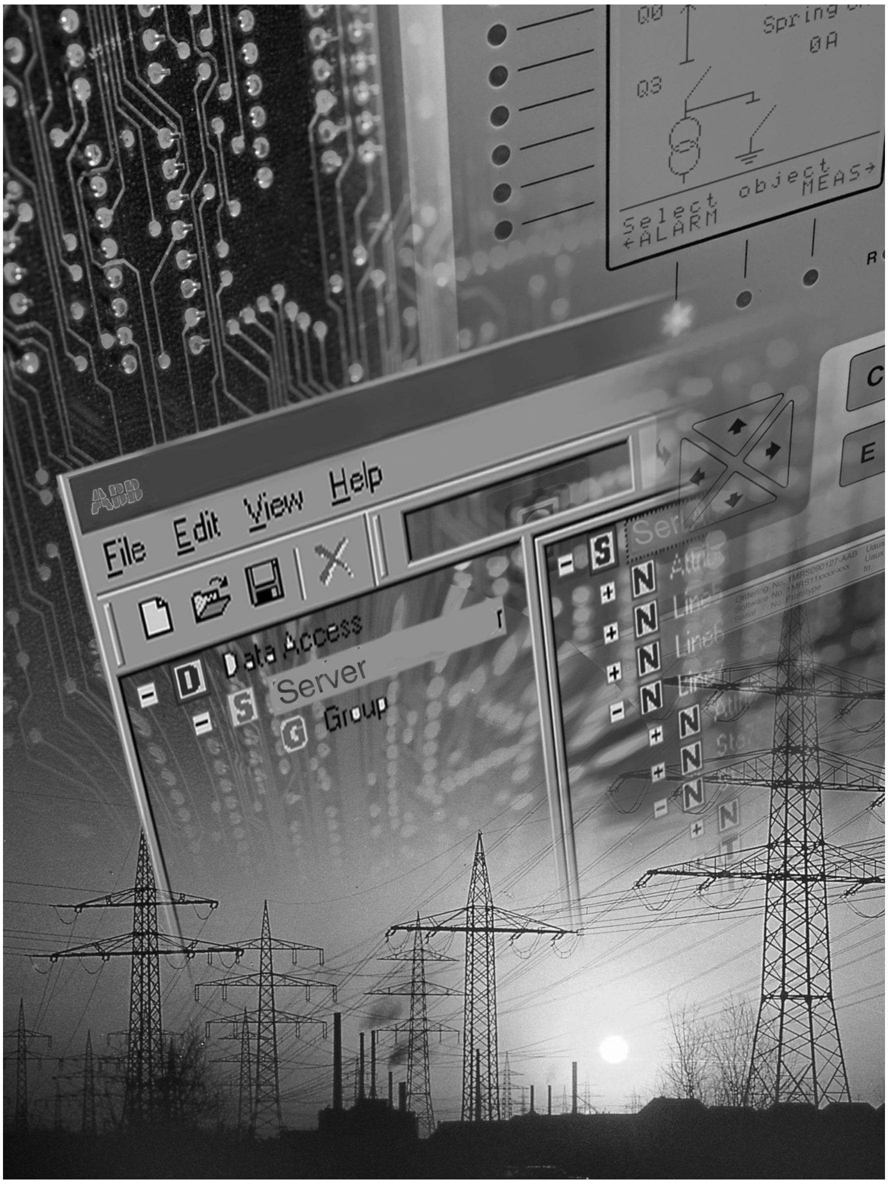
Power Factor Controller
REF 542*plus*

Application and Setting Guide



ABB

Contents

Copyrights

1. Scope

This document introduces the application of the power factor controller of REF 542*plus*. The power factor controller is designed to optimize the power factor during power system operation at heavy reactive power. The operation principle is based on measuring the power factor and the reactive power. If the power factor needs to be regulated, the power factor controller will switch on or off the dedicated capacitor bank, depending on the value of the reactive power. Up to four capacitor banks can be controlled by the power factor controller.

KEYWORDS: *power factor*, *reactive power*, *power factor controller*, *capacitor bank*

2. Introduction

The power factor controller is used for compensation of the reactive power of power systems. The magnitude of the reactive power Q in the power system can be calculated from the apparent power S and the active power P.

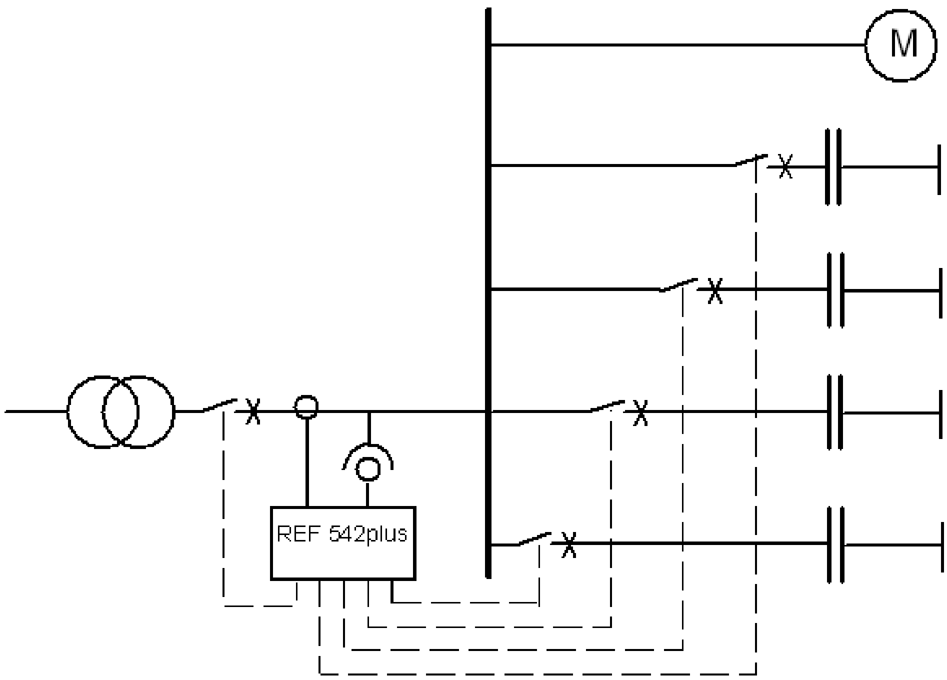
$$Q^2 = S^2 - P^2$$

The power factor cosφ is defined as the ratio between the active power and the apparent power:

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

Consequently, the power factor controller must permanently monitor the value of the power factor, which is used for calculating the reactive power component of the apparent power.

$$Q = S\sqrt{1 - \cos^2\varphi}$$



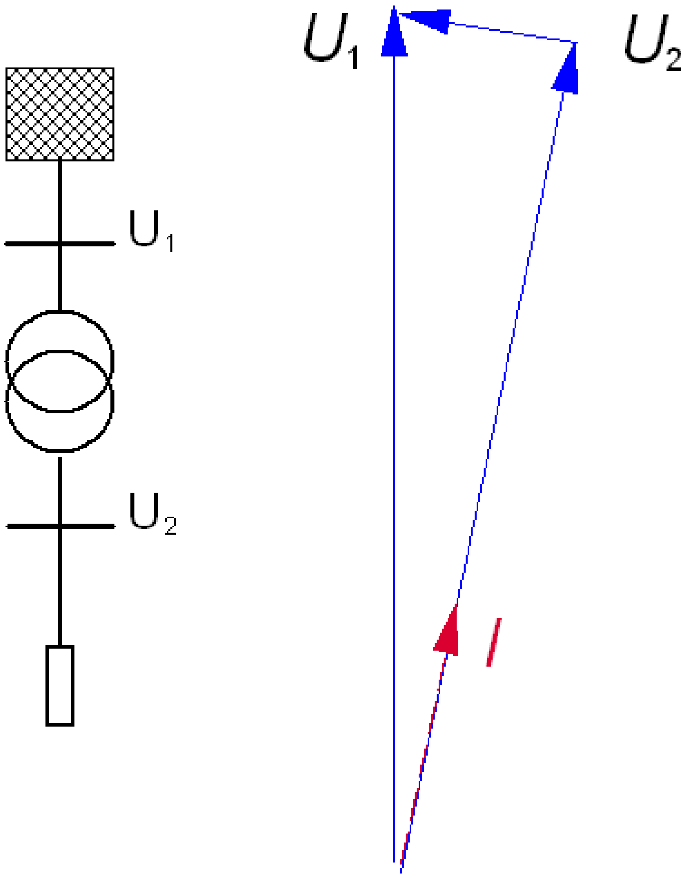
A070949

Fig. 2.-1 Principle of power factor control using REF 542*plus*

Fig. 2.-1 shows how REF 542*plus* can be used for power factor control. The REF 542*plus* terminal is located on the incomer. The power factor and the reactive power can be continuously calculated from the system voltages and currents. Based on the need for compensation at any given time, one to four capacitor banks can be switched on or off by the controller.

2.1. Voltage drop due to reactive power

When a consumer of reactive power is connected to the network, the currents will increase. At the same time, the phase displacement in relation to the corresponding voltage will increase. Consequently, the active power increases and the power factor is reduced accordingly. Because of the increasing current and the angle of the phase displacement, an increased voltage drop in the power system must be taken into account.



A070950

Fig. 2.1.-1 System voltages in connection with active power load

Fig. 2.1.-1 shows the system voltages in connection with an active power load. The single-line diagram of the power system is shown on the left-hand side. For the sake of simplicity, the transformation ratio of the transformer is assumed to be 1. The source voltage U_1 is assumed to be constant and the voltage U_2 is the load voltage at the point of consumption of active power. Under these operation conditions the current I and the voltage U_2 are in phase. As shown in the corresponding vector diagram, the amplitude of the voltage U_2 is almost unaffected by the active load.

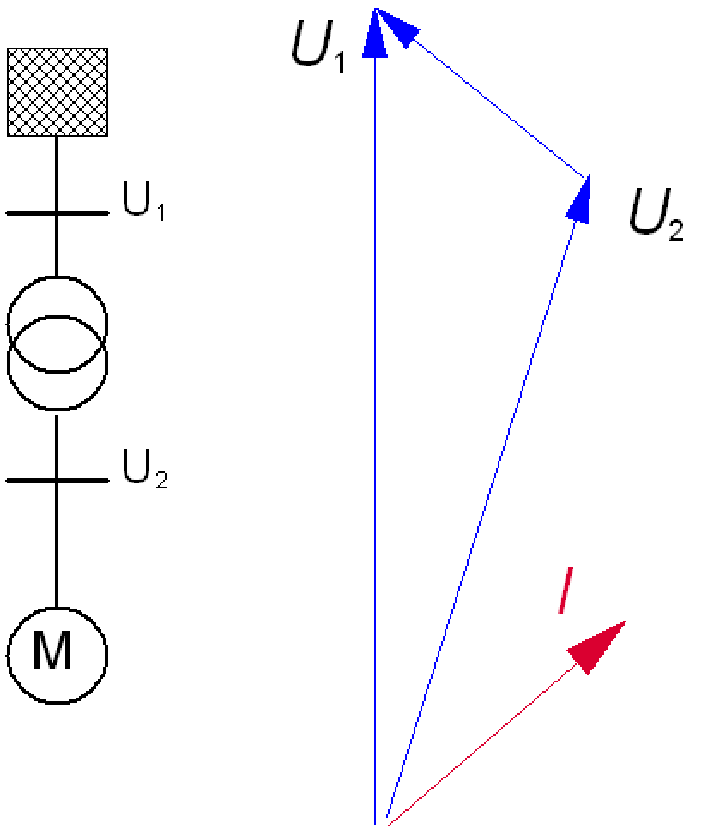


Fig. 2.1.-2 System voltages in connection with motor load

In a power system with motor load both active power and reactive power are drawn from the network. The vector diagram is shown in Fig. 2.1.-2. If additional inductive reactive power is required, as shown in the vector diagram, the amplitude of the voltage U_2 of the network can be substantially reduced.

To keep the voltage drop within certain limits at high consumption of reactive power, capacitors must be employed for compensation. By optimal switching of the required capacitor banks, the power factor controller function implemented in the REF 542*plus* allows the capacitive reactive power to be regulated to compensate the inductive reactive power of the motor load.

2.2. Compensation of reactive power

The principle of reactive power compensation is illustrated in Fig. 2.2.-1, where P_1 is the active power and Q_1 the reactive power. The active power is indicated by the horizontal axis and the reactive power by the vertical axis. The power factor $\cos\varphi_1$ shows the relationship between the active power P_1 and the apparent power S_1. The apparent power S_1, on the other hand, depends on the magnitude of the consumed active power P_1 and the reactive power Q_1.

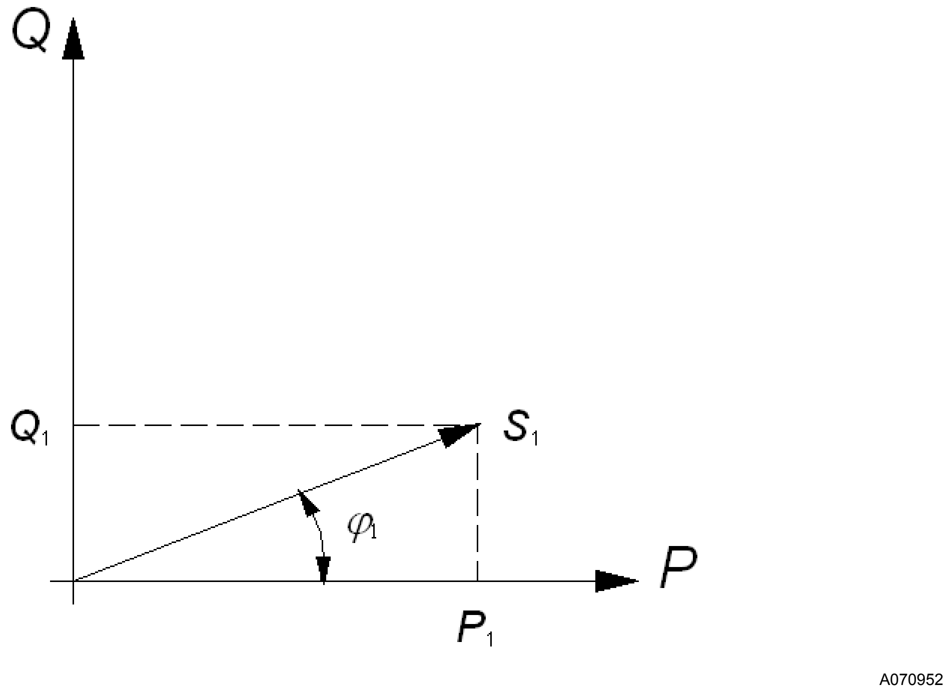


Fig. 2.2.-1 Reactive power diagram

The consumption of the inductive reactive power can generally be compensated by providing capacitive reactive power. Therefore, the power factor and the power consumption in the system must be continuously monitored. If the inductive reactive power is too high, a capacitor bank can be switched on to keep the voltage drop in the network within the required tolerance.

The principle of the switching operations is shown in Fig. 2.2.-2. If the reactive power demand is high, say, at the time *t*1 and *t*2, the required capacitor bank must be switched on, but if there is no demand any longer, the reactive power in the system becomes negative. In that case one of the connected capacitor banks must be switched off again, e.g. at the time *t*3.

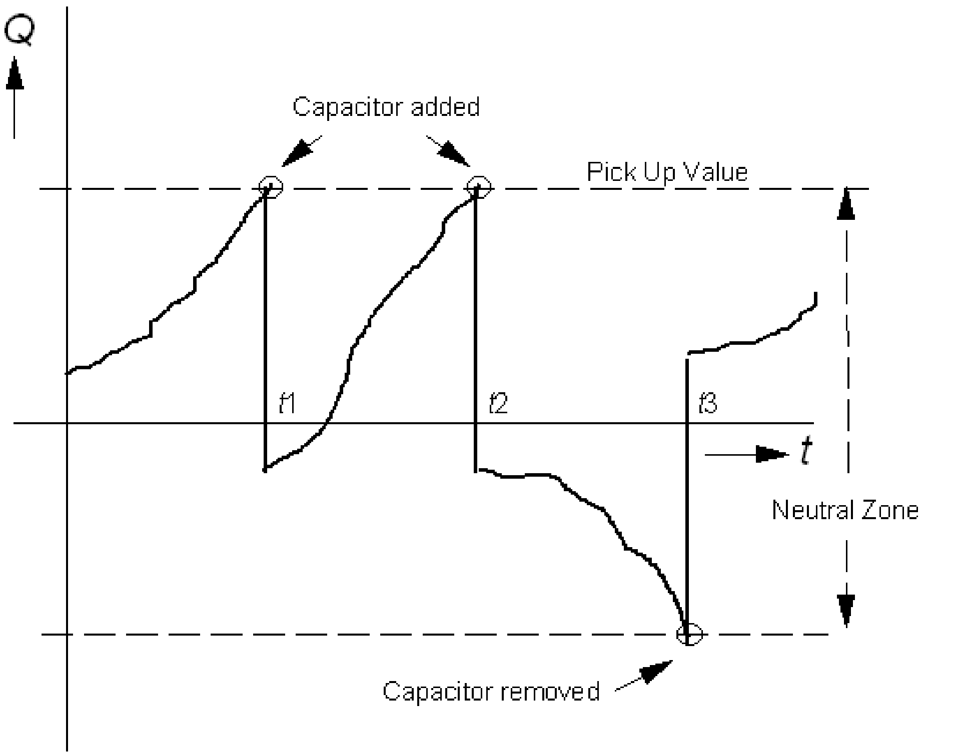


Fig. 2.2.-2 Principle of switching capacitors on and off

The need for compensation of the reactive power can be determined as shown in the power diagram in Fig. 2.2.-3. In this case the power factor $\cos\varphi_1$ is assumed to be the pick-up value, which, in power factor control, generally is referred to as the reversal point. Further, Fig. 2.2.-3 shows P_1 as the active power, Q_1 as the permitted reactive power and S_1 as the resulting apparent power. Furthermore, in the same diagram the momentary actual values are displayed too. Thereby P_2 is the actual active power, Q_2 the actual reactive power and S_2 is the actual resulting apparent power.

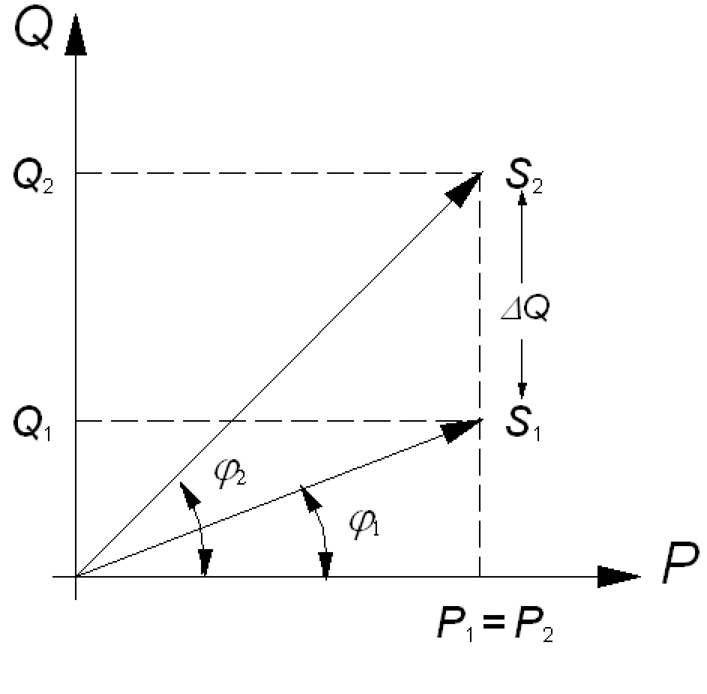


Fig. 2.2.-3 Determination of the capacitor output for compensation

To determine the capacitor value required for the compensation of the reactive power consumption, the active power P_1 at the pick-up value of the power factor $\cos\varphi_1$ is set to be equal to the active powerP_2. Then the corresponding reactive power Q_1can be calculated from the following equation:

$$Q_1 = S_1\sqrt{1-\cos^2\varphi_1} = P_1\frac{\sqrt{1-\cos^2\varphi_1}}{\cos\varphi_1}$$

The reactive power ΔQ to be compensated can be calculated from the difference between the reactive power Q_2 and the reactive power Q_1, at the pick-up value for the activation of the power factor controller, as shown in Fig. 2.2.-2.

$$\Delta Q = Q_2 - Q_1$$

As a result, the capacitance value of the capacitor banks to be switched on for compensating the reactive power can be determined.

Consequently, the automatic compensation of the reactive power can be based on continuous monitoring of the power factor and the corresponding reactive power. The sign of the reactive power difference ΔQ indicates whether a capacitor bank needs to be switched on or off. If the sign is positive, the capacitor bank needs to be switched on and if the sign is negative, the capacitor bank must be switched off.

To switch on a capacitor bank, the reactive power must first be defined as the activating pick-up value Q_{ON}.

$$Q_{ON} = \frac{K_{ON}}{100\%} Q_{CO}$$

The activating pick-up value is calculated by multiplying the factor K_{ON} expressed in percent by the smallest installed reactive power of the capacitor bank Q_{ON}, which can be switched on or off. The factor K_{ON} is the setting parameter "Pick Up Value" for starting the switching operation.

Hereby it is assumed that the capacitor bank number 0 (C_0) is the installed bank with the lowest reactive power.

The moment for switching on the capacitor bank can be estimated by continuously monitoring the reactive power ΔQ. The equation for calculating the difference of the reactive power can be changed as follows:

$$\Delta Q = Q_2 - Q_1 > Q_{CO}$$

The power factor controller will now be activated when

- the instantaneous power factor value falls below the pick-up value and
- the ratio of the calculated reactive power ΔQ to the smallest installed capacitor output Q_{C0} is greater than the set pick-up value K_{ON} in percent.

This is shown by the following expression:

$$\frac{\Delta Q}{Q_{CO}} > \frac{K_{ON}}{100\%}$$

The number N_{ON} (Q_{CO}) of the capacitor banks to be switched on can be determined by the following relationship:

$$N_{ON}(Q_{CO}) = \left(\frac{\Delta Q}{Q_{CO}} - \frac{K_{ON}}{100\%}\right) + 1$$

Once a capacitor bank is switched on, a set dead time starts. The dead time delays a control operation until the transient condition in the system is over. Power calculation shall be resumed after the dead time has expired and not until then a control operation will be permitted to start again.

However, if the inductive reactive power decreases, the instantaneous power factor value in the network may become capacitive. In this case, the reactive power ΔQ will assume a negative sign. This capacitive system condition is an undesirable state for operating the power system, because under these conditions a system overvoltage might occur. As a result, at least one capacitor bank must be switched off under these conditions. A criterion for determining the switch-off threshold, similar to that above for switching on, must also be defined.

$$Q_{OFF} = (K_{ON} - K_{OFF})Q_{CO}$$

Hereby, Q_{OFF} is the switch-off pick-up value, K_{OFF} the factor in percent of the smallest installed reactive power of the capacitor bank Q_{C0} to start the switch off operation. The expression (K_{ON} - K_{OFF}) is thereby equal to the setting parameter "Neutral Zone".

As already mentioned above, K_{ON} is a factor for switching on the capacitor bank, whereas Q_{C0} is the smallest installed power of the capacitor bank. For the proper operation of the power factor controller the condition for the so called neutral zone must be fulfilled:

$$(K_{ON} - K_{OFF}) > 1 \text{ or } 100\% \text{ respectively}$$

If a neutral zone is set to be less than 100%, the capacitor bank will be switched on and off without restrain.

The power factor controller is to switch off the capacitor bank if the ratio of the negative reactive power difference ΔQ to the smallest installed capacitor output is greater than the factor K_{OFF} in percent. This is shown by the following equation:

$$\left(\frac{\Delta Q}{Q_{CO}} - \frac{K_{OFF}}{100\%}\right) > 0$$

The number N_{OFF} (Q_{C0}) of capacitor banks to be switched off can be determined by the following relationship:

$$N_{OFF}(Q_{CO}) = \left(\frac{\Delta Q}{Q_{CO}} - \frac{K_{OFF}}{100\%}\right) - 1$$

3. Technical implementation

3.1. Operation modes

Fig. 3.1.-1 shows the power factor controller function block. The power factor controller features a manual and an automatic operation mode.

Fig. 3.1.-1 Power factor controller function block

At manual operation each capacitor bank can be switched on and off using the defined inputs of the function block. This means that pulse-type signals are to be used for switching on and off, which has to be considered in the configuration of the complete controller scheme. If a capacitor bank is switched on, a logical signal 1 will appear on the associated output. When this signal is switched off, the output will show a logical signal 0. To ensure that the controller is always informed of the switch status of the capacitor banks a check-back signal confirming the switch position must be fed back via the binary inputs. Fig. 3.1.-2 shows a configuration example for a power factor controller managing two capacitor banks.

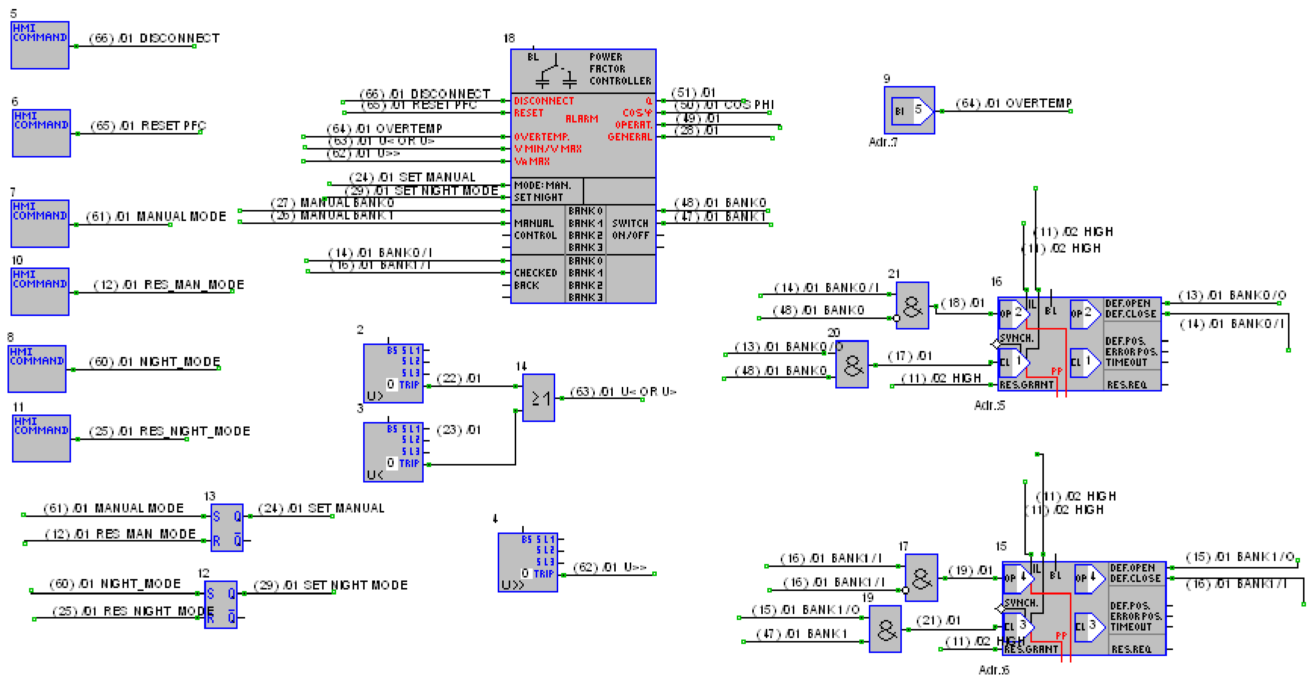

A070956

Fig. 3.1.-2 Configuration example for power factor controller

Compensation of reactive power is only required when the power system is in its operational state. Therefore, the operability of the power factor controller can be made dependent on the level of the system voltage. For this reason, the power factor controller should always include an overvoltage and undervoltage function for monitoring the system voltage. If one of the voltage limit pick-up values, either overvoltage or undervoltage, is exceeded and the respective time delay has expired, all active capacitor banks will be switched off immediately.

The above mentioned function is independent on whether the power factor controller is in manual or automatic operating mode. To activate this function the binary input VMIN/MAX shall be connected to the related output of the dedicated overvoltage or undervoltage function block. The binary input DISCONNECT can also be used to disconnect all active capacitor banks, when a logical signal 1 is connected to the input.

3.2. Time settings

When the auxiliary supply is switched on, the power factor controller is blocked for the initialization period and will not start operating until the initialization time has expired. The same initialization time starts when the system voltage is recovering after a power system fault, e.g. when the undervoltage signal has been reset and the binary input DISCONNECT is inactive. The initialization time is preferably given a value longer than the set blocking time for the capacitor banks to discharge.

If, during an ongoing power factor control sequence, a capacitor bank is switched on to compensate for the reactive power, transient phenomena will generally occur. This is why the calculation of the power factor control must be delayed until most of the transient phenomena have subsided. A dead time must be set for the power factor controller to bridge the transient condition of the system. Further switching of the capacitor group will not be enabled until the dead time has expired. However, a prerequisite for enabling switching of the capacitor group is that the concerned capacitor bank is fully discharged.

When a capacitor bank is switched off, the stored electrical energy of the capacitors must be discharged before the capacitor bank is switched on again. Therefore, the power factor controller should include a blocking time to ensure that there is enough time for the discharge of the capacitor bank.

3.3. Indications

As stated in the previous section, automatic control of the power factor will not be started unless the value of the power factor is lower than the pick-up value and the magnitude of the reactive power is higher than the permitted value calculated. If the reactive power no longer is to be compensated, an alarm can be generated by setting a specific pick-up value for the "Limiting value cos phi (Alarm)". The binary output "ALARM COS PHI" will then be generated, if the pick-up condition is fulfilled.

It is recommended that the pick-up value for the "Limiting value cos phi (Alarm)" is set below the pick-up value for starting the control process. This means that the binary output "ALARM COS PHI" will only be generated if the power factor controller is unable to switch on another capacitor bank.

If, however, the condition for starting the power control process still persists after the available capacitor banks have all been switched on, an alarm signal ALARM Q will be issued. This signal indicates that no more reactive power can be compensated, because all capacitor banks already have been switched on.

In the event of a power system outage, for example, the signal at the input V MIN/ V MAX will be a logical high signal, and all capacitor banks will automatically be switched off. Afterwards the output ALARM GENERAL will be a logical high. The power factor controller also includes inputs assigned to generate the Alarm GENERAL, if activated. These inputs are OVERTEMP and Va MAX. The input OVERTEMP is assigned to an overload protection function supervising the load or the temperature of the capacitor bank. The binary input Va MAX is to be used to alert the power factor controller when the system voltage exceeds the upper tolerance limit.

In the automatic operation mode, the power factor controller function will be blocked once ALARM GENERAL is present. Reactivation is possible only if the condition no longer exists and the power factor controller has been reset by activating the concerned input RESET.

Note
If ALARM GENERAL is activated, the power factor controller will be blocked until reset by the concerned RESET input.

In addition, the number of circuit-breaker switching cycles is constantly monitored and compared with the set parameter for limiting the number of switching cycles. If the set limit value is exceeded, the output Alarm OPERAT will be activated. The same monitoring applies to ALARM GENERAL before the power factor controller function is blocked. To make the power factor controller operative again a cold reset by switching off and on the power supply is required.

Note
If the ALARM OPERAT is activated, the power factor controller will be blocked until a cold reset is performed by switching the power supply off and on.

3.4. Automatic control of reactive power

In the automatic operation mode the instantaneous value of the power factor and the related reactive power in the system are continuously monitored. The sign of the reactive power ΔQ, which is calculated from the difference between the instantaneous reactive power and the reactive power at the pick-up value of the power factor, shows whether the capacitor banks need to be switched on or off. If the sign is positive, a capacitor bank must be switched on. If the sign is negative, an appropriate capacitor bank must be switched off.

The multifunction protection and control unit REF 542*plus* is capable of controlling a total of four capacitor banks. Fig. 3.4.-1 shows a single-line diagram of the capacitor bank configuration for compensating reactive power.

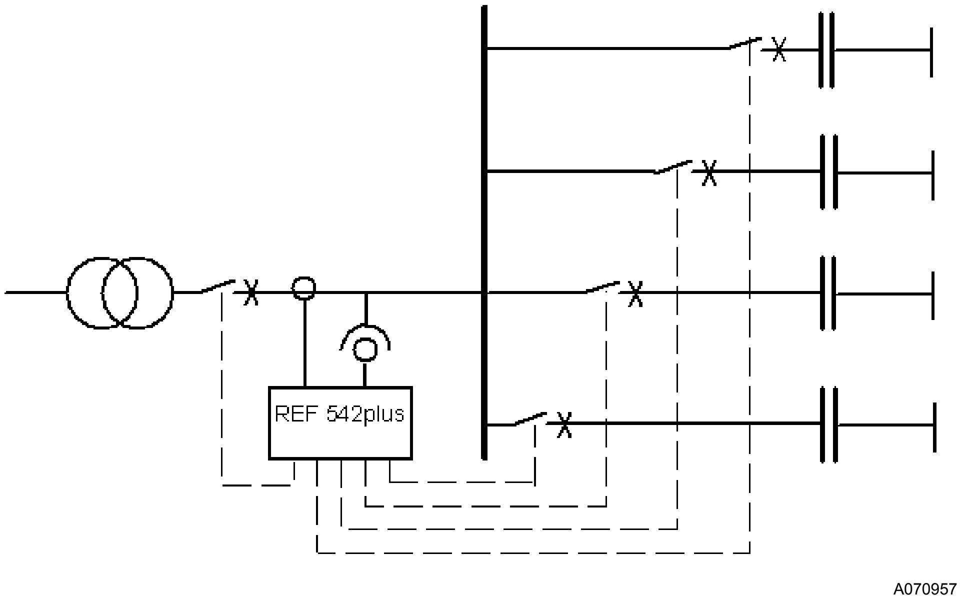


Fig. 3.4.-1 Capacitor banks for reactive power compensation

The setting parameters of the function block are defined as bank C_0, bank C_1, bank C_2 and bank C_3. The capacitor banks can have the same value or different reactive power values. If different reactive power values are used, bank C_0 must be configured as the smallest capacitor bank. Then the recommended reactive power rating based on C_0 is listed in Table 3.4.-1.

Table 3.4.-1 Possible reactive power ratings of the capacitor banks

C_0/C_0	C_1/C_0	C_2/C_0	C_2/C_0
1	1	1	1
1	1	2	2
1	2	2	2
1	2	4	4
1	2	4	8

If all capacitor banks are equally rated, they can be switched on and off either according to a linear or to a circular switching sequence. With a linear switching sequence the capacitor banks are switched on in ascending order and switched off in descending order of indices. On the contrary, with a circular switching sequence the capacitor banks are always switched on and off in ascending order.

The capacitor banks are always switched on and off in accordance with the calculated number N_{ON} or N_{OFF}. Only the calculated integer is taken into account. For example, if the calculated number of capacitor banks to be switched on is assumed to be equal to 3 and if the configuration of the capacitor banks is set to 1:2:4:8, the controller first attempts to switch on the second lowest bank C_1 with the reactive power $2Q_{C0}$. If the status check-back signal indicates that the capacitor bank C_1 is already switched on, the lowest bank C_0 with the reactive power Q_{C0} will be selected. However, if the banks C_1 and C_0 are already switched on, the next free bank in the order, that is, bank C_2 with the reactive power $4Q_{C0}$, will be selected and switched on.

When the C_2 bank with the reactive power $4Q_{C0}$ has been switched on, the control function will be blocked for the duration of the set dead time. The power controller is reactivated after the above mentioned dead time has expired. Because the switched on reactive power of the capacitor bank now is too high, the power factor controller will discover that the capacitor bank C_0 with Q_{C0} is to be switched off again. If the switch-off conditions, which must be determined from the setting of the neutral zone, are fulfilled, the switch-off process for bank C_0 will be started. Switching off the capacitor banks is in principle a similar process as switching-on a process.

3.5. Setting example

Two capacitor banks of 6.36 µF each shall be applied to compensate the reactive power in a 10 kV power system. Consequently, each capacitor bank is able to compensate a reactive power of

$$Q_{CO} = 200 kVAr$$

which equals the capacity of the smallest capacitor bank. The maximum number of switching cycles shall be limited to 10 000, which is given by the CB ratings provided by the manufacturer of the circuit breaker. The related setting parameter can be seen in Fig. 3.5.-1.

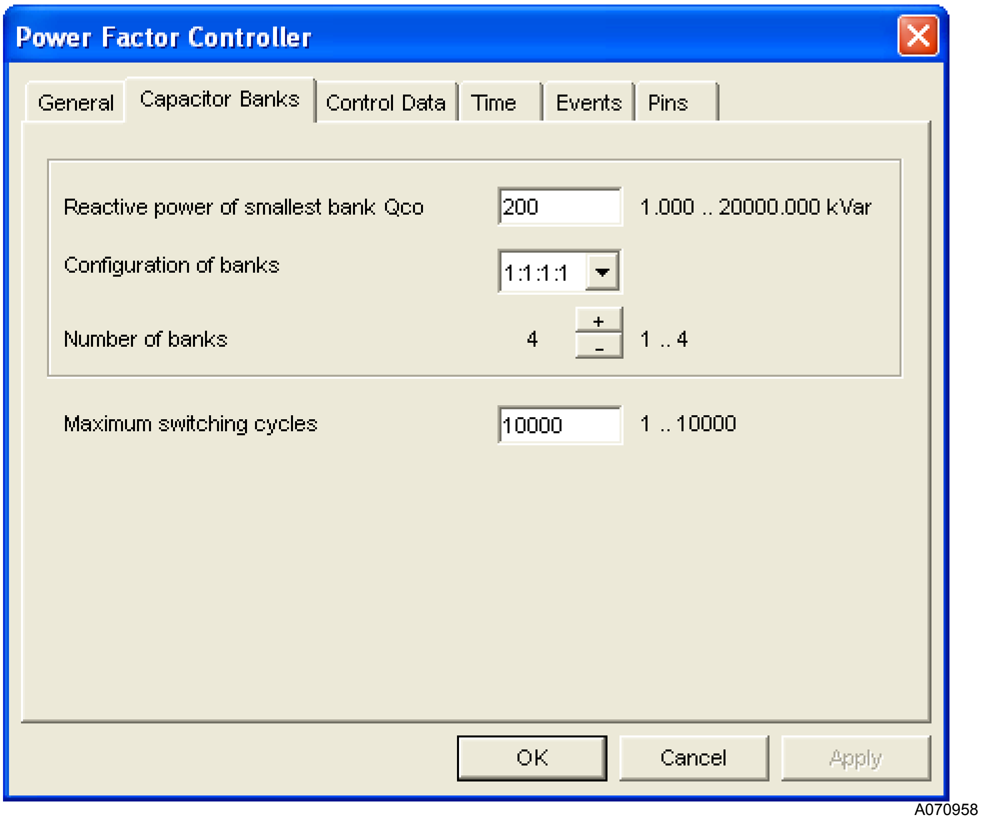
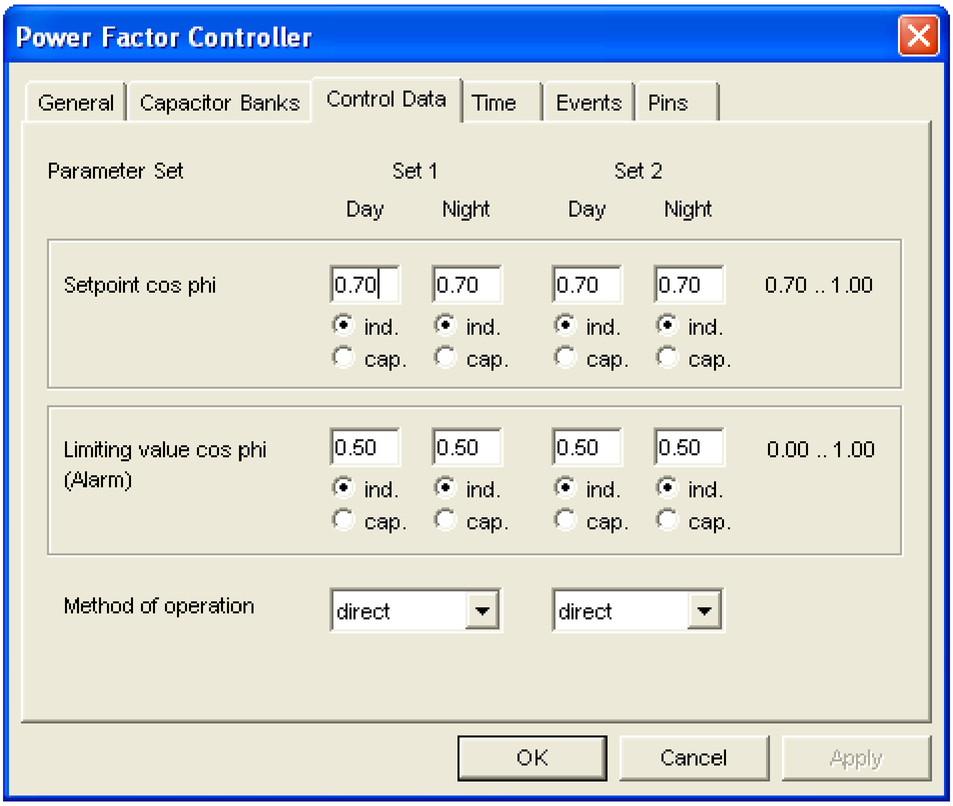


Fig. 3.5.-1 Setting parameter for the capacitor bank

One of the capacitor banks must be switched on at a certain apparent power, e.g. 250 kVAr and a power factor less than or equal to 0.7. As shown in Fig. 3.5.-2 the set-point for cos phi is selected to be 0.7 for day and night time. If required, a different value can be selected.



A070959

Fig. 3.5.-2 Setting parameter for the control data.

The limit value cosφ for generating the signal ALARM COS φ is selected to be 0.5. The method of operation can be direct or integration. The direct method uses the measurement value received from the DSP. If integration is used the mean value is calculated for a specified period of time, which can be set separately.

The portion of the reactive power for switching on the capacitor bank can be calculated as follows:

$$Q_{ON} = \sin(\arccos 0.7) \times 250kVAr = 178.5kVar$$

Accordingly, the pick-up value of the power factor controller shall be set to:

$$K_{ON} = \text{Pick Up} = \frac{178.5}{200}100\% = 89.2\%$$

The pick-up value mentioned above is equal to the factor K_{ON} described in Section 2.2. Compensation of reactive power and found to be 89%. To avoid the capacitor banks from being uninterruptedly switched on and off, the condition for the neutral zone must be fulfilled.

$$(K_{ON} - K_{OFF}) > 100\%$$

The lowest possible neutral zone setting of the is the power factor controller is therefore 105%. In this example a setting value of 115% is selected. This means that the capacitor bank will be switched off again, if the value of the reactive power falls below:

$$Q_{OFF} = (K_{ON} - K_{OFF})Q_{CO} = (0.89 - 1.15)200kVAR = -52kVAR$$

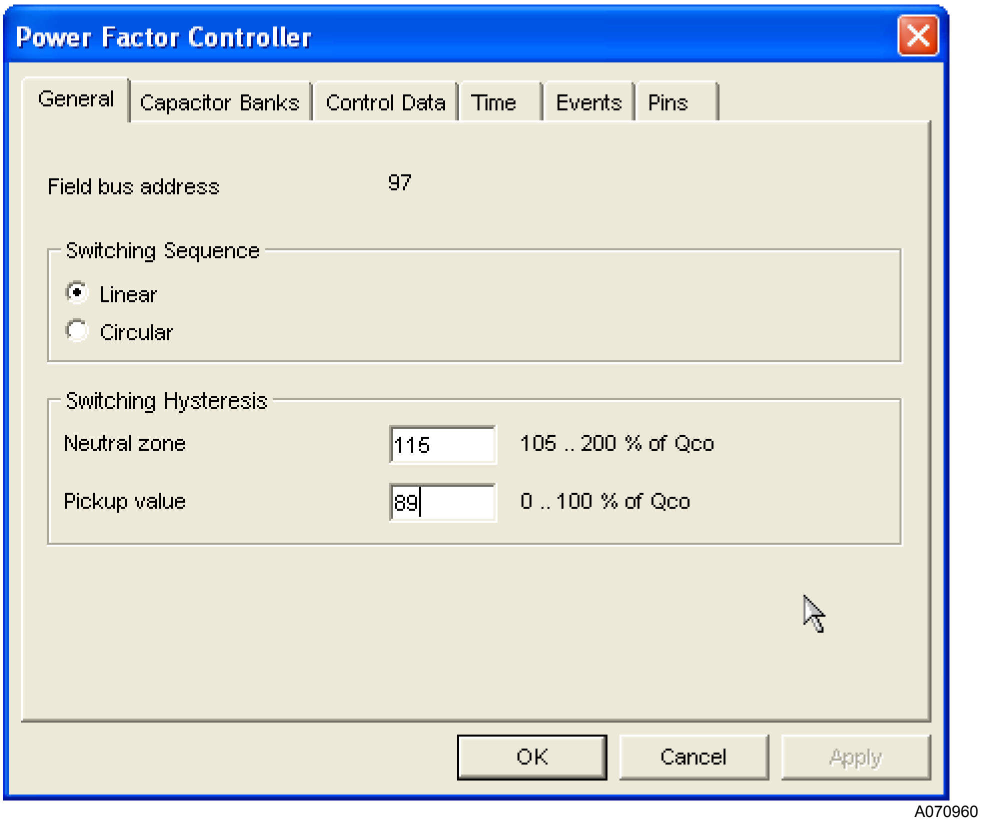


Fig. 3.5.-3 Setting parameter for general data.

The setting parameter can be seen in Fig. 3.5.-3. As mentioned above, the pick-up value is found to be 89% and the neutral zone 115%. The linear switching sequence is to be used.

The time setting has to be adapted to the operation condition of the power system. The discharge blocking time is the blocking period of a capacitor bank after it has been switched off. After switching on a capacitor bank, any power factor control is disabled until the dead time has expired. After a complete switch-off of all banks and recovery of the power supply of the power factor controller no capacitor banks can be switched on until the power-on delay time has elapsed. The setting of the dead times is shown in Fig. 3.5.-4.

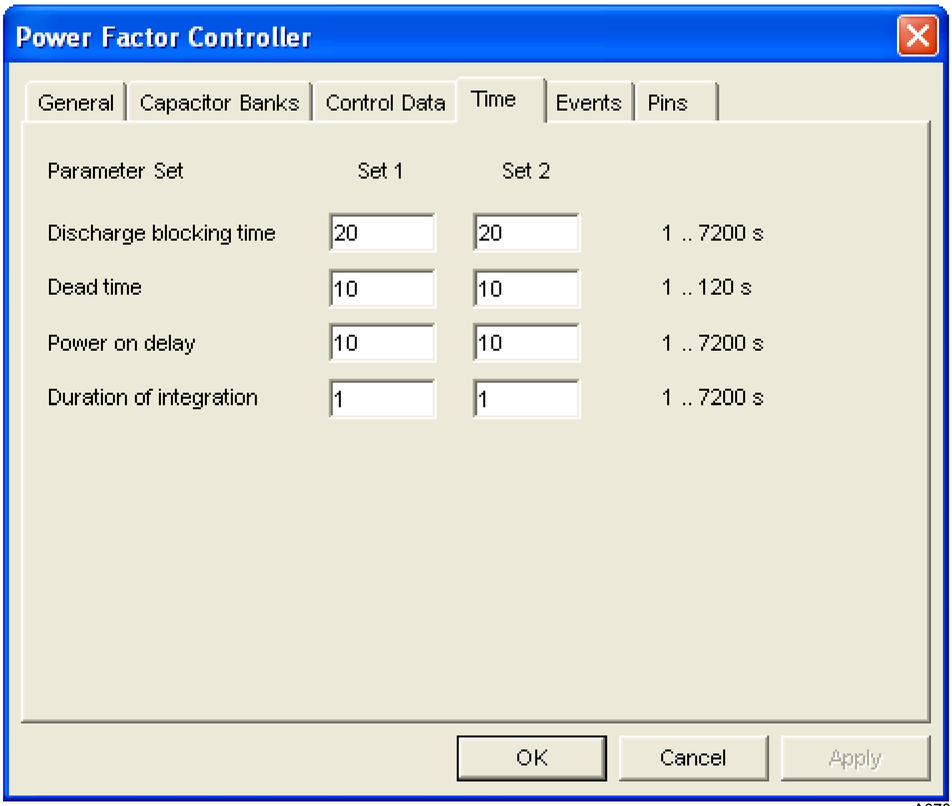


Fig. 3.5.-4 Setting parameter for the dead time

4. Summary

The power factor controller of REF 542*plus* is needed for controlling the compensation of reactive power in the power system. When a consumer of reactive power is switched into the network, the current magnitudes will increase. Simultaneously the phase displacement increases in relation to the voltage magnitude. Consequently, the active power increases and the power factor is reduced correspondingly, which, in turn, leads to a voltage drop in the power system.

The compensation of reactive power can be based on continuous monitoring of the power factor and the related reactive power. The sign of the difference of the reactive power, which can be calculated from the difference between the instantaneous reactive power and the reactive power at the pick-up value for the activation, gives an indication on whether a capacitor bank needs to be switched on or off. If the sign is positive, a capacitor bank must be switched on and if the sign is negative, a capacitor bank must be switched off.

The setting of the power factor controller is exemplified by an application with two controllable capacitor banks. The setting parameters for performing the power factor control are all described.

5. References

W. Hofmann, W. Just: Blindstrom-Kompensation in der Betriebspraxis, 4. Auflage 2003, VDE Verlag GmbH, ISBN: 3800726513

1MRS755860: Protection Functions, Configuration and Settings

6. List of symbols

S	Apparent power
P	Active power
Q	Reactive power
φ	Phase shift angle between current and voltage quantity
Cos φ	Power factor
K_{ON}	Activating pick-up value KON in percent
K_{OFF}	Switch off pick-up value in percent and equal to parameter "Neutral Zone"
N_{ON}	Number of the capacitor banks to be switched on
N_{OFF}	Number of the capacitor banks to be switched off
Q_{C0}	Smallest installed reactive power of the capacitor bank
Q_{ON}	Activating pick up value

ABB Oy
Distribution Automation
P.O. Box 699
FI-65101 Vaasa
FINLAND
Tel. +358 10 22 11
Fax. +358 10 224 1094
www.abb.com/substationautomation

1MRS756441 EN 11.2007