ} 1) MVA
to 630	4.0	7.2 12 17.5 and 24	500
from 630 to 1 250	5.0	36	1 000
from 1 250 to 3 150	6.25	52 and 72.5	3 000
from 3 150 to 6 300	7.15	100 and 123	6 000
from 6 300 to 12 500	8.35	145 and 170	10 000
from 12 500 to 25 000	10.0	245	20 000
from 25 000 to 200 000	12.5	300	30 000
		420	40 000

1) If not specified

12.1.4 Losses, cooling and overload capacity

Transformer losses

Fig. 12-4 shows the usual values of no-load losses P_0 and impedance loss P_k for two-winding transformers. The total losses P_v of a transformer at any loading a = S/S_r can be calculated from the relationship:

$$P_v = P_0 + a^2 P_k.$$

The no-load losses P_0 are composed of the hysteresis losses and eddy-current losses in the iron, and leakage losses in the dielectric. These losses are not affected by the load.

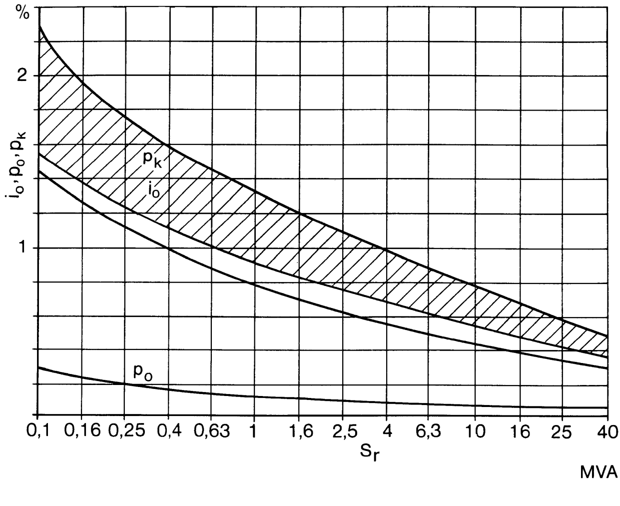


Fig. 12-4

Typical values for two-winding transformers. i_0 (percentage no-load current), p_0 (percentage no-load losses) and p_k (percentage impedance losses) as a function of rated power S_r.

Power range 2.5 MVA to DIN 42500

Power range 2 to 10 MVA to DIN 42504 and 12.5 to 80 MVA to DIN 42508
Upper limit of p_k for rated high voltage 123 kV,
Lower limit of p_k for rated high voltage 36 kV.

The *impedance losses* P_k comprise the copper losses in the windings and the additional losses. Impedance losses, which are caused by eddy currents inside and outside the windings, vary as the square of the load. The efficiency η of a transformer at any load is determined sufficiently accurately from

$$\eta = 100\,\% - \frac{P_0 + a^2\,P_k}{a \cdot S_r \cdot \cos\varphi + P_0} \cdot 100\,\%$$

Example

Find the efficiency of a 250 kVA transformer for 20/0.4 kV with P_0 = 610 W and P_k = 4450 W at half-load (a = 0.5) and cos φ = 0.8.

$$\eta = 100\,\% - \frac{0.61 + 0.5^2 \cdot 4\,45}{0.5 \cdot 250 \cdot 0.8 + 0.61} \cdot 100\,\% = 98.29\,\%.$$

In order to assess a transformer, however, it is more informative to evaluate the losses and their distribution, rather than the efficiency.

Cooling

The method of cooling is stated by the manufacturer in the form of four capital letters, the first two letters denoting the coolant and the manner of circulation for the winding, and the last two letters indicating the coolant and manner of circulation for cooling the outside of the transformer. These code letters are explained in Table 12-5.

Table 12-5

Key to cooling systems

Coolant	Symbols
Mineral oil or equiv. synth. liquid with fire point ≤ 300 °c	O
Other synth. liquids	K
Gas with fire point > 300 °C	G
Air (dry-type transformers)	A
Water	W

Coolant circulation	Symbols
Natural circulation	N
Forced circulation (non-directed)	F
Forced circulation (directed)	D

Examples

AN = Dry-type transformer with natural air circulation,
ONAN = Oil-immersed self-cooled transformer.

Overload capacity to DIN 57536 (VDE 0536)

The maximum time for which transformers can be overloaded at a given bias load and coolant temperature is shown in Fig. 12-5 for air-cooled oil-immersed transformers in the case of two different loads recurring regularly in a 24-hour cycle.

In the diagram:

K_1 Initial load as a proportion of rated power,
K_2 Permitted overload as a proportion of rated power (normally > 1),
t Duration of K_2 in h,
Θ_a Coolant temperature in °C.

Hence

$$K_1 = \frac{S_1}{S_r};\; K_2 = \frac{S_2}{S_r};\; \frac{K_2}{K_1} = \frac{S_2}{S_1}$$

Here, S_1 is the initial load, S_2 the maximum permitted load and S_r the rated power. Under normal circumstances, K_2 should not exceed 1.5.

Example:

Transformer 1250 kVA with ONAN cooling. Bias load 750 kVA. What is the maximum permitted load over 4 hours at 20 °C?

$K_1 = 0.6$; t = 4 h. Fig. 12-5a yields $K_2 = 1.29$.

$S_2 = K_2 \cdot S_r = 1.29 \cdot 1250$ kVA = 1612 kVA.

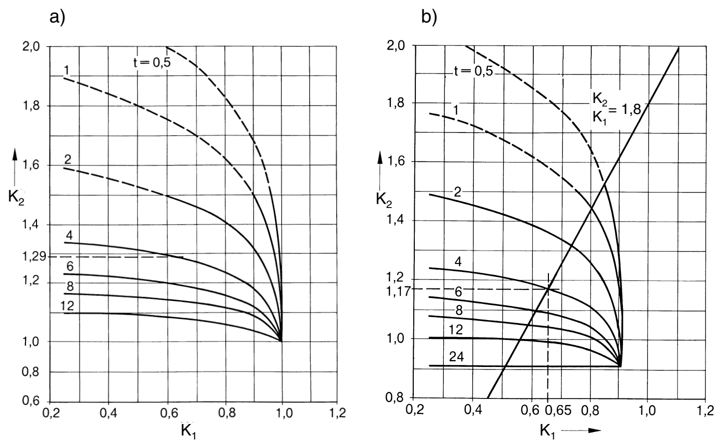


Fig. 12-5

Transformer with ONAN and ONAF cooling. Values of K_2 for given values of K_1 and t (in hours), a) $\Theta_a = 20$ °C, b) $\Theta_a = 30$ °C

For a given case of transformer loading, the power rating S_r can be calculated from:

$$S_r = \frac{S_1}{K_1} = \frac{S_2}{K_2}$$

Example:

At Θ_a = 30 °C, a transformer with ONAN cooling is to run for 4 hours at 450 kVA and otherwise at 250 kVA. What power rating is required?

$$S_1 = 250 \text{ kVA}, \quad t_1 = 20 \text{ h}; \qquad S_2 = 450 \text{ kVA}, \quad t_2 = 4 \text{ h}.$$

$$\frac{S_2}{S_1} = \frac{450}{250} = 1.8 = \frac{K_2}{K_1}$$

From Fig. 12-5 b for K_2/K_1 = 1.8 when t = 4 h: K_1 = 0.65; K_2 = 1.17.

$$S_r = \frac{450}{1.17} = \frac{250}{0.65} = 385 \text{ kVA} \rightarrow 400 \text{ kVA}.$$

12.1.5 Parallel operation

Transformers are in parallel operation if they are connected in parallel on at least two sides. A distinction is made between busbar interconnection and network interconnection. The following conditions must be satisfied in order to avoid dangerous transient currents:

1. vector groups should have the same phase angle number; terminals of the same designation must be connected together on the HV and LV sides; Exception: Phase angle numbers 5 and 11 (Table 12-6);
2. the ratios should be as similar as possible, i.e. the same rated voltages on the HV and LV sides;
3. approximately the same impedance voltages u_k maximum permissible discrepancies ± 10 %. In the event of larger differences, an inductance (reactor) can be connected ahead of the transformer with the lower impedance voltage.
4. rated output ratio smaller than 3:1.

Table 12-6 Parallel operation of transformers with phase angle numbers 5 and 11

Phase angle number required	Phase angle number available		Connection to conductors HV side L1	L2	L3	Connection to conductors LV side L1	L2	L3
5	5		1U	1V	1W	2U2	2V2	2W2
5	11		1U	1W	1V	2W1	2V1	2U1
		or	1W	1V	1U	2V1	2U1	2W1
		or	1V	1U	1W	2U1	2W1	2V1
11	11		1U	1V	1W	2U1	2V1	2W1
11	5		1U	1W	1V	2W2	2V2	2U2
		or	1W	1V	1U	2V2	2U2	2W2
		or	1V	1U	1W	2U2	2W2	2V2

Load distribution of parallel transformers with different rated impedance voltages

Transformers connected in parallel assume a partial load such that all the transformers have the same average impedance voltage. If the impedance voltage of a transformer is referred to an output other than its rated output, its magnitude varies in accordance with the output. A 100 kVA transformer with u_{kr} = 4 % has at 60 kVA an impedance voltage u_k of 0.6 · 4 = 2.4%.

Example:

transformer 1:	S_{r1} = 100 kVA,	u_{kr1} = 4.0 %
transformer 2:	S_{r2} = 250 kVA,	u_{kr2} = 6.0 %
transformer 3:	S_{r3} = 500 kVA,	u_{kr3} = 4.5 %
total	S = 850 kVA	

We have:

$$\frac{S}{u_k} = \frac{S_{r1}}{u_{k1}} + \frac{S_{r2}}{u_{k2}} + \ldots$$

The resultant impedance voltage is then:

$$u_k = \frac{S}{\frac{S_{r1}}{u_{kr1}} + \frac{S_{r2}}{u_{kr2}} + \frac{S_{r3}}{u_{kr3}}} = \frac{850}{\frac{100}{4} + \frac{250}{6} + \frac{500}{4.5}} = 4.78\ \%$$

The power assumed by the individual transformers is:

$$S_1 = S_{r1}\frac{u_k}{u_{kr1}} = 100 \cdot \frac{4.78}{4} = 120\ \text{kVA}$$

$$S_2 = S_{r2}\frac{u_k}{u_{kr2}} = 250 \cdot \frac{4.78}{6} = 199\ \text{kVA}$$

$$S_3 = S_{r3}\frac{u_k}{u_{kr3}} = 500 \cdot \frac{4.78}{4.5} = 531\ \text{kVA}$$

$$S_{tot} = S_1 + S_2 + S_3 = 120\ \text{kVA}$$

Transformer 1 is thus overloaded by 20 % and transformer 3 by 6 %. Since the individual transformers should not be subjected to overload, the transformers may only assume a partial load such that the impedance voltage of each is u_k = 4 %, as in the case with transformer 1. Therefore,

$$S_1 = 100 \cdot \frac{4}{4} = 100\ \text{kVA}$$

$$S_2 = 250 \cdot \frac{4}{6} = 167 \text{ kVA}$$

$$S_3 = 500 \cdot \frac{4}{4.5} = 444 \text{ kVA}$$

$$S_{tot} = S_1 + S_2 + S_3 = 711 \text{ kVA}$$

If this output is not sufficient, another 160 kVA transformer with u_{kr} = 4 % will have to be installed.

Effect of dissimilar transformation ratios of transformers connected in parallel

Dangerous transient currents can occur if transformers with different voltages between taps are operated in parallel. Disregarding any dissimilarity in impedance phase angle φ_k, the voltage difference Δu proportional to the difference in ratio drives through both sides a circulating current of

$$I_a = \frac{\Delta u}{u_{k1}/I_{r1} + u_{k2}/I_{r2}}$$

If, for example, $u_{k1} = u_{k2} = 6\ \%$, $I_{r1} = 910$ A, $I_{r2} = 1445$ A und $\Delta u = 4\ \%$, then

$$I_a = \frac{4\ \%}{6\ \% / 910\ A + 6\ \% / 1445\ A} = 377.34\ A.$$

This balancing current is superimposed on the transformer load currents that are supplied to the network. It is added to the current of that transformer which has the greater secondary no-load voltage.

12.1.6 Protective devices for transformers

Overcurrent time relays respond to short circuits; they trip the circuit-breakers.

Thermal relays respond to unacceptable temperature rises in the transformer, and signal overloads.

Make-proof percentage differential relays detect internal short circuits and faults, including those on lines between the current transformers; they trip the appropriate transformer breakers, but do not respond to the inrush current of a sound transformer.

Buchholz relays detect internal damage due to gassing or oil flow; they signal minor disturbances and trip the breaker if the trouble is serious.

Temperature monitors signal when a set temperature is reached, or trip circuit-breakers.

Dial-type telethermometers indicate the temperature in the transformer's topmost oil layer with maximum and minimum signal contacts.

Oil level alarms respond if the oil level is too low.

Oil flow indicators detect any disruption in the circulation in closed-circuit cooling and trigger an alarm.

Airflow indicators detect any break in the flow of forced-circulation air, and trigger an alarm.

12.1.7 Noise levels and means of noise abatement

Since transformers are located in or near residential areas, the noise they produce must be determined so as to assess the need for any countermeasures.

The noise of transformers is defined as the A-weighted sound pressure level measured in dB (A) at a specified measuring surface with a sound level meter, and then converted to a sound power level with the following formula:

$$L_{WA} = L_{PA} + L_S$$

In which:

L_{WA} A-weighted sound power level in dB
L_{PA} A-weighted sound pressure level in dB
L_S Measuring-surface level in dB

The measurements must be performed according to DIN EN 60551 (VDE 0532 Part 7). For transformers with water cooling or fan-less air cooling, at least 6 measurements must be taken at a distance of 0.3 m from the surface of the transformer. For transformers with other cooling systems, the relevant measurement regulations as per DIN EN 60551 (VDE 0532 Part 7) apply.

Table 12-7

A-weighted sound power level in dB (A) for transformers up to a rated power of 2.5 MVA

Rated power	Oil-insulated transformers as per DIN 42500			Resin-encapsulated transformers
kVA	List A'	B'	C'	as per DIN 42523[1)]
50	55	50	47	–
100	59	54	49	59 (51)
160	62	57	52	62 (54)
250	65	60	55	65 (57)
400	68	63	58	68 (60)
630	70	65	60	70 (62)
1 000	73	68	63	73 (65)
1 600	76	71	66	76 (68)
2 500	81	76	71	81 (71)

[1)] Values in parentheses for the reduced series

The causes and effects of the noise produced by transformers and their cooling systems are so diverse that it is not possible to recommend generally applicable noise abatement measures. Each case must be carefully investigated as necessary.

Possible measures include:

Actions by the transformer manufacturer to reduce airborne and structure-borne noise.

Structural measures against airborne noise, e.g. sound-absorbent walls or enclosures.

Anti-vibration treatment of the foundations to reduce transmission of structure-borne noise, e.g. spring-mounted supporting structure.

12.2 Current-limiting reactors EN 60289 (VDE 0532 Part 20)

12.2.1 Dimensioning

Current-limiting reactors (series reactors) to DIN VDE 0532, Part 2 are reactances employed to limit short-circuit currents. They are used when one wishes to reduce the short-circuit power of networks or installations to a value which is acceptable with regard to the short-circuit strength of the equipment or the breaking capacity of the circuit-breaker.

Since the reactance of a series reactor must remain constant when short-circuit currents occur, only the air-core type of construction is suitable[1)]. If iron cores were used, saturation of the iron brought about by the short-circuit currents would cause a drop in the inductance of the coil, thus seriously reducing the protection against short circuits.

Voltage drop and voltage variation

The rated impedance is the impedance per phase at rated frequency. The resistance of a current-limiting reactor is negligible and in general, amounts to not more than some 3 % of the reactance X_L.

The rated voltage drop ΔU_r is the voltage induced in the reactor when operating with rated current and rated reactance:

$$\Delta U_r = I_r \cdot X_L$$

When referred to the nominal voltage of the system, the rated voltage drop is denoted Δu_r and usually stated in %:

$$\Delta u_r = \frac{\Delta U_r \cdot \sqrt{3}}{U_n} 100\ \%.$$

Example:

A reactor in a three-phase system with a rated voltage of 10 kV has a reactance of 5 %. Its rated current is 400 A. This statement indicates that the voltage drop at the reactor is 5 % of the system phase-to-earth voltage. The absolute value in volts is

$$\Delta U_r = \frac{\Delta U_r \cdot U_n}{\sqrt{3} \cdot 100\ \%} = \frac{5\ \% \cdot 10\ 000\ \text{V}}{\sqrt{3} \cdot 100\ \%} = 289\ \text{V}.$$

1) Air-core reactors can cause the frequency of the recovery voltage to assume extremely high values (150 to 250 kHz). Reduction of these natural frequencies to the values for circuit-breakers defined by VDE 0670 Part 104 can be achieved by fitting capacitors.

For given values of reactance and current, the voltage variation U_φ in the network, i.e. the difference between the network voltage before and after the reactor, is also dependent on cos φ, Fig. 12-6. Thus, whereas the voltage difference U_φ across the reactor is small under normal operating conditions, it increases in the event of a short circuit

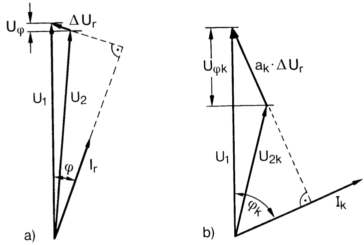
1. in proportion to the short-circuit current and

2. with the increase in phase displacement angle under fault conditions.

Fig. 12-6

Vector diagram of a reactor:

a) Normal operation
b) Short-circuit operation
U_1 System voltage before reactor
U_2 System voltage after reactor
U_φ Voltage variation in system



According to Fig. 12-6, for a given load a= I/I_r and a given power factor cos φ

$$U_\varphi = a \cdot \Delta\, U_r \cdot \cos\,(90\,° - \varphi)$$

or $$u_\varphi = a \cdot \Delta\, u_r \cdot \sin\,\varphi.$$

Example:

At a power factor of cos φ = 0.8 and rated current, a reactor with $\Delta\, u_r$ = 6 % causes a voltage variation in the network of u_φ = 6 % • 0.6 = 3.6 %.

If large motors are connected after reactors and the current ratings of the motor and the reactor are of the same order of magnitude, account must be taken of the voltage drop due to the large starting current of the motor. The drop must not be so large as to endanger the safe run-up of the motor.

Inherent power and throughput power

The inherent power of a reactor is the product of the voltage drop $\Delta\, U_r$ and the rated current I_r.

$$S_E = 3 \cdot \Delta\, U_r \cdot I_r \text{ (three-phase).}$$

The throughput of a reactor is the product of the line-to-earth voltage $U_n/\sqrt{3}$ and the rated current I_r.

$$S_D = \sqrt{3} \cdot U_n \cdot I_r \text{ (three-phase).}$$

Selection of a current-limiting reactor

If the given short-circuit power S''_{k1} of a grid system is to be reduced to a value of S''_k by fitting a reactor, its required percentage rated voltage drop is

$$\Delta\, u_r = 1.1 \cdot 100\,\% \cdot S_D \cdot \frac{S''_{k1} - S''_{k2}}{S''_{k1} \cdot S''_{k2}}.$$

12

Example:

$$U_n = 6\ \text{kV},\quad I_r = 600\ \text{A};$$
$$S''_{k1} = 600\ \text{MVA},\quad S''_{k2} = 100\ \text{MVA};$$

$$\Delta u_r = 1.1 \cdot 100\ \% \cdot \sqrt{3} \cdot 6\ \text{kV} \cdot 0.6\ \text{kA}\ \frac{600\ \text{MVA} - 100\ \text{MVA}}{600\ \text{MVA} \cdot 100\ \text{MVA}} = 5.72\ \%.$$

In practice, one will select the next-highest standardized value, 6 % in this instance.

If the short-circuit power S''_{k1} before a reactor is given, and its percentage rated voltage drop is Δu_r, the short-circuit power S''_{k2} after the reactor is:

$$S''_{k2} = \frac{1.1 \cdot 100\ \% \cdot S_D \cdot S''_{k1}}{1.1 \cdot 100\ \% \cdot S_D + \Delta u_r \cdot S''_{k1}}.$$

Taking the values of the example above, this yields:

$$S''_{k2} = \frac{1.1 \cdot 100\ \% \cdot \sqrt{3} \cdot 6\ \text{kV} \cdot 0.6\ \text{kA} \cdot 600\ \text{MVA}}{1.1 \cdot 100\ \% \cdot \sqrt{3} \cdot 6\ \text{kV} \cdot 0.6\ \text{kA} + 6\ \% \cdot 600\ \text{MVA}} = 96\ \text{MVA}.$$

12.2.2 Reactor connection

The scheme shown in Fig. 12-7 under a), with the reactors in the tee-offs, is the one most commonly used. The circuit shown in b), with the reactors in the feeder, is often chosen for reasons of saving space. For the same degree of protection, the costs of purchase and operation are higher than with reactors in the branches.

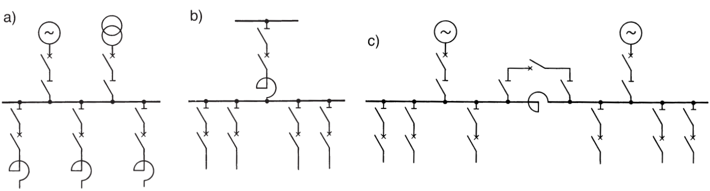


Fig. 12-7

The most common reactor connections:
a) Feeder connection, b) Tee-off connection, c) Busbar sectionalizer connection.

In power stations with a high short-circuit power, it is usual to fit busbar sectionalizing reactors together with bypass circuit-breakers, as shown in c). In this way, a permanent connection is established between the busbars, although in the event of a fault, when the circuit-breaker opens, the short-circuit power is limited approximately to that of the individual systems.

It is even better to use I_s-limiters (Section 8.1.6) instead of circuit-breakers for bypassing reactors, because these devices interrupt the bypass without any delay and therefore prevent hazardous peak current values from occurring.

12.2.3 Installation of reactors

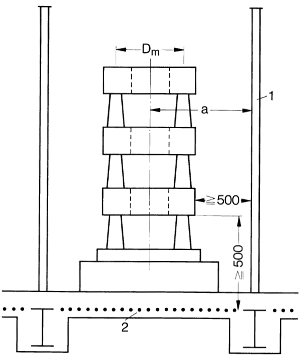
When installing reactors, care must be taken to ensure that the heat losses occurring during operation are dissipated by adequate ventilation. As a rough estimate, one can assume a fresh air requirement of 4 to 5 m^3/min per kilowatt of heat loss. The air flow cross-sections necessary in the rooms can be calculated more accurately using the method described in Section 4.4.2 for transformers.

Care must also be taken that reactors are situated sufficiently far away from neighbouring metal parts to ensure that these are not heated excessively by eddy currents.

Reactors should not be situated at distances of less than 500 mm from constructional items of steel, and steel reinforcement in ceilings, floors and walls. If the floor is steel-reinforced, the reactor must be placed on a concrete pedestal, Fig. 12-8.

Fig. 12-8

Installation of a current-limiting reactor: D_m mean diameter of reactor, a distance between centre line of reactor and metal item
1 Steel-reinforced wall
2 Reinforcing bars
(dimensions in mm)



With cell enclosures of non-magnetic materials (aluminium alloys), the minimum clearance for the highest equipment voltage in question (DIN VDE 0101) is sufficient. Closed structures (short-circuit loops) with a good electrical conductivity must be avoided in the vicinity of strong magnetic fields. If necessary, the short-circuit loop should be split and the junction joined by means of non-conducting material to prevent excessive heating by circulating currents.

If one is forced to use magnetic materials, the distance between reactor and metal structure should be selected so that under rated conditions, the root-mean-square value of the magnetic field strength does not exceed 20 A/cm. The field strength is calculated as

$$H = 0.1 \cdot \frac{I_r \cdot w \cdot D_m}{a^2}$$

Here, I_r rated current in A, w number of turns in reactor, for D_m and a, see Fig. 12-8.

12.3 Capacitors

12.3.1 Power capacitors

The term power capacitor is chiefly applied to capacitors having a rated frequency of 50 or 60 Hz which compensate the reactive power at points of heavy demand in public and industrial networks. This general designation also includes “furnace capacitors” and “medium-frequency capacitors”, which cover the high reactive power requirement of melting furnaces and inductive heating coils, and also “welding machine capacitors” and “fluorescent lamp capacitors” used for compensating welding transformers and the ballasts of fluorescent lamps. The design of power capacitors is regulated by the following standards: DIN VDE 0560-1 (VDE 0560 Part 1), and DIN EN 60831-1 (VDE 0560 Part 46) – self-restoring up to 1000 V –, DIN EN 60931-3 (VDE 0560 Part 45) – non-self-restoring up to 1000 V – and DIN EN 60871-1 (VDE 0560 Part 410) – over 1000 V –.

The reactive power of a capacitor is determined by its capacitance, the rms value of the operating voltage and the system frequency:

$$Q_c = U^2 \cdot \omega \cdot C.$$

The rated power of a capacitor as stated on its nameplate is always in relation to its rated voltage U_r and rated frequency f_r.

In three-phase networks, the capacitors, always three of the same size, are connected in either star or delta. If

C_1 is the capacitance in one phase with star connection, and

C_{12} is the capacitance in one phase with delta connection,

then for the same reactive power:

$$C_1 = 3\,C_{12}.$$

The temperature range for power capacitors is specified by the temperature classes (DIN EN 60831-1, Table 1). The following temperature values are applicable for the permissible ambient temperatures, e.g. for the -25°C class (preferred temperature class),

maximum:	50 °C,
max. average over 24 h:	40 °C,
max. average over 1 year:	30 °C,
minimum:	-25 °C.

Voltage and frequency increases and total harmonic distortion of the voltage or the current place additional stress on capacitors.

Capacitors must be able to carry continuously 1.3 times the current flowing with sinusoidal rated voltage and frequency at an ambient air temperature corresponding to its temperature class. With this loading, the voltage must not be higher than 1.1 U_r, no account being taken of transient overvoltages.

If the limiting conditions stated above are exceeded, the chosen capacitor must be replaced by one with a higher voltage rating and a rated power according to the equation

$$Q_{r2} = Q_{r1}\,(U_{r2}/U_{r1})^2.$$

Where such a capacitor is directly connected to the system, the connection lines and the switching and protection devices must be rated correspondingly higher. However, this does not ensure that the system conditions are compatible for other consumers. For this reason, in most cases it is better to include inductor-capacitor units.

When selecting the switchgear apparatus, protective devices and conductors, attention must be paid to the possibility of overloading mentioned above. Taking account of the permissible difference in capacitance, this is $(1.1 \cdot 1.3) = 1.43$ times the capacitor current rating.

HRC fuses serve only as short-circuit protection and do not provide adequate protection against overcurrents. Bimetal and secondary thermal relays are recommended as thermal protection for capacitor banks of above 300 kvar. The tripping current of these relays should be set to 1.43 times the rated current of the capacitor (capacitor bank). Protection by means of overcurrent relays does not at the same time provide protection against overvoltages.

All capacitor installations must be connected direct to a means of discharge, without intervening isolators or fuses. Low-voltage capacitors must discharge to a residual voltage $\leq$ 75 V within 3 minutes. A maximum discharge time of 10 minutes is stipulated for high-voltage capacitors.

The residual voltage at the capacitator must not exceed 10 % of the nominal voltage before switching on.

When capacitors are connected in star, the neutral point must not be directly earthed. Earthing via surge arresters (blow-out fuses) is permissible.

For installation, connection and special protective measures, note must be taken of specifications DIN VDE 0100, DIN VDE 0101, DIN VDE 0105 and the “Technical connection requirements for power installations” of VDEW.

12.3.2 Compensation of reactive power

Only the active power produced by the active current is utilized at the point of consumption. The reactive power produced by the reactive current does not contribute to the conversion into useful power and is therefore not counted by the active power meter. However, the reactive power has an unfavourable effect on the electrical equipment in that it constitutes an additional load on generators, transformers and conductors. It gives rise to additional voltage drops and heat losses.

Static reactive-power (var) compensation in systems with the aid of thyristors is dealt with in Section 11.6.

It is economically sound to draw the reactive power from capacitors, Fig. 12-9. These are located in the vicinity of the largest reactive loads (motors and transformers) in order to relieve the transmission networks, including transformers and generators, from the corresponding share of the reactive current. If the capacitors are properly positioned, by reducing the reactive current in this way, it is possible in many instances to connect additional loads to existing supply systems without having to increase the power or extent of the network.

Fig. 12-10 shows the reactive power before compensation with $Q_1 = P \cdot \tan \varphi_1$ and after compensation with $Q_2 = P \cdot \tan \varphi_2$, where φ_2 is the phase displacement angle of the desired $\cos \varphi_2$. The capacitor rating required for this is

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

Table 12-8 provides an aid to calculation.

Example:

A motor draws active power of P = 60 kW from a system at $\cos \varphi = 0.6$. Since $\tan \varphi = 1.333$, the reactive power consumed by the motor is $Q = 60 \cdot 1.333 = 80$ kvar.

If one wishes to compensate this reactive power to $\cos \varphi = 1$ by means of a capacitor, the capacitor must also have a power rating of 80 kvar. In most cases, such extensive compensation, to $\cos \varphi = 1$, will not be necessary. If a power factor of $\cos \varphi = 0.8$ is sufficient in this particular instance, the capacitor rating can be calculated as follows:

$\cos \varphi_1 = 0.6$; $\tan \varphi_1 = 1.333$; desired $\cos \varphi_2 = 0.8$; $\tan \varphi_2 = 0.750$:

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

$= 60 (1.333 - 0.75) = 60 \cdot 0.583 = 35$ kvar.

Thus the capacitor only has to be sized for this reactive power.

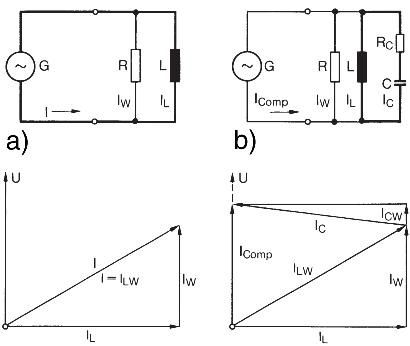


Fig. 12-9
Active and reactive currents in an electrical installation:
a) uncompensated,
b) compensated with capacitors.
With full compensation, the generator G supplies only the current I_w for the purely active load R, and active current I_{cw} for the capacitor loss resistance R_c.

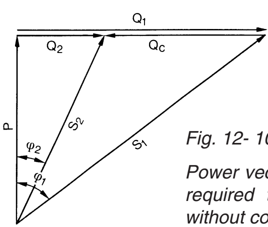


Fig. 12- 10

Power vector diagram for determining the capacitor rating Q_c required to compensate reactive power; Index 1: Values without compensation, Index 2: Values with compensation.

Table 12-8

To determine the factor ($\tan \varphi_1 - \tan \varphi_2$) for calculating reactive power at different power factors

Existing $\cos \varphi_1$	Desired power factor $\cos \varphi_2$ 0.7	0.75	0.8	0.82	0.84	0.86	0.88	0.9	0.92	0.94	0.98
0.30	2.16	2.30	2.42	2.48	2.53	2.59	2.65	2.70	2.76	2.82	2.89
0.35	1.66	1.80	1.93	1.98	2.03	2.08	2.14	2.19	2.25	2.31	2.38
0.40	1.27	1.41	1.54	1.60	1.65	1.70	1.76	1.81	1.87	1.93	2.00
0.45	0.97	1.11	1.24	1.29	1.34	1.40	1.45	1.50	1.56	1.62	1.69
0.50	0.71	0.85	0.98	1.04	1.09	1.14	1.20	1.25	1.31	1.37	1.44
0.52	0.62	0.76	0.89	0.95	1.00	1.05	1.11	1.16	1.22	1.28	1.35
0.54	0.54	0.68	0.81	0.86	0.92	0.97	1.02	1.08	1.14	1.20	1.27
0.56	0.46	0.60	0.73	0.78	0.84	0.89	0.94	1.00	1.05	1.12	1.19
0.58	0.39	0.52	0.66	0.71	0.76	0.81	0.87	0.92	0.98	1.04	1.11
0.60	0.31	0.45	0.58	0.64	0.69	0.74	0.80	0.85	0.91	0.97	1.04
0.62	0.25	0.39	0.52	0.57	0.62	0.67	0.73	0.78	0.84	0.90	0.97
0.64	0.18	0.32	0.45	0.51	0.56	0.61	0.67	0.72	0.78	0.84	0.91
0.66	0.12	0.26	0.39	0.45	0.49	0.55	0.60	0.66	0.71	0.78	0.85
0.68	0.06	0.20	0.33	0.38	0.43	0.49	0.54	0.60	0.65	0.72	0.79
0.70		0.14	0.27	0.33	0.38	0.43	0.49	0.54	0.60	0.66	0.73
0.72		0.08	0.22	0.27	0.32	0.37	0.43	0.48	0.54	0.60	0.67
0.74		0.03	0.16	0.21	0.26	0.32	0.37	0.43	0.48	0.55	0.62
0.76			0.11	0.16	0.21	0.26	0.32	0.37	0.43	0.50	0.56
0.78			0.05	0.11	0.16	0.21	0.27	0.32	0.38	0.44	0.51
0.80				0.05	0.10	0.16	0.21	0.27	0.33	0.39	0.46
0.82					0.05	0.10	0.16	0.22	0.27	0.33	0.40
0.84						0.05	0.11	0.16	0.22	0.28	0.35
0.86							0.06	0.11	0.17	0.23	0.30
0.88								0.06	0.11	0.17	0.25
0.90									0.06	0.12	0.19
0.92										0.06	0.13
0.94											0.07

The value read from the table is multiplied by the active power *P* in kW to obtain the required capacitor rating in kvar.

The electricity supply utilities generally specify a power factor of 0.8 to 0.9. Compensation beyond $\cos \varphi = 1$ (over-compensation $Q_c > Q_1$) must be avoided as this gives rise to capacitive reactive power which stresses the conductors in the same way as inductive reactive power, and in addition, unwelcome voltage increases can occur.

Reactor-less capacitor banks cannot be used directly for compensating reactive power in systems to which sources of harmonics such as converters are connected.

Network impedance and capacitor bank form a parallel resonant circuit, the resonant frequency of which is

$$\omega_r = \frac{1}{\sqrt{L_N \cdot C}} \quad \text{or} \quad \upsilon_r = \frac{1}{w_1 \cdot \sqrt{L_N \cdot C}}$$

ω_1 = Angular frequency at nominal network frequency
L_N = Phase value of network/consumer inductance
C = Phase value of bank capacitance
υ_r = Mode number of resonant frequency

In a first approximation, this resonant frequency can also be calculated from the network fault power S_k'' and the compensating power at nominal network frequency Q_{c1}:

$$\upsilon_r = \frac{\omega_r}{\omega_1} = \sqrt{\frac{S_k''}{Q_{c1}}}$$

At this resonant frequency, the source of harmonics (e.g. rectifiers) encounters a higher network impedance.

In consequence, the harmonic current causes a larger drop in harmonic voltage than in an uncompensated network (X_L), which can result in unacceptably severe distortion of the voltage.

Between network and capacitor flow transient currents whose values can be a multiple of the exciting current harmonic. Transformers and particularly capacitors are thus subjected to additional stresses and can become overloaded.

Since the position of the point of parallel resonance can be calculated from the network inductance and the capacitor rating, it would be possible to position the resonant point so that it creates less disturbance. In practice, however, the network impedance is not constant because it depends on the system fault level and the consumers connected to the network.

Since the system fault level can alter according to the state of the circuit, and also loads are constantly being connected and disconnected, the point of parallel resonance will move according to the network configuration, so passing through zones of disturbance. The situation is more difficult if compensation is arranged to be switched in stages.

Measures must therefore be taken which in fact cannot avoid parallel resonance with the network, but shift the point of resonance into non-critical areas. Compensation facilities in networks containing harmonic sources must hence be provided with series reactors.

Capacitor banks with reactors constitute a series resonant circuit which exhibits the smallest resistance, theoretically zero, at the point of resonance.

Such series resonant circuits can be tuned to defined harmonics frequencies occurring in the network.

If the reactor coil is designed to subject the filter to a minimum amount of harmonic currents, this is called a “heavily detuned filter circuit”.

Heavily detuned filter circuits are used when harmonic sources in the network must be expected, but their extent is unknown. In practice, it can be taken that:

$$a = \frac{Q_L}{Q_{c1}} 100\ \% = \frac{X_L}{X_c} 100\ \%$$

referred to the nominal network frequency, with *'a'* having a value of 6 %.

The resulting frequency ratio of the series resonant frequency is calculated as:

$$\upsilon_r = \frac{\omega_r}{\omega_1} = \frac{10}{\sqrt{a}}$$

with '*a*' in %.

When $a = 6$ % therefore, the point of series resonance is at $v_r = 4.08$ times the nominal network frequency.

In systems with audio-frequency ripple control, the capacitors damp the audio frequency. The electricity supply utilities therefore stipulate special measures, such as the fitting of suppression chokes ahead of capacitors.

Single compensation

The phase-shifting capacitor is coupled direct to the terminals of the load and switched in common with it.

The advantages are: reduced load on distribution lines and switchgear, no capacitor switches or discharge resistors required, installation simple and inexpensive.

This technique is used when relatively large loads (e.g. motors) are as far as possible in continuous operation.

Single compensation of three-phase motors

Motor and capacitor are connected in parallel. They are switched on and off by the same switching device and are supervised by the same protective system. No discharging device is needed. The capacitor discharges through the motor windings.

The switchgear must be selected according to the capacitor making current, and the electrical connections according to the compensated full-load current of the motor. The capacitor should be located in the immediate vicinity of the motor.

To avoid over-compensation at part-load and self-excitation of the motor as it runs down after disconnection, compensation should amount to only 90 % of the open-circuit reactive power. This will give $\cos \varphi \approx 0.9$ at full load, and roughly 0.95 to 0.98 at no-load.

The capacitor power rating required is

$$Q_c \approx 0.9 \cdot \sqrt{3} \cdot U \cdot I_0$$

where I_0 is the no-load current of the motor.

For star-delta starting of motors equipped with capacitors, see Fig. 12-11.

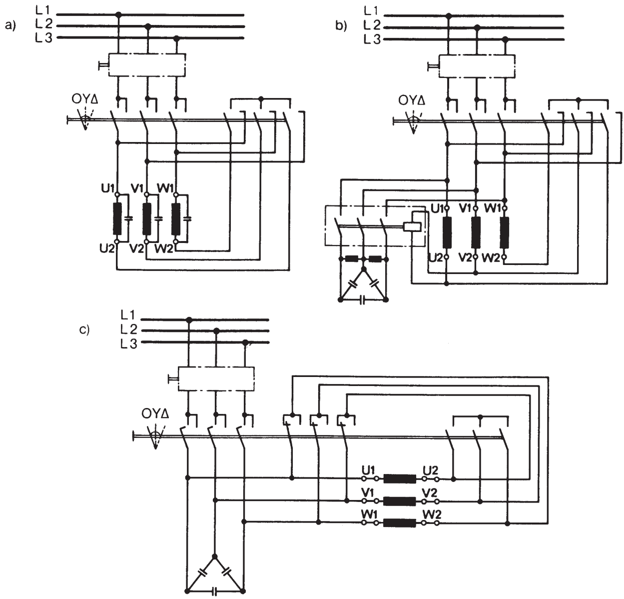


Fig. 12-11

Compensation of a three-phase motor.

a) When using a normal star-delta switch, b) Capacitor connected to delta position of star-delta switch, c) With special star-delta switch;

Operating sequence of switching elements on starting: Change from “off” to “star”: 1. Delta connections open, 2. Network connection closes, 3. Neutral point connections close;

Change from “star” to “delta”: 1. Neutral point connections open, 2. Delta connections close. The sequence is reversed when stopping.

Single compensation of transformers

Direct connection of a capacitor to a transformer, together with which it is switched on and off, is possible and permissible on both the HV and LV sides.

According to VDEW specifications, when connecting capacitors on the low-voltage side, the capacitor ratings must be as stated in Table 12-9.

If the capacitor is fitted on the low-voltage side of the transformer, in the case of networks having a high harmonics content, it is necessary to check whether a voltage resonance at a harmonic present in the network (usually the 5th and 7th harmonic) can occur between the capacitance of the capacitor and the leakage inductance of the transformer. The maximum capacitor rating can be defined approximately as

$$Q_c < \frac{S_{rT} \cdot 100\ \%}{v^2 \cdot u_{kr}}$$

where S_{rT} is the transformer rated power in kVA, and Q_c the capacitor rating in kvar, and u_{kr} the rated impedance voltage (in per cent) of the transformer and the feeding network, and v is the number of the highest critical harmonic.

Table 12-9

Capacitors connected on the low-voltage side of transformers

Transformer rated power kVA	Transformer voltage, HV side 5 to 10 kV capacitor rating kvar	15 to 20 kV capacitor rating kvar	25 to 30 kV capacitor rating kvar
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	22
315	18	20	24
400	20	22.5	28
630	28	32.5	40

Example:

In order to avoid resonance up to and including the 7th harmonic, for a 400 kVA transformer and $u_{kr} = 6.2\ \%$, the rating of the capacitor must definitely be less than

$$Q_c < \frac{400\ \text{kVA} \cdot 100\ \%}{7^2 \cdot 6.2\ \%} = 130\ \text{kvar}$$

It must also be noted that the capacitor has the effect of raising the voltage. Under low-load conditions, this can lead to unwelcome increases in voltage if the capacitor rating selected is more than covers the reactive current requirement of the transformer. The voltage at the capacitively loaded transformer then rises instead of falling. The increase can be calculated with sufficient accuracy from

$$\Delta u \approx u_{kr} \cdot \frac{Q_c}{S_{rT}}.$$

Single compensation of welding equipment

The capacitor rating for welding transformers and resistance welding machines can be between 30 and 50 % of the transformer rating. In the case of welding rectifiers, a capacitor rating of approximately 10% of the nominal rating is sufficient.

Group compensation

The phase-shifting capacitor is connected to the distribution bus feeding, for example, a large number of small motors running continuously or intermittently, Fig. 12-12.

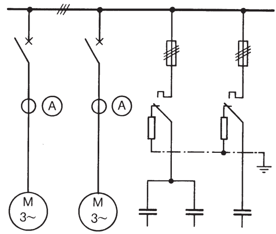


Fig. 12-12

Group compensation

The motors and capacitors are switched by separate switches and supervised by separate protection systems. The capacitors can be switched on and off individually or in groups, as required.

Centralized compensation

In comparatively large installations with many small and medium-size loads (motors, etc.) which are not usually in operation at the same time, the phase-shifting capacitors are connected centrally to the main busbar. The capacitors are switched either jointly by hand (Fig. 12-13a) or automatically via regulators responding to time or reactive load (Fig. 12-13b).

Advantages: automatic control allows the capacitor rating to be closely matched to the reactive power required at any time, thus keeping cos *φ* closer to the specified value.

Disadvantage: distributing lines between busbar and points of consumption still carry the same reactive current.

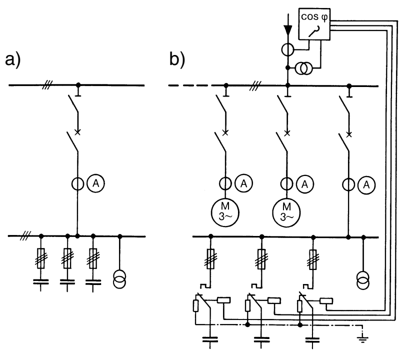


Fig. 12-13

Centralized compensation:

a) Total compensation,
b) Compensation with automatic control

Short-circuit protection should consist of HV fuses, for each capacitor if required. Voltage transformers in V connection are necessary for discharging after disconnection.

Centralized compensation can be used for all voltages.

12.4 Resistor devices

Resistor devices for low and high voltage are used in switchgear installations as

- Damping resistors for high-pass filters, in conjunction with arc suppression coils and for limiting capacitive and inductive overvoltages,
- Earthing resistors for earthing the neutrals of transformers and generators and also for earth fault protection,
- Loading resistors,
- Voltage dividers,
- Discharge resistors for capacitors,
- Transition and series resistors for tap changers,
- Starting and braking resistors and rheostats for electric motors.

The live parts are in the form of wire or cast elements or corrugated sheet-steel lattices. These components are made up into assemblies with ceramic insulators and can take the form of banks mounted on a frame.

Insulators are used for medium and high voltages.

In a resistor unit, electrical energy is converted into heat which the body of the resistor can absorb only partly and only for a very short time. It must always be dissipated to the ambient air. Resistor units are therefore usually air-cooled. Natural ventilation is generally sufficient. Separate ventilation or oil cooling is advisable in special cases.

The resistor elements normally have a tolerance of $\pm$ 10 %. Smaller tolerances are possible in special cases.

The rise in temperature, which can be up to about 400 K, increases the resistance. With cast iron resistors, for example, the resistance increase is 7.5 %/100 K (Table 12-10). When the maximum temperature of about 400 °C is reached, a nominal initial current of 600 A has fallen to 460 A.

Resistors are often not designed for a 100 % load factor, but only to operate for a limited time. If during this short period the load duration $t_B < T_\vartheta$, a higher loading is permissible. The maximum load duration t_{Bmax} during which the resistor element heats up to the permitted temperature limit with an overload of $I_a = a \cdot I_r$, is

$$t_{Bmax} = T_\vartheta \cdot \ln \left(\frac{a^2}{a^2 - 1} \right).$$

A sufficiently long interval must then follow to allow complete cooling.

Example:

Earthing resistors in medium and high-voltage installations for impedance earthing of generator and transformer neutrals must limit the earth fault current to values of 0.5 to 0.75 I''_{k3}. The resulting values are no danger, particularly with regard to electrical machines, and voltage rises due to any capacitive effects of network asymmetry are avoided. Also, in branched networks, a defined active current can be produced which makes it easier to measure and localize an earth fault. The load factor for these earthing resistors is governed by the protective devices in question and their speed of response.

For example, an earth resistor of this kind must limit the earth fault current to 400 A. The fault is cleared quickly. Cast iron resistors are chosen with a continuous load capacity of I_r = 60 A. Their thermal time constant is T_ϑ = 450 s. The maximum load duration is thus

$$t_{Bmax} = T_\vartheta \cdot \ln\left(\frac{a^2}{a^2-1}\right) = 450\ \text{s} \cdot \ln\left(\frac{(400/60)^2}{(400/60)^2-1}\right) = 10.25\ \text{s}.$$

Such earthing resistors are usually sized to operate for 10 s.

Table 12-10

Characteristics of commercially available resistor elements

Characteristics	Form of resistor elements Wire elements	Cast iron elements	Sheet steel grid
Material	CuNi44 (Constantan) NiCr8020	Surface-treated cast iron	Corrosion-resistant steel sheet CrNi alloy steel sheet
Resistance of individual elements at 20 °C	150–0.5 Ω	02–0.01 Ω	0.75–0.04 Ω
Continuous load capacity of elements	0.5–20 A[3)]	25–125 A[3)]	25–250 A
Therm. time constant T_ϑ	20-90 s	240-600 s	120 s
Resistance increase with temperature	0.4%/100 K[1)]	7.5%/100 K	5%/100 K[2)]
Insulation level to housing to earth across insulators	 600 V/1 kV 3.6-52 kV	 1 kV 3.6-52 kV	 1 kV 3.6-52 kV

1) Resistance variation of CuNi44 (constantan) negligible.
2) For CrNi alloy sheet 2 % / 100 K.
3) Wire elements cease to be economical at about 15 A. From 25 A, use cast-metal or steel-sheet elements.

12.5 Rectifiers

Semiconductor rectifiers are used exclusively today for rectifying alternating currents.

Rectifier assemblies are identified according to DIN VDE 0556. The identity code shows the connection, rated connected voltage, rated DC voltage and rated DC current of the assembly.

Example:

Code letter for connection
Rated connected voltage in V
Rated DC voltage in V
Rated DC current in A
Code letter for assisted cooling
(omitted with natural cooling)
F separate ventilation
O oil cooling

B 275 / 220 – 10

or: S 400 / 224 – 162 F

If a rectifier assembly consists of several stacks (e.g. 4) a single stack is designated:

1/4 B 275 / 220 – 10

Table 12-11 shows a summary of calculation data for common rectifier circuits. The symbols denote the following:

u_2 = Instantaneous value of applied AC voltage

U_2 = Root-mean-square value of applied AC voltage

u_g = Instantaneous value of rectified voltage

U_g = Arithmetic mean of rectified voltage

U_{go} = Open-circuit DC voltage

i_g = Instantaneous value of rectified current

I_g = Arithmetic mean of rectified current

Table 12-11

Basic calculation data for common rectifier connections

Connection to	Alternating current		3-phase AC			
Connection	Half-wave	Centre-tap	Bridge	Star	3-phase bridge	Double-star
Circuit diagram	Fig. 12-14	Fig. 12-16	Fig. 12-17	Fig. 12-18	Fig. 12-19	Fig. 12-20
No. of pulses p	1	2	2	3	6	6
Fundamental frequency of superimposed AC voltage (Hz)	50	100	100	150	300	300
Open-circuit DC voltage U_{go}/U_2	$\frac{\sqrt{2}}{\pi} = 0.45$	$\frac{\sqrt{2}}{\pi} = 0.45$	$\frac{2\sqrt{2}}{\pi} = 0.9$	$\frac{3\sqrt{2}}{2\pi} = 0.67$	$\frac{3\sqrt{2}}{\pi} = 1.35$	$\frac{3\sqrt{2}}{2\pi} = 0.67$
Rating of each valve						
as regards voltage for	U_2	U_2	U_2	U_2	U_2	U_2
as regards current for	I_g	$\frac{1}{2}I_g$	$\frac{1}{2}I_g$	$\frac{1}{2}I_g$	$\frac{1}{3}I_g$	$\frac{1}{6}I_g$
Connected network power $P_1/(U_{go} \cdot I_g)$	2.69	1.23 1.11[1)]	1.23 1.11[1)]	1.23	1.05	1.05
Mean transformer rating	3.09	1.49 1.34[1)]	1.23 1.11[1)]	1.37	1.05	1.55
Voltage ripple (in % of U_{go})	121.1	48.3	48.3	18.3	4.2	4.2

1) For operation with inductive load (e.g. large smoothing reactor)
All other figures apply to purely resistive load.

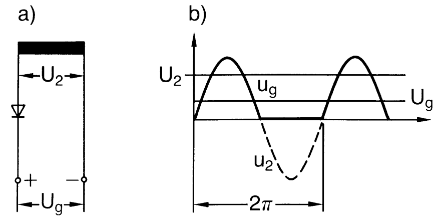
Common rectifier connections

1. *Half-wave connection, symbol E, see Fig. 12-14*

   The simplest of all rectifier connections. It consists of a branch which blocks one half-wave of the applied AC voltage. The result is a pulsating DC voltage with gaps while the voltage is negative. This arrangement is normally used only for small currents (often in conjunction with capacitors) and up to very high voltages with a suitable number of plates or stacks connected in series. The rectifier assembly must block the full transformer voltage and when capacitors are used, their charging voltage as well.

Fig. 12-14

Half-wave connection
a) Circuit diagram
b) Voltage curve

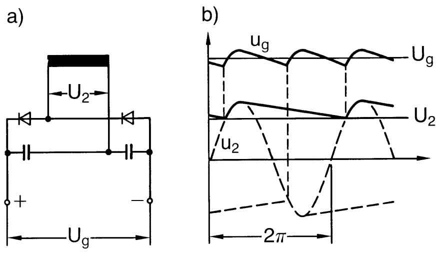


2. *Doubler connection, symbol V, see Fig. 12-15*

   This arrangement is again suitable only for small currents and relatively high voltages. It always requires two capacitors which are charged in each half-cycle and when connected in series, produce at no-load a DC voltage corresponding to twice the peak voltage of the applied AC voltage. Under load, the DC voltage decreases according to the relationship between capacitance and load current. Each branch of the rectifier assembly has to block the sum of transformer voltage and capacitor voltage.

Fig. 12-15

Doubler connection
a) Circuit diagram
b) Voltage curve



3. *Centre-tap connection, symbol M, see Fig. 12-16*

   This arrangement requires a transformer which has a centre tap on its secondary winding. In the blocking direction, each branch carries the full transformer voltage. The connection is economical only for low voltages using the basic unit. For higher voltages requiring semiconductor devices to be connected in series, it is inferior to the following bridge connection because of the special transformer construction for the same number of plates. It is then appropriate only if suitable transformers are already available, i.e. when hot cathode or mercury vapour rectifiers are to be replaced by semiconductor units.

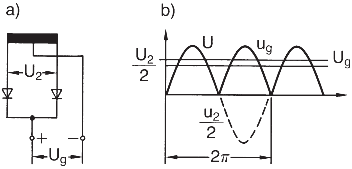


Fig. 12-16

Centre-tap connection
a) Circuit diagram
b) Voltage curve

4. Bridge connection, symbol B, see Fig. 12-17.

Provided the voltages involved are not very low, in which case the centre-tap connection may be preferable, the bridge connection is the most practical and economical over a wide range of currents and voltages, and therefore the most commonly used of all single-phase arrangements. In the blocking direction, each of the 4 branches is subjected to the full transformer voltage.

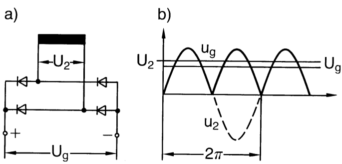


Fig. 12-17

Bridge connection
a) Circuit diagram
b) Voltage curve

5. Star connection, symbol S, see Fig. 12-18.

This three-phase arrangement requires transformers, or networks in the case of straight connection, whose neutral is able to withstand the full direct current. The connection's power rating is unlimited. However, it is practically used only when mercury vapour rectifiers require replacement. Each branch is subjected to the phase-to-phase voltage. With voltages which exceed the nominal blocking voltage of one rectifier device, the following three-phase bridge connection will probably be preferable with the same number of devices. When directly linked to 380 V three-phase networks with loadable neutral, the star connection provides a DC voltage of the order of 220 to 230 V.

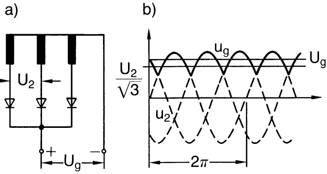


Fig. 12-18

Star connection
a) Circuit diagram
b) Voltage curve

6. *Three-phase bridge connection, symbol DB, see Fig. 12-19*

This is the most convenient and economical connection for all relatively high powers at voltages exceeding those of the basic star or double-star connections. Here again, each of the 6 branches carries the phase-to-phase voltage in the blocking direction.

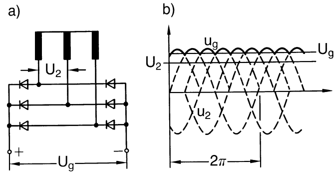


Fig. 12-19

Three-phase bridge connection
a) Circuit diagram
b) Voltage curve

7. *Double-star connection, symbol DS, see Fig. 12-20*

This arrangement corresponds to the centre-tap connection of the single-phase configurations. Again, it is used almost exclusively only with low voltages requiring one basic unit, but currents can be high. With higher voltages, it can be recommended only when replacing the glass or iron cells of mercury vapour rectifiers. In the blocking direction, each of the 6 branches carries twice the phase voltage.

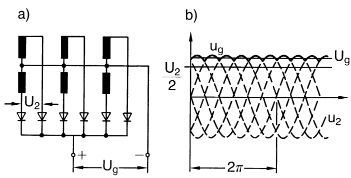


Fig. 12-20

Double-star connection
a) Circuit diagram
b) Voltage curve

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