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Reactive Power Compensation

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Reactive power is essential to the operation of AC electrical equipment, but its generation and transmission affects the operation of the power system. The adverse effects of reactive power generation and transmission include the increase in active power and energy losses, increased voltage drops, reduced capacity of network components and, consequently, higher costs of electricity supply. Power losses in a symmetrically loaded network component with the resistance R (e.g. a line or transformer) can be calculated from the formula:

$$\Delta P = 3I^2R = \frac{S^2}{V^2}R = \frac{P^2}{V^2\cos^2\varphi}R = \frac{P^2}{V^2}R + \frac{Q^2}{V^2}R = \Delta P_a + \Delta P_r, \qquad (13.1)$$

where I is the current flowing through the network component, R is the resistance of network component, S is the apparent power flowing through the network component, $\cos\varphi$ is the power factor, V is the phase to phase voltage, P and Q are the active and reactive power flowing through the network component respectiviely, ΔP_a and ΔP_r are the power losses due to active (a) and reactive (r) power flow respectiviely and φ is the the angle (in degrees) between current and voltage. The ratio of ΔP_r to ΔP_a vs. the power factor cos φ is shown in Figure 13.1.

The voltage drop ΔV across a symmetrically loaded network component with the resistance R and reactance X can be calculated from the formula:

$$\Delta V = \frac{PR + QX}{V} = \frac{PR}{V}\left(1 + \frac{QX}{PR}\right) = \frac{PR}{V}\left(1 + \tan\varphi\frac{X}{R}\right), \qquad (13.2)$$

where X is the the reactance of a network component and tan φ is the reactive to active power ratio.

Equation (13.2) shows that the voltage drop depends on both the ratio of the reactive power to active power tan φ and on the ratio of reactance to the resistance X/R of a network component.

Electrical Energy Efficiency: Technologies and Applications, First Edition. Andreas Sumper and Angelo Baggini.

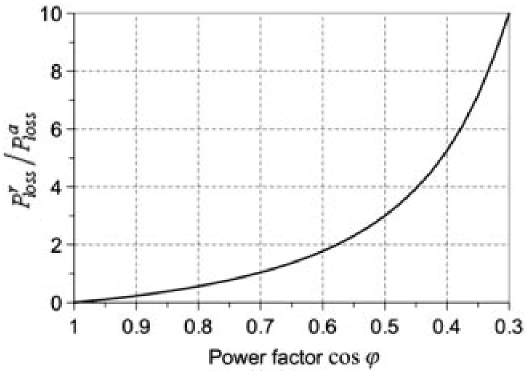

Figure 13.1 The ratio of active power losses caused by the reactive power flow to active power losses caused by the active power flow vs. the power factor

For overhead power lines the ratio X/R is $0.5 \div 3$, and for transformers it can be up to 20. The relative increase in the voltage drop as a function of power factor at different values of the X/R ratio is shown in Figure 13.2. The voltage drop value at power factor $\cos \varphi = 1$ was adopted as a benchmark.

Power network components are sized to the maximum rms current or the maximum apparent power that can be transmitted through them. The presence of reactive current or reactive power reduces the component's capacity for active power. For example, if the element capacity for the apparent power equals 1 p.u. the increase of reactive power from 0.6 to 0.8 p.u. reduces its active power capacity from 0.8 to 0.6 p.u. (see Figure 13.3).

Active power transmission at a low power factor requires higher ratings of electrical equipment (e.g. an increase in wire cross-section or the rated power of transformers), and consequently an increase in investment. The increase in investment as a function of power factor is illustrated in Figure 13.4.

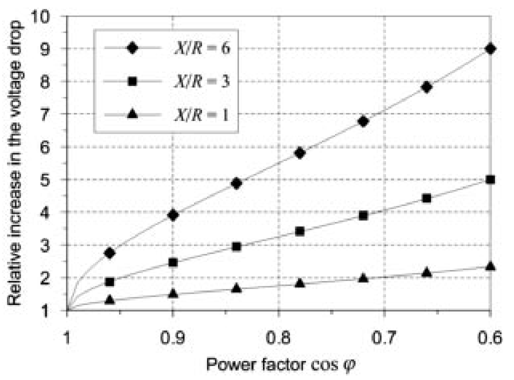

Figure 13.2 Relative increase in the voltage drop as a function of power factor at different values of the X/R ratio

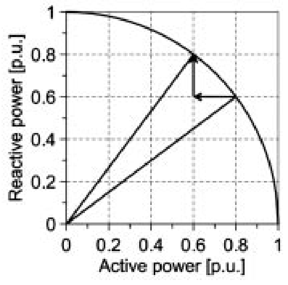

Figure 13.3 Limiting load for the active power due to the increased load reactive power

13.1 Reactive Power Compensation in an Electric Utility Network

Reactive power compensation in a power system is particularly important for both operational and developmental planning since the installation of capacitors near to electricity consumers contributes to a reduction of power and energy losses, and a reduction in voltage drop. It increases network capacity for active power, improves voltage regulation and power quality and, in the case of designing a new network, it also reduces investment cost.

The task of reactive power compensation in a power system is usually solved separately for transmission and distribution networks. In the case of transmission networks the primary reason for installing reactive sources is to improve voltage stability, thus increasing the security of the energy supply. In the case of distribution networks the compensation objectives are different for the electric utility network and for industrial networks. The aim of reactive power compensation in an electric utility network is to reduce distribution costs and improve power quality, while in industrial networks it is aimed at reducing the costs of energy supply.

In this chapter we will discuss the issues related to the effectiveness of the installation of capacitor banks in distribution networks.

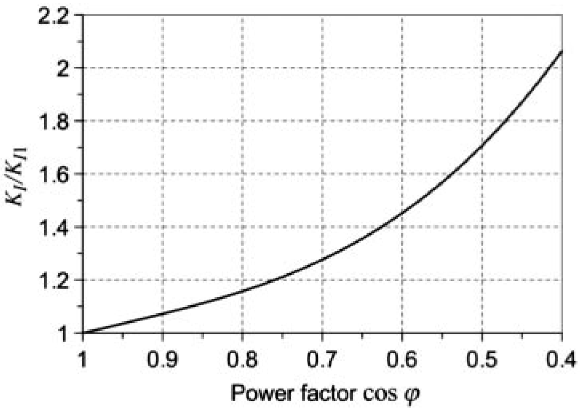

Figure 13.4 Relative investment increase vs. power factor: K_I is capital expenditures for cos $\varphi < 1$, K_{I1} is capital expenditures for cos $\varphi = 1$

Power losses ΔP_K in the network component with a capacitive load (a capacitor) connected can be calculated from:

$$\Delta P_K = \frac{P^2 + (Q - Q_K)^2}{V^2} R. \tag{13.3}$$

The difference between the losses prior to and after switching on the capacitor is:

$$\Delta P_R = \Delta P - \Delta P_K = \frac{Q^2 - (Q - Q_K)^2}{V^2} R = \frac{2QQ_K - Q_K^2}{V^2} R. \tag{13.4}$$

As seen from (13.4) the effect of reactive power compensation, i.e. the power loss reduction, depends on both: the compensator power Q_K and the reactive power Q flowing through the element before the compensation. With this dependence it is also apparent that the greatest reduction in power loss is obtained for the $Q_K = Q$ (active power losses reach a minimum value equal to the losses derived from the transmitted active power).

Since the load of the network changes over time, the amount by which the energy losses will decrease due to compensation requires knowledge of the load reactive power variation over time. If the voltage is assumed constant in time, the amount by which energy losses will be reduced during a time period T as a result of reactive power compensation with a fixed value of Q_K can be calculated according to:

$$\Delta W_R = \int_{t=0}^{t=T} \Delta P_R(t)\, \mathrm{d}t = \frac{R}{V^2} \int_{t=0}^{t=T} \left(2Q_K Q(t) - Q_K^2\right) \mathrm{d}t, \tag{13.5}$$

where $\Delta P_R(t)$ is the instantaneous value of the active power losses reduction, $Q(t)$ is the instantaneous reactive power flowing through the network component, V is the voltage and T is duration of the time period (usually taken to be $T \approx 8760$ h). It should be noted that $\int_{t=0}^{t=T} Q(t)\mathrm{d}t$ is equal to the amount of reactive energy W_r that has flown through the element R during time T. Thus (13.5) for the reduction of active energy losses takes the form:

$$\Delta W_R = \frac{R}{V^2} \left(2W_r Q_K - Q_K^2 T\right). \tag{13.6}$$

By differentiating (13.6) with respect to Q_K and comparing the differential to zero the compensator's rated power at which the largest reduction of active energy losses in the circuit is achieved during the period T can be determined:

$$\frac{\partial \Delta W_R}{\partial Q_K} = \frac{2R}{V^2} (W_r - Q_K T) \Rightarrow Q_K^{\max} = \frac{W_r}{T}. \tag{13.7}$$

The amount of reactive energy W_r can be measured using a reactive energy meter.

Power distribution grids consist of high, medium and low voltage networks. A high voltage network operates in a closed configuration while MV and LV networks, although they are often built as closed structures, always operate in open configurations. A simplified diagram of a medium voltage network fed from a HV/MV transformer station is shown in Figure 13.5.

In that network reactive power compensation capacitors can be connected to the MV busbar in the distribution station supplying the network, or in transformer substations to the low voltage windings of MV/LV transformers. The subject of these considerations is the

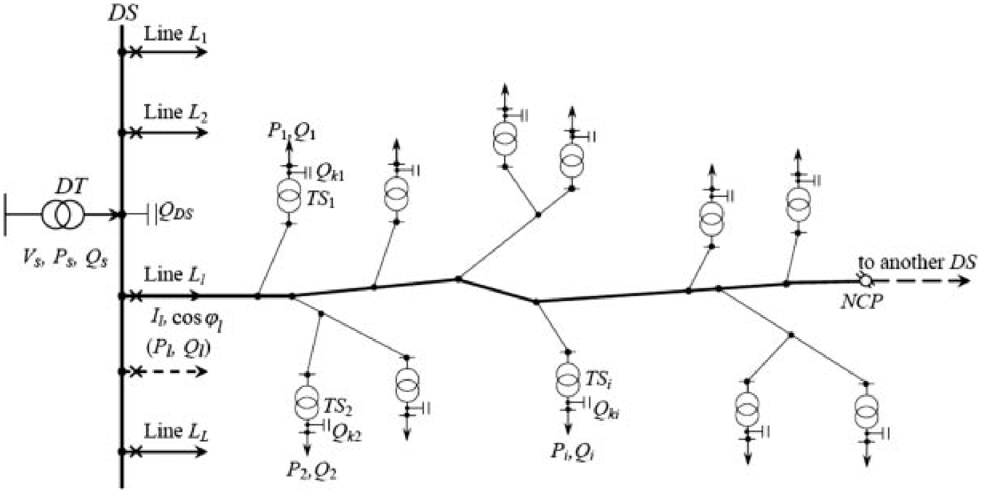

Figure 13.5 Simplified diagram of a medium voltage network: *DS* – HV/MV distribution station; *DT* – HV/MV distribution transformer; P_l, Q_l active and reactive power supplying the line L_l; TS_i – *i*-th MV/LV substation; P_i, Q_i – active and reactive power load of the *i*-th substation; Q_{ki} – rated power of the capacitor to be installed in the *i*-th transformer substation; Q_{DS} – rated power of the capacitor to be installed in the distribution station; P_S and Q_S are the active and reactive power supplying distribution station; *NCP* – point of networks division (network cut point), other symbols are explained in the text

distribution network as shown in Figure 13.5, in which the compensation capacitors are to be connected to the low voltage windings of MV/LV transformers.

In order to determine the effect of capacitors installation on power and energy losses in the network it is necessary to know the network components' loading. Unfortunately, because of the large number of network components and the lack of measurements, information about the network components' loading is not available. We therefore employ a simplified method for calculating the power and energy losses in networks with such configurations. Several simplified methods for calculating the losses in distribution networks are presented in [1–7]. In one of these methods, each individual circuit L_l of the network shown in Figure 13.5 can be represented by the equivalent circuit with the load distributed evenly along the line, as shown in Figure 13.6.

The use of these simplified methods requires the following assumptions:

- all MV/LV transformers supplied by the circuit are charged in proportion to their rated power;

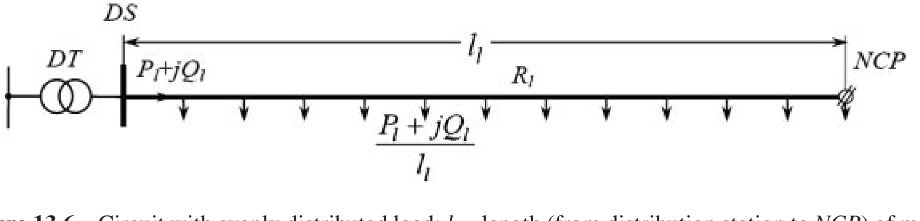

Figure 13.6 Circuit with evenly distributed load: l_l – length (from distribution station to *NCP*) of main line of circuit *l* [m]; R_l – resistance of main line of circuit *l* [Ω]

- load variation over time is the same for all transformers supplied from the circuit;
- the power factor of MV/LV loading is the same and is equal to the circuit load power factor.

Power losses in the circuit with the load distributed evenly along the line are three times lower than those in the circuit with the same load concentrated at the end and can be calculated using the relation:

$$\Delta P = \frac{P_l^2 + Q_l^2}{3V^2} R_l. \tag{13.8}$$

Taking into account the (13.8), the value of the reduction in power losses in an MV network single circuit after installing capacitors in MV/LV substations can be estimated using the equation:

$$\Delta P_{R_l} = \left(2Q_l Q_{K_l} - Q_{K_l}^2\right) \frac{R_l}{3V^2} + \left\{2Q_l (Q_{K_l} - Q_{M_l}) - (Q_{K_l} - Q_{M_l})^2\right\} \frac{\sum_{i \in NTS_l} P_{K_l}}{\left(\sum_{i \in NTS_l} S_{n_i}\right)^2}, \tag{13.9}$$

while the value of energy losses reduction can be estimated from the formula:

$$\Delta W_{R_l} = \left(2W_{r_l} Q_{K_l} - Q_{K_l}^2 T\right) \frac{R_l}{3V^2} + \left\{2W_{r_l}\left(Q_{K_l} - Q_{M_l}\right) - \left(Q_{K_l} - Q_{M_l}\right)^2 T\right\} \frac{\sum_{i \in NTS_l} P_{k_i}}{\left(\sum_{i \in NTS_l} S_{n_i}\right)^2}, \tag{13.10}$$

where NTS_l is a set of substations supplied by circuit l, Q_{K_l} is the sum of powers of capacitors installed in substations supplied by line l, Q_{M_l} is the sum of the magnetizing power of MV/LV transformers, P_{k_i} is the rated load ('full-load') loss of i-th MV/LV transformer and S_{n_i} is the rated power of i-th MV/LV transformer.

Equations (13.9) and (13.10) are derived under the assumption that the power of capacitors installed in substations is proportional to the rated power of transformers in these substations. If the amount of reactive energy received from the substation is known, the output capacitor should be determined from (13.7).

Reactive power compensation in MV network will also reduce power and energy losses in the HV/MV transformer supplying that network. The value of additional reduction in power losses in the HV/MV transformer can be estimated:

$$\Delta P_{R_{DT}} = \left(2Q_s Q_{K_l} - Q_{K_l}\right) \frac{P_{k_{DT}}}{S_{n_{DT}}^2}, \tag{13.11}$$

while the value of additional reduction of energy losses can be estimated from:

$$\Delta W_{R_{DT}} = \left(2W_{r_{DT}} Q_{K_l} - T Q_{K_l}^2\right) \frac{P_{k_{DT}}}{S_{n_{DT}}^2}, \tag{13.12}$$

where Q_s is the reactive power received from the distribution transformer, $P_{k_{DT}}$ is the rated load loss of the distribution transformer and $S_{n_{DT}}$ is the rated power of the distribution transformer.

Equations (13.11) and (13.12) also allow one to calculate the amount of loss reduction when a capacitor is connected only at the switchgear in distribution stations supplying a medium voltage network. In this case, the total power of capacitors installed in substations Q_{K_l} should be replaced with the power of the capacitor installed in this station Q_{DS}.

13.1.1 Economic Efficiency of Reactive Power Compensation

Annual savings resulting from the installation of capacitors can be calculated on the basis of a reduction in power loss at peak load ΔP_{R_s} and in energy loss during a yearΔW_{R_y}. These savings can be calculated from:

$$O_y = \Delta P_{R_s} k_P + \Delta W_{R_y} k_A, \tag{13.13}$$

where k_P is the unit cost of power losses and k_A is the unit cost of energy losses. In order to assess the economic efficiency of the installation of capacitors it is necessary to know the capacitors' prices and the installation and operation costs. To simplify calculations the capacitor price can be approximated by a linear function (see Figure 13.7):

$$C_p = k_v Q + k_f, \tag{13.14}$$

where C_p is the capacitor price, Q is the capacitor rated power, k_f is a constant, independent of the power, capacitor cost component and k_v is the variable, depending on the power, capacitor cost component.

To the price of the capacitor must be added the cost of installation k_i. The cost of purchase and installation of capacitors of the total rated power Q_{K_l} installed in NTS_l substations supplied by a circuit l is:

$$K_{I_l} = k_v Q_{K_l} + NTS_l \left(k_f + k_i\right), \tag{13.15}$$

where k_i is the cost of capacitor installation and NTS_l is the number of capacitors installed in substations supplied by circuit l.

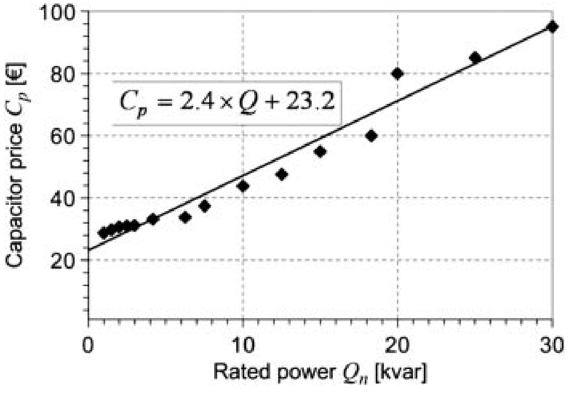

Figure 13.7 Price of MKPg type capacitors as a function of rated power

As a measure of economic efficiency the net present value ratio (*NPVR*) can be used, calculated for n years of the capacitors' operation:

$$NPVR = \frac{\sum_{y=0}^{n} \left(CI_y - CO_y\right) (1+i)^{-y}}{\sum_{y=0}^{n} K_{I_y} (1+i)^{-y}}, \tag{13.16}$$

where K_{I_y} is the capital expenditure incurred in year y, CI_y is the cash inflow in year y, CO_y is the cash outflow in year y, n is the calculation period (the period of construction + expected period of operation) and i is the discount rate (interest rate) expressed as a decimal fraction).

In (13.16) the investment K_{I_y} is substituted by the cost of the capacitors' purchase and installation calculated from (13.15), for the cash inflow CI_y are inserted the savings on reduction of power and energy losses calculated from (13.9), (13.10), (13.11) and (13.12); the expenditures CO_y are substituted by the capacitors' operating costs. It is usually assumed that operating costs are proportional to the investment value, thus the expenditure CI_y will be:

$$CO_y = K_{I_y} k_{ec}, \tag{13.17}$$

where k_{ec} is the fixed operating costs factor. Assuming that the purchase and installation of capacitors occurred at the end of year $y = 0$, and the savings resulting from the reduction of losses are the same in subsequent years, the formula for $NPVR_l$ of the circuit l takes the form:

$$NPVR_l = \frac{O_{y_l} SD - K_{I_l} (1 + k_{ec} SD)}{K_{I_l}} = \frac{O_{y_l} SD}{K_{I_l}} - (1 + k_{ec} SD), \tag{13.18}$$

where SD is the sum of discount factors:

$$SD = \sum_{y=1}^{n} (1+i)^{-y} = \frac{(1+i)^n - 1}{i (1+i)^n}. \tag{13.19}$$

The higher the *NPVR* value, the more profitable is the compensation of reactive power.

Another measure of the effectiveness of reactive power compensation can be the equivalent unit cost of the reduction of energy losses (averaged over the whole analysed period using the discount method). The equivalent unit cost is calculated as the quotient of the sum of the discounted annual costs incurred within the analysed period by the sum of the discounted annual effects in this period:

$$k_{eq} = \frac{\sum_{y=0}^{n} \left(K_{I_y} + CO_y\right) (1+i)^{-y}}{\sum_{y=0}^{n} \delta W_{R_y} (1+i)^{-y}}, \tag{13.20}$$

where ΔW_{R_y} is the reduction in energy loss in the year y, computed from (13.10) and (13.12). The lower k_{eq}, the more profitable is the compensation of the reactive power. The compensation becomes infeasible if $k_{eq} \geq k_A$.

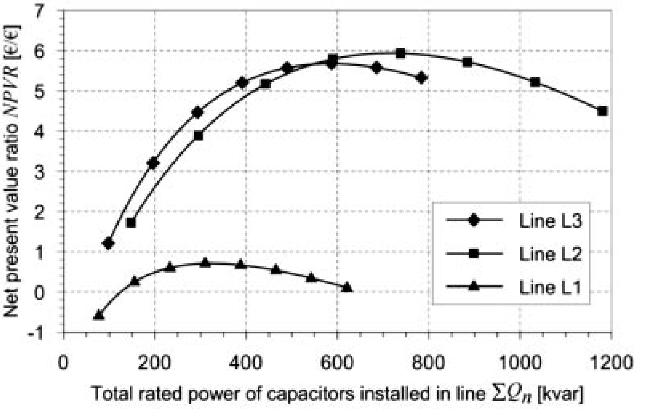

Figure 13.8 The dependence of the net present value ratio dependence on the total rated power of capacitors installed in lines

Figure 13.8 illustrates the dependence of the Net Present Value Ratio (NPVR) on the total rated power of the capacitors installed in three circuits powered by a 25 MVA transformer installed in a 110/15 kV distribution station. Figure 13.9 shows the equivalent unit cost of energy losses reduction on the total rated power of the installed capacitors.

Analysis of the above results shows that installation of reactive power compensation capacitors in MV/LV stations can be an effective method for energy loss reduction in distribution networks. It is, however, not always economically feasible, e.g. in the line L1 its cost-effectiveness is low. The optimum power of capacitors installed in a given circuit is the power at which the highest *NPVR* is achieved.

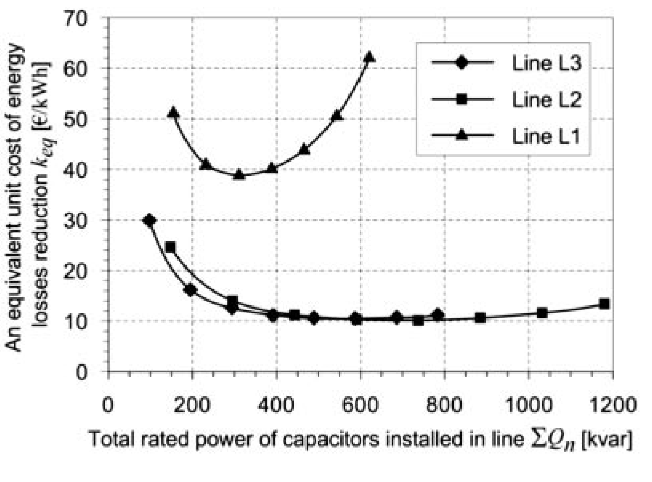

Figure 13.9 The dependence of the equivalent unit cost of energy loss reduction on the total rated power of capacitors installed in lines

13.2 Reactive Power Compensation in an Industrial Network

Electrical energy supply is subject to an agreement between the energy supplier and the consumer. The supplier usually guarantees the tariff costs of energy if the ratio of reactive to active power does not exceed a specific value, e.g. 0.4, which is equivalent to keeping the power factor at approximately 0.93. Any exceeding of the value is financially penalized, so the consumer is responsible for controlling its own reactive power load.

There could be two main approaches to the problem of reactive power. The first approach using 'natural methods' involves detailed analysis of the installed loads and a change in its working pattern, controls and connection to the supply line, so that the overall reactive to active power ratio doesn't exceed its limit value. The approach is sometimes difficult to apply in practice because it requires in-depth knowledge about the operation and working conditions of the loads. Also the needed changes are not always possible to apply. The method is usually the cheapest because it doesn't consider the installation of special compensation equipment. However the analysis could suggest changing a load to one that is better suited to the operation. An example of natural method application is to consider the controlled rectifier, whose nominal DC voltage $V_{\mathrm{DC,N}}$ is significantly lower that the maximal one $V_{\mathrm{DC,max}}$. The rectifier output DC voltage V_{DC} is approximately equal to: $V_{\mathrm{DC}} \approx 1.35\, V \cos\alpha$, where V is phase to phase supply voltage and α is the firing angle. The maximal DC voltage is therefore equal to: $V_{\mathrm{DC,max}} \approx 1.35\, V$ and depends only on supply voltage. Neglecting higher harmonic components, the power factor (PF) of the rectifier is equal to: $PF = \cos\alpha$, which yields the power factor $PF = V_{\mathrm{DC}}/(1.35\, U)$. In the case of a large difference between $V_{\mathrm{DC,max}}$ and $V_{\mathrm{DC,N}}$ the control angle is large and consequently the power factor, PF, is low. Decreasing the supply voltage of the rectifier, e.g. by exchanging the supply transformer for one with a lower secondary side nominal voltage, improves the power factor in this case.

The second approach is reactive power compensation – in other words on-site generation of inductive reactive power by means of dedicated compensators. The method is very effective, provided that the natural method was used to properly design the whole system, the compensator could be used to keep the power factor below the limit.

Some typical cases for installing a var compensator are as follows:

- *linear static loads* – linear loads whose reactive power is well determined and does not changes rapidly, e.g. induction motors, power transformers. It is the easiest case, and it does not impose any restrictions on the compensator, so a typical battery of capacitors with a typical regulator could be used.
- *dynamic loads* – loads whose reactive power changes rapidly. The compensator has to be fast enough to react to the power changes. Usually the load is also nonlinear, e.g. an arc furnace. A basic solution involves switched capacitors. The most advanced solutions are: TSC (Thyristor Switched Capacitors) FC/TCR (Fixed Capacitor with Thyristor Controlled Reactor), STATCOM (STATic COMpensator). The most advanced solution – Active Power Filter (APF) – can also be used for power factor correction, but the installation of APF should be carefully considered due to the overall costs of the device.
- *nonlinear loads* – loads that cause flow of non-sinusoidal current, mostly power electronic devices, e.g. DC drives fed by rectifiers. Presence of nonlinear loads usually also indicates a non-sinusoidal supply voltage due to voltage drop. There is the possibility of resonance, so special care should be taken during when designing the compensator. If the power does

not vary rapidly, a battery of capacitors could be equipped with a series reactor that changes the spectral properties of the battery and introduces series resonance. In this case, the compensator becomes a passive filter. The filter could be further extended to compensate for different harmonic components. The most advanced solution involves installation of an APF, which also provides harmonic filtration.

When considering the location of the compensator, three cases should be mentioned:

1. *Individual compensation:* loads are compensated for separately by a capacitor of proper power.
2. *Centralized compensation* of all loads in one point. The compensator is installed in the main supply station close to the point of common coupling (PCC) and settlement point. The compensator is usually of varying reactive power so it can compensate varying load to the desired power factor.
3. *Group compensation* of the group of loads, applied when there is a wide internal network i.e. several substations connected to the main supply station. Compensators are installed in the substations in order to avoid reactive power flowing over the internal network. Note that settlement of energy is done in the main station, so the power factor at the station should be kept below the limit.

A typical case arises when an energy consumer is fed only from one supply line. There is only one point of energy settlement and the point is taken into consideration. A more complex case arises when there are several feeding lines i.e. several settlement points when energy is calculated conforming the tariff. The desired reactive power, i.e. power factor (or tangent equivalently), should be kept in all of the points.

13.2.1 Linear Loads

Reactive power balance rule:

$$Q_{\mathrm{des}} = Q_{\mathrm{nat}} - Q_{\mathrm{comp}}, \tag{13.21}$$

where Q_{des} is the desired amount of reactive power in PCC; usually it depends on active load power and is derived as a percentage of the latter, e.g. in most cases the feeder guarantees the cost of energy if the ratio of active to reactive power is less than 40%, that is if $\tan\varphi < 0.4$, which is equivalent to a power factor of approximately 0.93; Q_{nat} is the natural or nominal reactive power of the load; Q_{comp} is the reactive power of the compensator, the amount of reactive power that is needed to keep the desired power Q_{des}. The compensator acts as a source of (inductive) reactive power. Assuming that compensation does not change active power flow, i.e. losses are neglected and compensation is achieved by means of power capacitors, the balance rule could be transformed into:

$$Q_{\mathrm{comp}} = P_{\mathrm{load}} \left(\tan\varphi_{\mathrm{nat}} - \tan\varphi_{\mathrm{des}}\right), \tag{13.22}$$

where P_{load} is the the load active power; $\tan\varphi_{\mathrm{nat}}$ is the natural, i.e. non-compensated, power $\tan\varphi$ value; $\tan\varphi_{\mathrm{des}}$ is the value that should be achieved by means of the compensator.

The value of the natural reactive power Q_{nat} and $\tan\varphi_{\mathrm{nat}}$ consequently could be obtained by means of two approaches:

1. *Analytical calculation*: knowing the parameters of the device and its working pattern, reactive power could be calculated. This is usually done during the design stage by the design engineer. The method could be inaccurate because equipment rarely works with its nominal conditions and its working pattern is also difficult to determine during the design stage because, for example, the actual production size is unknown. For centralized compensation there is also simultaneity of working loads to be taken into consideration. Consequently the analytical calculation gives only an approximate value of the natural reactive power.
2. *Measurement*: performed by an analyser capable of determining active and reactive power in a sufficient period of time, for example a week, with a sufficient averaging window, for example, 10 minutes. The main advantage of this method is that the measured powers are the actual ones consumed by the load. Provided that the measurement period is long enough to cover the whole technological process, detailed information about value and changes of reactive power could be obtained. Measurement can also be useful to check the correctness or to adjust compensators designed on the basis of analytical calculation. The method obviously can not be used at the design stage. The main drawback is that the measurement could only be made when the company is working under normal conditions, so var compensation would have to be designed by the other method.

13.2.1.1 Example 1 – Centralized Compensation

Let us consider a 400 V switchboard that is fed from the transformer with rated power $S_{\mathrm{N}} = 400\,\mathrm{kVA}$ and short-circuit voltage $e_{\%} = 4.5\%$. The switchboard supplies loads with total active power ranging from $P = 190\,\mathrm{kW}$ to 208 kW and a power factor varying from 0.62 to 0.68. Determine the maximal and minimal power of the compensator in order to compensate reactive power to the power factor value of 0.92.

For the purpose of this calculation the power system short-circuit capacity, resistances of components and compensator active power losses can be neglected. Assume the supply voltage is non-distorted.

As the active power varies so the power factor and the load reactive power are variable. Since there is no information on the correlation between the power factor and the active power, we shall assume extreme cases and calculate both the maximal and minimal compensating power for the given Q/P value. The maximal power is drawn at the maximal active power and the maximal difference between $\tan\varphi$ values, i.e. at the minimal power factor of 0.62. Correspondingly, the minimal power occurs for the minimal active power and maximal power factor 0.68. Therefore, we obtain

$$Q_{k,\min} = 190(1.078 - 0.426) = 123.93\,\mathrm{kvar}, \quad Q_{k,\max} = 208(1.265 - 0.426) = 174.61\,\mathrm{kvar},$$

where $Q_{k,\min}$ and $Q_{k,\max}$ are minimal and maximal compensator powers respectively. Thus the compensator reactive power has a certain constant value of $Q_{const} = 123.93$ kvar, whereas the regulation range is $Q_{\mathrm{reg}} = 50.61$ kvar.

13.2.2 Group Compensation

Group compensation is useful when a consumer maintains an internal network that covers, for example, a wide area. In this case there are several substation connected to the main supply station by means of overhead lines or cables. In order to avoid reactive power flow between the main station and substations, compensation of local loads is deployed in the local substations. Therefore the purpose of the compensator is not only keeping reactive power below the limit, but also the minimization of internal network losses. Consequently it is essential to take into consideration the line resistances during the evaluation of local var compensators.

Lets assume that there exists i local substations supplied from the main station. Each substation feeds its own loads with active power P_i and reactive power Q_i. The total reactive power Q_{K} needed to compensate the loads so that a specified value of $\tan\varphi_{\mathrm{des}}$ is kept in the main station is equal to:

$$Q_{\mathrm{K}} = P_{\mathrm{tot}}\left(\tan\varphi_{\mathrm{tot}} - \tan\varphi_{\mathrm{des}}\right), \tag{13.23}$$

where P_{tot} is the sum of the local load powers:

$$P_{\mathrm{tot}} = \sum_i P_i, \tag{13.24}$$

where P_i is the active power of loads in substation i; $\tan\varphi_{\mathrm{tot}}$ is the total natural reactive to active powers ratio derived from:

$$\tan\varphi_{\mathrm{tot}} = \frac{Q_{\mathrm{tot}}}{P_{\mathrm{tot}}} = \frac{\sum_i Q_i}{\sum_i P_i}, \tag{13.25}$$

where Q_{tot} is the total natural reactive power of the loads equal to the sum of the reactive powers in substations; Q_i is the natural reactive power of local loads in substation i.

The next step is to distribute the total reactive power Q_{K} into the local substations according to conduction losses. Local var compensator in substation i should have power equal to:

$$Q_{k,i} = Q_i - \left(Q_{\mathrm{tot}} - Q_{\mathrm{K}}\right)\frac{R}{R_i}, \tag{13.26}$$

where Q_i is the natural reactive power, Q_{tot} is the total natural reactive power, Q_{K} is total compensation power, R_i is the resistance of i-th substation connection to the main station, R is the total equivalent resistance, which can be derived from:

$$\frac{1}{R} = \sum_i \frac{1}{R_i}. \tag{13.27}$$

Such a selection of compensator powers could cause power tangents in the local substation to be different from the desired value. However, the reactive to active power ratio is kept at the desired level in the main supply station. The difference depends on line resistances, i.e. conduction power losses.

13.2.2.1 Example 2 – Group Compensation

Let us consider a main supply station that supplies four local substation (LSS). The parameters are shown in the Table 13.1 where P_n is the nominal active power, Q_n is the nominal (natural) reactive power. The system is schematically shown in Figure 13.10.

Design var compensation so that the power factor does not exceed $PF_{des} = 0.93$ (equivalent to $\tan\varphi_{des} = 0.4$). Assume that the internal supply lines are made of copper with unit conductance $\gamma = 55$ [mΩ/mm^2]. Inductance and capacitance of the lines could be omitted. The problem could be solved by means of two approaches:

1. group compensation with compensation of each substation to $PF_{des} = 0.93$ ($\tan\varphi_{des} = 0.4$), i.e. equally distributed compensation;
2. group compensation with a desired power factor in MSS equal to $PF_{des} = 0.93$ ($\tan\varphi_{des} = 0.4$), i.e. loss minimization compensation.

Table 13.1 Group compensation (Example 2)

Parameters				
	LSS 1	LSS 2	LSS 3	LSS 4
P_n [kW]	30	35	45	70
Q_n [kvar]	30	46.5	42	75
Line length, l [m]	150	30	120	60
Cross-section, s [mm^2]	16	25	35	35
Equally distributed compensation – tangent and reactive power				
$\tan\varphi_i$	1	1.328	0.933	1.071
PF_i	0.707	0.601	0.731	0.628
$Q_{k,i}$ [kvar]	18	32.5	24	47
Power losses in equally distributed compensation case				
R_i [mΩ]	170.45	21.82	62.34	31.17
$\Delta P_{p,i}$ [W]	958.81	167.05	788.96	954.55
$\Delta P_{q,i}$ [W]	153.41	26.73	126.23	152.73
Loss minimization compensation – tangent and reactive power				
$Q_{k,i}$	25.77	13.44	30.43	51.86
$\tan\varphi_i$	0.414	0.944	0.257	0.331
PF_i	0.924	0.727	0.968	0.949
Power losses in loss minimization compensation case				
$\Delta P_{p,i}$ [W]	958.81	167.05	788.96	954.55
$\Delta P_{q,i}$ [W]	19.07	149.02	52.16	104.31
Power losses in centralized compensation case				
$\Delta P_{p,i}$ [W]	958.81	167.05	788.96	954.55
$\Delta P_{q,i}$ [W]	958.81	294.85	687.27	1095.78

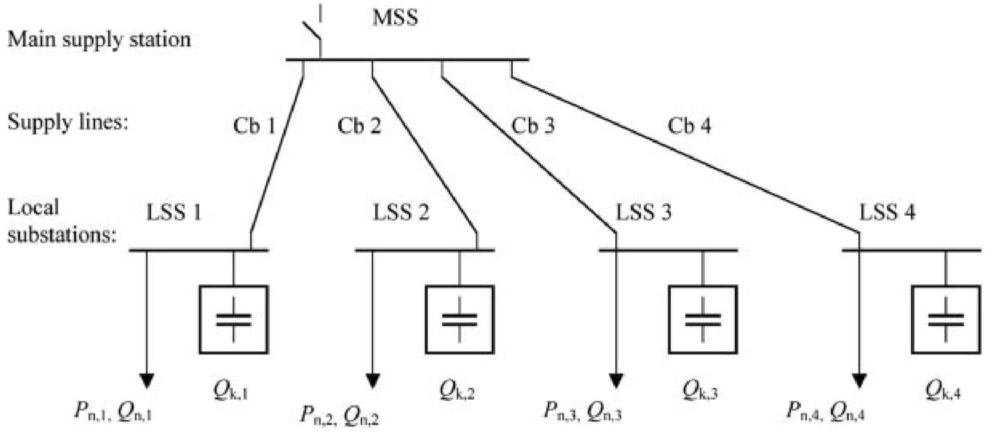

Figure 13.10 Supply system diagram for Example 2 – group compensation in local substations

The first approach, group compensation with equally distributed var compensation does not take into consideration losses, however the compensation is deployed in local substations. The objective is to compensate local reactive power so that in each substation the power factor is equal to the desired value $PF_{\text{des}} = 0.93$ (the tangent $\tan\varphi_{\text{des}} = 0.4$). Consequently, the power factor in the main supply station would also be equal to $PF_{\text{des}} = 0.93$. The computations are similar to the those from the central case, but compensation is derived separately for each substation. The natural reactive to active power ratios and powers of compensators are equal to:

$$\tan\varphi_i = Q_i/P_i \quad Q_{\text{k},i} = P_i\,(\tan\varphi_i - \tan\varphi_{\text{des}}).$$

Now the total losses could be considered. Let us consider two kind of losses separately: the power loss due to the active power transition $\Delta P_{\text{p},i}$, and the power loss due to the reactive power transition $\Delta P_{\text{q},i}$ in substation i which are equal to:

$$\Delta P_{\text{p},i} = \frac{P_i^2}{V^2}R_i \quad \Delta P_{\text{q},i} = \frac{(Q_i - Q_{ki})}{V^2}R_i,$$

where V is the supply voltage. The cable resistance R_i is equal to $R_i = l_i/(s\gamma)$, where l_i is the length of the cable, s is the cross-section and γ is the unit conductance of the cable. The results are shown in the Table 13.2. Total losses are:

$$\Delta P_{\text{p}} = \sum_i \Delta P_{\text{p},i} = 2869.36\,[\text{W}] \quad \Delta P_{\text{q}} = \sum_i \Delta P_{\text{q},i} = 459.10\,[\text{W}]$$

$$\Delta P = \Delta P_{\text{q}} + \Delta P_{\text{p}} = 3328.46\,[\text{W}]\,.$$

The losses due to the reactive power transition are 13.79% of the total loss ΔP.

The second case, loss minimization compensation allows for further loss reduction. The total active and reactive power and power tangent is equal to:

$$P_{\text{tot}} = 30 + 35 + 45 + 70 = 180\text{ kW} \quad Q_{\text{tot}} = 30 + 46.5 + 42 + 75 = 193.5\text{ kvar}$$

$$\tan\varphi_{\text{tot}} = \frac{193.5}{180} = 1.075.$$

Table 13.2 Comparison of losses in different compensation methods

Compensation	Equally distributed	Loss minimization	Centralized
LSS 1	153.41 kvar	19.07 kvar	958.81 kvar
LSS 2	26.73 kvar	149.02 kvar	294.85 kvar
LSS 3	126.23 kvar	52.16 kvar	687.27 kvar
LSS 4	152.73 kvar	104.31 kvar	1095.78 kvar
Reactive power transmission loss	459.1 W	324.57 W	3036.71 W
Total transmission loss	3328.46 W	3193.93 W	5906.07 W

Total compensation power is therefore equal to:

$$Q_\mathrm{K} = 180 \cdot (1.075 - 0.4) = 121.5 \text{ kvar}.$$

The total equivalent resistance could be derived from:

$$\frac{1}{R} = \frac{1}{170} + \frac{1}{114} + \frac{1}{62} + \frac{1}{15}, \quad R = 10.26\,[\mathrm{m}\Omega].$$

Consequently the local compensator powers and local power factors are presented in Table 13.1.

Assuming that the cable cross-sections are the same as in the group compensation case, losses could be computed, Table 13.1. Total losses are:

$$\Delta P_\mathrm{p} = \sum_i \Delta P_{\mathrm{p},i} = 2869.36\,[\mathrm{W}] \quad \Delta P_\mathrm{q} = \sum_i \Delta P_{\mathrm{q},i} = 324.57\,[\mathrm{W}]$$
$$\Delta P = \Delta P_\mathrm{q} + \Delta P_\mathrm{p} = 3193.93\,[\mathrm{W}].$$

Losses due to reactive power transition are 10.16% of the total loss ΔP.

For a better comparison let us consider centralized compensation. This approach takes into consideration only the main station and does not involve any loss calculation. There is only one compensator and its power is Q_K. However, the natural reactive power $Q_{\mathrm{n},i}$ should be transmitted to local substations, which causes additional power loss. The results are shown in Table 13.1. Total losses are:

$$\Delta P_\mathrm{p} = \sum_i \Delta P_{\mathrm{p},i} = 2869.35\,[\mathrm{W}] \quad \Delta P_\mathrm{q} = \sum_i \Delta P_{\mathrm{q},i} = 3036.71\,[\mathrm{W}]$$
$$\Delta P = \Delta P_\mathrm{q} + \Delta P_\mathrm{p} = 5906.07\,[\mathrm{W}]\,.$$

The loss due to reactive power transition is 51.42% of the total loss ΔP. Note that transmission of reactive and active power in this case results in current flow that could overload supply lines. The main results are summarized in Table 13.2. It could be noted that the total reactive power needed for compensation is the same in every case. The difference lies in the placement of compensators.

13.2.3 Nonlinear Loads

Nonlinear loads cause the flow of non-sinusoidal currents, that is, currents that can be decomposed into a fundamental harmonic component and higher harmonic components. The case should be considered separately because a capacitor changes the spectral properties of the system. Consequently some of the higher harmonics could be amplified, causing compensator overcurrent and voltage distortion in the PCC.

Let us consider a simple system with a nonlinear load, a compensator and a transformer. The system could be represented as in Figure 13.11, where: $I_{(n)}$ is the n-th harmonic source current; X_{Tr} is the transformer reactance calculated for the fundamental harmonic; X_{c} is the compensator reactance for the fundamental harmonic; n is the relative frequency (with respect to the fundamental, so $f = nf_{(1)}$; integer n is equivalent to harmonic order). In this case the equivalent impedance (actually the reactance, assuming the resistance is neglected) is:

$$Z_z\,(n) = \frac{-nX_{\mathrm{Tr}}X_{\mathrm{c}}}{n^2X_{\mathrm{Tr}} - X_{\mathrm{c}}}. \tag{13.28}$$

The resonance conditions are related to the zeros of the numerator or denominator. For positive values of circuit components only the denominator can become zero. This occurs for: $n^2X_{\mathrm{Tr}} - X_{\mathrm{c}}$ and is the condition of parallel resonance; the resonance frequency n_{r} is: $n_{\mathrm{r}} = \sqrt{X_{\mathrm{C}}/X_{\mathrm{Tr}}}$. Any harmonic current component will be causing voltage drop across the system impedance, i.e. transformer reactance is equal to $V_{(n)} = I_{(n)}Z_z\,(n)$, for $n = n_{\mathrm{r}}$ the voltage drop is infinite. Noting that $THD = (\sqrt{\sum V_{(n)}^2}/V_N) \cdot 100\%$, where V_{N} is nominal rms value of the phase voltage. The harmonic component of frequency near n_{r} will significantly distort the supply voltage in the PCC.

In order to deal with the problem, a series reactor could be added. The reactor creates conditions for series resonance. The equivalent circuit for this case is shown in Figure 13.12, where X_{d} is the reactance of the series reactor. The equivalent impedance of this circuit is:

$$Z_z(n) = \frac{nX_{\mathrm{tr}}\left(n^2X_{\mathrm{d}} - X_{\mathrm{c}}\right)}{n^2\left(X_{\mathrm{tr}} + X_{\mathrm{d}}\right) - X_{\mathrm{c}}}. \tag{13.29}$$

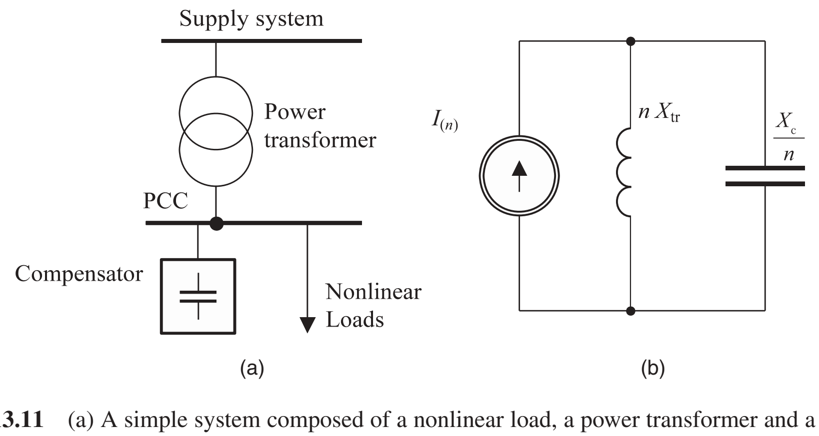

Figure 13.11 (a) A simple system composed of a nonlinear load, a power transformer and a compensator. (b) Equivalent circuit for the system

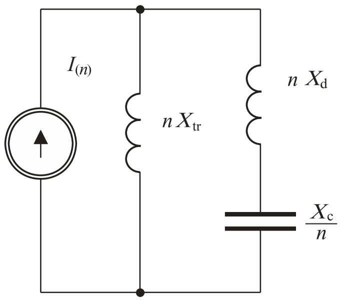

Figure 13.12 Equivalent circuit for the compensator with a choke

Two options are possible when the numerator or denominator equals zero. The nominator becomes zero if the relationship: $n^2X_{\rm d} - X_{\rm c} = 0$ is satisfied, which is the condition of series resonance. If the resonance frequency $n_{\rm s}$ is known (e.g. chosen during the project process) the reactor reactance can be calculated from $X_{\rm d} = X_{\rm C}/n_{\rm s}^2$. For the denominator, we obtain the relationship $n^2\,(X_{\rm tr} + X_{\rm d}) - X_{\rm c} = 0$, which is the condition of parallel resonance. The resonance frequency is:

$$n_{\rm r} = \sqrt{\frac{X_{\rm c}}{X_{\rm tr} + X_{\rm d}}}. \tag{13.30}$$

It should be noted that the parallel resonance frequency has been shifted towards the lower frequencies compared with that of the circuit without the series reactor. Therefore, when choosing the reactor the series resonance frequency should be selected to match the lowest harmonic present. In the other case, the reactor will shift the parallel resonance frequency towards the lower harmonic in the current spectrum, which could result in current resonance. This may increase the voltage distortion compared with that of the circuit without the reactor.

The correct selection of the compensator components, i.e. the capacitors and reactor, requires determining their operating conditions. The current in the compensator branch $I_{\rm f}$ can be found by employing Kirchhoff current law according to Figure 13.12.

$$I_{f(n)} = I_{(n)}\frac{n^2X_{\rm tr}}{n^2\,(X_{\rm tr} + X_{\rm d}) - X_{\rm c}}, \tag{13.31}$$

where $I_{(n)}$ is the rms of n-th harmonic current, $X_{\rm d}$, $X_{\rm Tr}$, $X_{\rm c}$ are component reactances for the fundamental harmonic. We calculate the rms current value from the formula $RMS = \sqrt{\sum I_{(n)}^2}$. This value should be smaller than the admissible current value, which is in some cases derived according to formula $I_{\rm rms} = 1.35I_{\rm CN}$ where $I_{\rm CN}$ is the nominal rms current of the capacitor.

The capacitor voltage can be found from the Kirchhoff voltage law, or using the calculated values of the compensator branch current. Applying the voltage divider, the capacitor fundamental harmonic voltage rms value is $V_{\rm C(1)} = X_{\rm C}V/\,(X_{\rm C} - X_{\rm d})$. It can be noted that, due to different reactance signs, the voltage across the capacitor could be higher than the voltage without the choke. The voltage is even higher due to distorted current flow through the capacitor. The rms value derived from $RMS = \sqrt{\sum V_{(n)}^2}$ should be less than the maximal permissible continuous voltage, determined as: $V_{C,rms} < 1.1\,V_{CN}$ where V_{CN} is the nominal capacitor voltage. The limit values are chosen according to [5].

The peak capacitor voltage condition should also be checked. The composition of the sinusoidal waves could yield a high peak magnitude, which could exceed the capacitor breakdown capacity. The worst case is determined from the formula $MAX = \sum V_{(n)}$ and the value should be less than the maximal permissible peak voltage, which is $V_{C,max} < 1.2\,V_{CN}$.

13.2.3.1 Example 3 – Var Compensation in the Presence of Nonlinear Loads

Let us go back to Example 1, where a group of loads of varying active and reactive powers was fed from the transformer with rated power $S_n = 400$ kVA and short-circuit voltage $e_{\%} = 4.5\%$. Assume that load current is distorted; the maximal values of the harmonic currents are given in Table 13.3.

Let us check whether the voltage distortion is maintained within the allowed limits and calculate the series reactor impedance, if needed.

Since the load current is distorted, there is a possibility that resonance may occur. Moreover, neglecting the resistance implies that attenuation introduced by certain elements will not be taken into account. It should be noted that harmonic currents values are small compared with the 400 kVA transformer rated current. In this case, the equivalent circuit in Figure 13.12 could be applied. The reactance values can be determined from simple formulae:

$$X_{c,min} = \frac{V^2}{Q_{k,max}} = \frac{400}{147.61 \cdot 10^3} = 0.916\,\Omega \quad X_{c,max} = \frac{V^2}{Q_{k,max}} = \frac{400}{123.93 \cdot 10^3} = 1.291\,\Omega$$

$$X_{Tr} = \frac{e_{\%}}{100}\frac{V^2}{S_{Tr}} = 0.045\frac{400}{400 \cdot 10^3} = 18\,\text{m}\Omega.$$

Table 13.3 Var compensation in the presence of nonlinear loads (Example 3)

Maximal values of harmonic currents				
Harmonic order n	5	7	11	13
$I_{(n)}$ [A]	10	7.14	5.13	4.1
Voltage harmonics computation				
$Z_{(n)}$ [Ω]	0.177	3.365	0.144	0.1
$U_{(n)}$ [V]	1.768	24.03	0.738	0.414
Maximal voltage distortion THD, which will occur for the minimal compensator power				
$I_{(n)}$	10	7.14	5.13	4.1
$Z_{(n)}$	0.448	0.046	0.117	0.144
$U_{(n)}$	4.48	0.327	0.6	0.592
Elements current and voltage rise – worst-case calculation results				
$I_{(n)}$	10	7.14	5.13	4.1
$I_{f(n)}$	59.81	4.54	2.1	1.57
$X_{C(n)}$	0.183	0.131	0.083	0.07
$U_{C(n)}$	10.94	0.59	0.17	0.11

As the compensator reactive power varies, so does its reactance and, consequently, the resonance frequency varies. Substituting the above values, we determine the maximal and minimal resonance frequency $n_{r,max} = 8.47$ for $Q_{r,min}$, $X_{r,max}$ and $n_{r,min} = 7.13$ for $Q_{r,max}$, $X_{r,min}$. Since the 7th harmonic is present in the load current, a resonance can occur when the capacitor bank is loaded with maximal power. This will result in an increase in the 7th harmonic current and, consequently, significant voltage distortion at the point of common coupling (at the switchboard bus-bars).

In order to check whether the capacitor bank operation is possible under such conditions, the maximal total harmonic voltage distortion, *THD*, should be calculated. The resonance will obviously occur at frequency n_r equal to 7.13, i.e. for the capacitor maximal reactive power. Knowing the maximal harmonic current values, the voltage drops and hence the voltage THD can be calculated.

Table 13.3 shows the values calculated for each harmonic. The calculated value of total harmonic distortion, *THD*, will be:

$$THD = \frac{\sqrt{1.768^2 + 24.03^2 + 0.708^2 + 0.414^2}}{230} \cdot 100\% = 10.48\%.$$

This value exceeds the limit of 8% set out in standard EN 50160 [1] with regard to low voltage. Such a high voltage distortion occurs only at the maximal capacitor bank power, therefore either the power needs to be reduced or a series reactor should be connected.

The reactor should create a series resonance for the lowest harmonic component in the current, i.e. for the 5th harmonic. A typical mistake is to choose the 7th harmonic because the parallel resonance occurs for the 7th harmonics. However, this will shift the parallel resonance frequency towards the 5th harmonic, causing voltage distortion to be far higher than the permissible 8%. Therefore the reactor will be chosen for the frequency n_s to be equal to the 5th harmonic. Then we obtain:

$$X_d = \frac{X_c}{n_s^2} = \frac{0.919}{5^2} 36.76\,\mathrm{m}\Omega.$$

The parallel resonance frequency will vary within the range $n_{r,max} = 4.86 \quad n_{r,min} = 4.09$. It is thus sufficiently far from the current harmonics (namely the 5th harmonic).

Now we calculate the maximal voltage distortion, *THD*, which will occur for the minimal compensator power, i.e. at the resonant frequency 4.86. The calculations are in Table 13.3.

Maximal total voltage distortion *THD* is:

$$THD = \frac{\sqrt{4.48^2 + 0.327^2 + 0.6^2 + 0.592^2}}{230} \cdot 100\% = 1.99\%,$$

which is far below the admissible value. The next step is to check for the proper working condition of the elements. We calculate the fundamental harmonic current from the formula:

$$I_{f(1)} = \frac{V}{\sqrt{3}\,(X_c - X_d)} = 262.53\,\mathrm{A}$$

The worst-case calculation results are presented in Table 13.3.

The rms current value we calculate from $\mathrm{R}M\mathrm{S} = \sqrt{\sum I_{(n)}^2}$. This yields

$$RMS = \sqrt{262.53^2 + 59.81^2 + 4.54^2 + 2.1^2 + 1.57^2} = 269.31\,\mathrm{A}.$$

This value should be smaller than the admissible current value I_{rms}. The capacitor voltage increase can be found from the Kirchhof voltage law, or using the calculated values of the compensator branch current. Thus we obtain results as in Table 13.3. From the voltage divider the capacitor fundamental harmonic voltage rms value is: $V_{\mathrm{C(1)}} = X_{\mathrm{C}}V/(X_{\mathrm{C}} - X_{\mathrm{d}}) = 416.67\mathrm{V}$, which yields the rms value: $RMS = \sqrt{240.56^2 + 10.94^2 + 0.59^2 + 0.17^2 + 0.11^2} = 240.81$ V. This value should be less than the maximal permissible continuous voltage. The peak capacitor voltage is determined from the formula $\mathrm{MAX} = V_{(n)}$. This yields $\mathrm{MAX} = 240.56 + 10.94 + 0.590.17 + 0.11 = 252.37$ V. This value should be less than the maximal permissible peak voltage of the capacitor.

13.3 Var Compensation

The use of reactive power follow-up compensators is one of the most effective ways of improving the power factor and/or the voltage stabilization factor at the point of their connection.

Figure 13.13 shows the classification of various technical solutions. They are mostly three-phase systems of considerable rated power, designed for the compensation/voltage stabilization of a selected load or group of loads characterized by a fast variation of the fundamental harmonic reactive power.

13.3.1 A Synchronous Condenser

A synchronous machine is a traditional source of the fundamental harmonic reactive power, and is inductive or capacitive in nature. It can also be the source of a mechanical moment, when

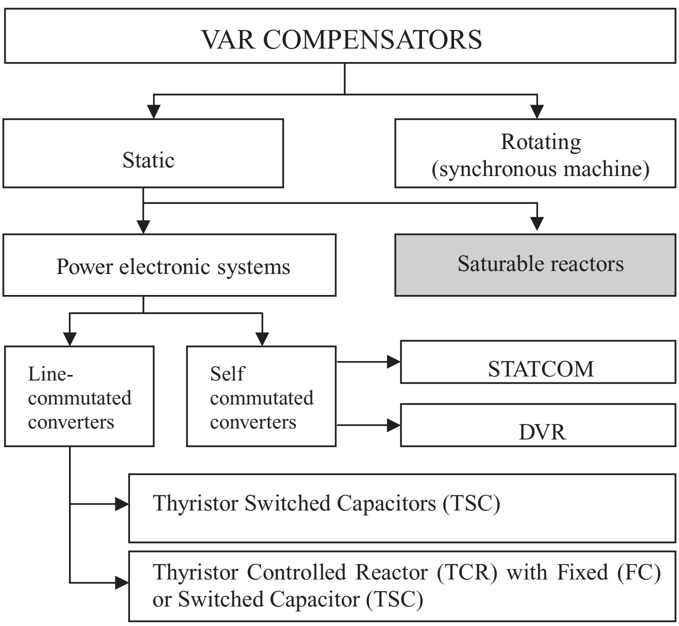

Figure 13.13 The classification of reactive power follow-up compensators/dynamic voltage stabilizers

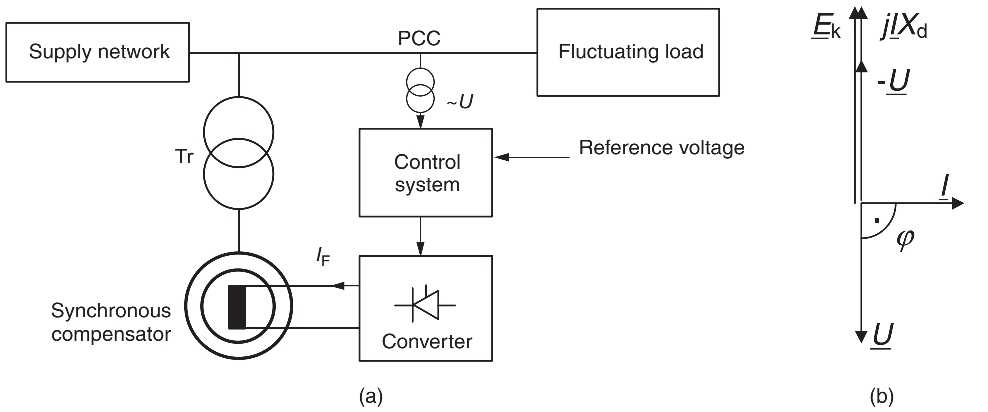

Figure 13.14 (a) A synchronous machine operating in the circuit of a dynamic voltage stabilizer and (b) a phasor diagram

it operates as both a condenser and a synchronous motor at the same time. The high dynamics of the compensation process as well as the continuous – not discrete – reactive power variation result from the fact that a controlled converter unit has been installed in the machine excitation circuit and that it works in a closed control circuit (Figure 13.14). The regulation of reactive power also makes it possible to stabilize the voltage at the point of machine connection.

What is assumed as the criterion of the operation quality in the case of a synchronous machine – in contrast to static compensators – is not the response time (in dynamic states) but the speed of the current/reactive power variations. It is also this value that is the measure of how fast the compensator corrects the voltage variations at the PCC. It is approximately equal to the speed of excitation current variations and it is higher upon de-excitation than on re-excitation of the machines. It depends on a number of various factors, such as: the machine's constructional characteristics, the admissible maximum value of the excitation voltage, the assumed voltage forcing factor, etc.

The disadvantages of synchronous compensators are as follows:

- Relatively high losses, 1.25–5.5% of the nominal power. The losses increase with the decrease of the charge, being 2.9–8% to 50% of the nominal charge and 5–14% to 25% of the nominal charge. Losses due to hydrogen cooled compensators are 10–30% lower than those for air cooled compensators.
- The cost of the installed reactive power unit increases with the decrease in the power of the compensator.

13.3.2 Capacitor Banks

Capacitor banks can fulfill the same function as overexcited synchronous compensators, so they can locally supply reactive power and reduce voltage drops in the lines. The advantages of capacitor banks are as follows:

- The cost for the installed reactive power unit varies very little with the total installed power of the installation.

- They can be mounted sequentially, so they do not need initial high investment.
- The power losses in the capacitors are 0.25–0.30% of the nominal power.
- The operating expenses are reduced more than in the case of synchronous machines.
- The price for the reactive energy produced in the capacitor banks is 3–4 times smaller than that for those produced in the other static compensation installation.

Capacitor banks have the inconvenience that they do not allow continuous control of the voltage, they do not absorb the capacitive power of the lines, their power decreases with the square of the voltage at their terminals.

13.3.3 Power Electronic Compensators/Stabilizers

Generally speaking, static compensators are circuits including reactors and/or thyristor controlled capacitors, connected to a power node. They can be treated as regulated parallel susceptance. They are also used to compensate reactive power, symmetrize currents/voltages, or limit voltage fluctuations. The most common solutions in this group include: thyristor switched capacitors (TSC), a fixed capacitor bank circuit (FC) and a circuit with an inductive current fundamental harmonic control switch (TCR), FC/TCR and TSC/TCR circuits as well as the STATCOM circuit.

13.3.3.1 Thyristor Switched Capacitors (TSC)

In such a circuit delta-connected capacitor banks are divided into sections; each section is switched on (or switched off) separately by means of AC thyristor switches (Figure 13.15(a)). The synchronization of the switch switch-on moment together with the initial battery charging makes it possible to avoid overcurrents and overvoltages, which appear in a non-synchronous capacitor connection (Figure 13.15(b)). Response time at symmetrical operation does not exceed 20 ms.

In addition, other configurations that could be called ‘economical’ are used; in these cases, one of the semi-conduction switch thyristors is replaced by a diode.

13.3.3.2 Fixed Capacitors/Thyristor Controlled Reactors (FC/TCR)

This solution is an example of an indirect compensation method, where, depending on the needs arising from the functions of a voltage stabilizer or a reactive power compensator, the value of the sum of two current components is regulated (Figure 13.16):

- a current fundamental harmonic i_{FC} of a capacitor, functioning almost always as a harmonic filter/filters;
- a current fundamental harmonic of a reactor i_{TCR}, regulated by phase control of an AC thyristor switch (T).

Figure 13.16(a) shows a one-phase schematic diagram of such an installation, whereas Figure 13.16(b) shows waveforms illustrating the working principle and reactor current waveforms for various values of the control angle α (in relation to voltage zero-crossing points).

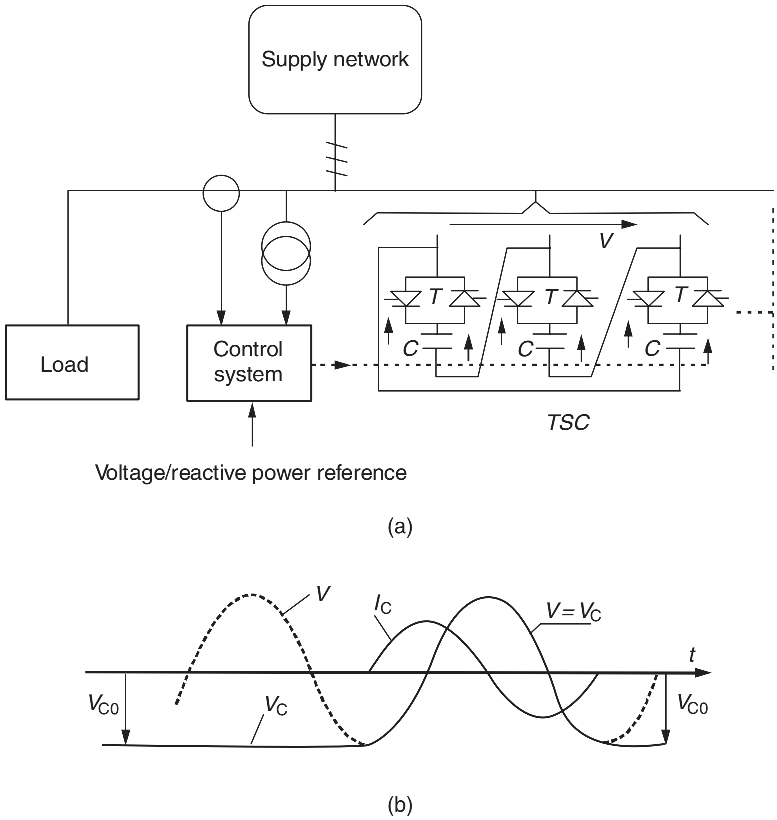

Figure 13.15 (a) Schematic diagram of a TSC compensator; (b) current and voltage waveforms during capacitor switching (V_{C0} – voltage initial condition of the capacitor)

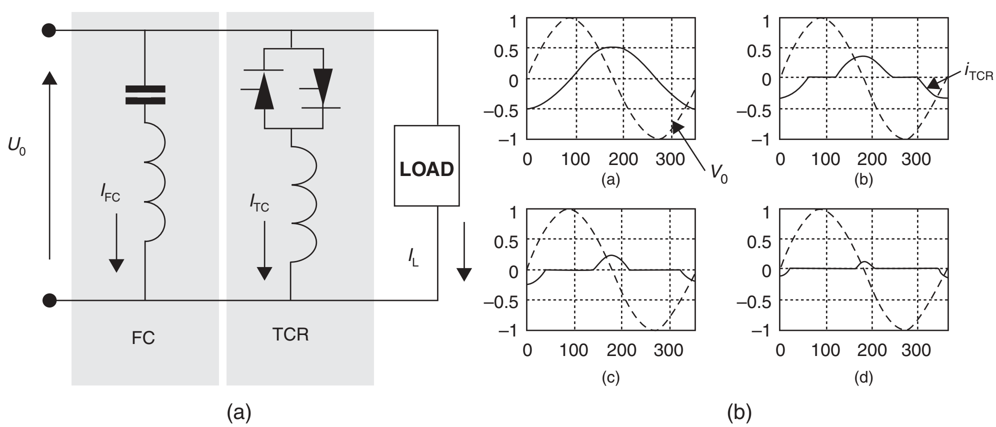

Figure 13.16 (a) Conceptual diagram of a one-phase FC/TCR compensator; (b) TCR current waveforms

In such a compensator, the reactor current (fundamental harmonic) is regulated by means of a phase-controlled thyristor switch, which consists of two antiparallel-connected thyristors. A capacitor bank, constituting the source of a capacitive reactive current, is parallel-connected to the reactor branch.

The control angle, together with the value of the reactor current fundamental harmonic and compensator current fundamental harmonic (as well as the value and sign of the voltage drop on the system impedance), can change in each supply voltage half-period, assuming any value from the range $(0.5\pi, \pi)$. What follows is the variation of reactor reactive power, from the maximum value to zero, respectively; also, the value (and sometimes also the nature – inductive or capacitive) of compensator resultant current changes.

The increase of the angle α results in the decrease of the fundamental harmonic in the reactor current, which means that its equivalent inductive reactance for this harmonic increases, while its input fundamental harmonic reactive power decreases.

If the current in the reactor branch equals zero ($\alpha = \pi$), the compensator returns the reactive power to the supply network, while its current is capacitive in nature. When the thyristors are fully controlled ($\alpha = \pi/2$), and the reactor power exceeds the capacitor power, the compensator takes reactive power, while its current is inductive in nature. The regulation of the compensator current within the range from I_{Cmax} to I_{Lmax} is continuous in nature.

Phase control of a thyristor switch results in the generation of higher harmonics of odd orders, and when retardation angles for both thyristors are not equal, even harmonics are generated as well [3]. ‘Triple’ harmonics (the orders of which are multiples of three) are eliminated from the compensator phase currents by connecting the reactor branches in a delta (Figure 13.17). These three-phase reactor configurations, together with parallel harmonic filters function for the supply network as equivalent susceptances switched on phase-to-phase (Figure 13.18). Their values change as a result of changing the control angles ($\alpha_{12}, \alpha_{23}, \alpha_{31}$, where 1, 2, 3 − 1, 2, 3 – ordinal numbers of phases), steplessly and independently of each

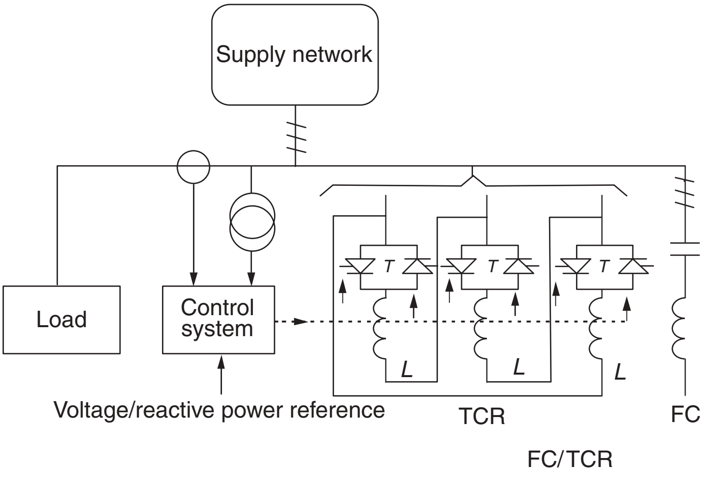

Figure 13.17 A schematic diagram of a three-phase FC/TCR compensator

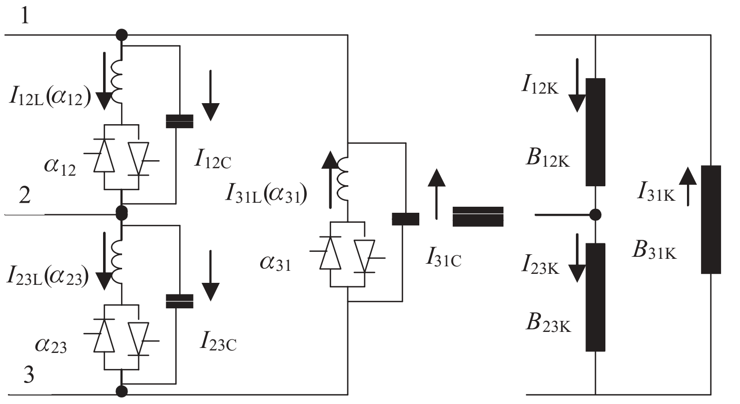

Figure 13.18 An FC/TCR compensator as a symmetrization device

other. Also, equivalent reactances of a transformer of a large short-circuit voltage (known as a *thyristor controlled transformer* circuit – TCT) can function as a reactor.

The static compensator circuit in question is particularly successful for the compensation of loads, the working conditions of which are asymmetrical and change quickly with time, for example for the compensation of an arc furnace.

In order to limit odd harmonics, two six-pulse circuits supplied by a three-winding Yyd transformer can be used (twelve-pulse circuit) or higher harmonics filters can be used as well.

In *Thyristor Switched Capacitors/Thyristor Controlled Reactors* (TSC/TCR) compensators, apart from TCR, thyristor switched capacitor steps are also used. The circuit has a significantly expanded regulation range in the area of capacitive currents. This solution, used almost exclusively in voltage stabilization circuits, combines the advantages of TSC and FC/TCR circuits. It makes it possible to minimize the value of harmonics of currents generated during TCR operation and to minimize active power losses in a compensation installation.

13.3.3.3 STATCOM

The circuit includes a converter – most frequently a VSI (Voltage Source Inverter). Its connection conditions of semiconducting elements (PWM modulation) decide the value and also the nature (inductive or capacitive) of the compensator reactive power.

A compensator can be regarded as a controlled voltage source, connected to the supply network by means of a reactor (Figure 13.19(a)). In order to control the reactive power flow the regulation of voltage amplitude is used. Such a compensator has possibilities analogous to these of a synchronous machine (but it works much faster).

For the phase angle between converter output voltages and the network voltage at the point of connection of the compensator $\delta = 0$, the circuit draws only the reactive power: capacitive when $V_{VSC} > V_{bus}$ or inductive when $V_{VSC} < V_{bus}$ (Figure 13.19(b)). In this way, the compensator is either a source or a load of the reactive power.

The STATCOM-type compensators applied in distribution systems for power quality improvement are called DSTATCOMs (Distribution STATCOMs). They can perform complex

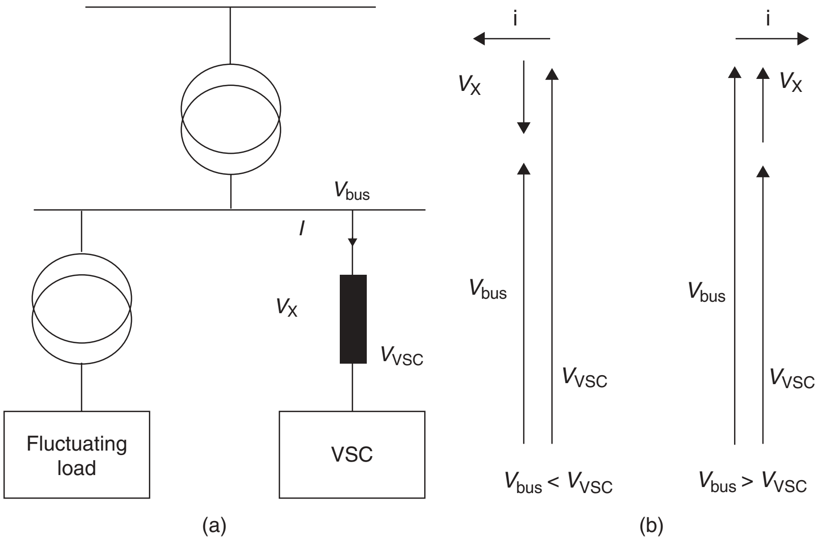

Figure 13.19 (a) Schematic diagram of a STATCOM compensator, connected to the supply network; (b) voltage and current phasor diagrams for different relations between V_{bus} and V_{VSC}, where X_k is the reactor or converter transformer reactance, V_{VSC} is the phase voltage at converter terminals, V_{bus} is the voltage drop on converter input reactance ($= X_k I$), I is the compensator current fundamental harmonic

Table 13.4 Comparison of selected compensators

	Synchronous machine	SVC		STATCOM
		FC/TCR	TSC (with TCR if it is needed)	
Compensation accuracy	Good	Very good	Good, very good with a TCR	Exceptionally good
Reactive power variability	Capacitive/ inductive	Capacitive/indirect inductive	Capacitive/Indirect inductive	Capacitive/Inductive
Control	Continuous	Continuous	Discrete/Continuous with TCR	Continuous
Response time	Relatively slow	1–2 periods	1–2 periods	Very short, depending on the control circuit and switching frequency
Harmonics	No	Large	No/Present in the case of a TCR	Small, depending on switching frequency
Losses	Medium	Low; increase together with the increase of the inductive power	Low; increase together with the increase of the capacitive power	Very low; increase together with the increase of switching frequency
Symmetrization ability	Limited	Good	Limited/Good	Very good in the case of three one-phase units; limited in a three-phase configuration
Cost	High	Medium	Medium	From low to medium

tasks simultaneously: reactive power compensation, load balancing and harmonic filtering. The basic element of the DSTATCOM system is a PWM voltage inverter in which fully controlled semiconductor devices are used, for example IGBT, IGCT. A new quality to designing STATCOM circuits is the use of multi-level converters. Their main advantage is the reduction of harmonics emission and the possibility of a direct connection to the network of an ever higher voltage because of a series connection of bridges or semi-conductors.

Table 13.4 gives a comparison of a few selected compensators.

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Further Readings

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