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One approach for reactive power control of capacitor banks in distribution and industrial networks

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ABSTRACT

This paper presents an efficient solution for reactive power control of capacitor bank using changes in reactance of connected reactor. This solution ensures smooth control of reactive power of capacitor banks as important operational characteristic for maintaining the quality of supply. The proposed method works for a wide-range of reactive power variations in the system and is capable of injecting or absorbing reactive power when necessary. This control method can be successfully used in distribution and industrial networks where many loads vary their demand for reactive power. Other applications of this method are voltage regulation, power-factor correction and reactive power compensation. The effectiveness of the proposed method is demonstrated through the case studies in order to prove its feasibility for improvement of voltage profile and reduction of power losses.

Introduction

Reactive power control has been recognized as a significant factor in design and operation of transmission and distribution (and industrial) networks for a long time. The rapid development and relative economy of shunt compensation devices led to their almost displacing of synchronous condensers in the transmission networks. At the same time, shunt compensation devices installed in distribution and industrial networks have become the best way to improve of voltage regulation, power-factor correction, load (phase) balancing and the handling of harmonics. Reactive power control is very important operational function for maintaining the quality of supply, particularly in preventing voltage disturbances that are the most frequent type of disturbance. Certain types of industrial load, including electric furnaces, rolling mills, mine hoists and dragline excavators, impose on the supply large and rapid variations in their demand for reactive power and it is often necessary to compensate for them with voltage stabilizing equipment in the form of static reactive power compensators [1,2].

Voltage regulation becomes an important and sometimes critical issue in the presence of loads that vary their demand for reactive power [3–8]. All loads vary their demand for reactive power, although they differ widely in their range and rate of variation. In all cases, the variation in demand for reactive power causes variation in the voltage at the supply point that can interfere with the efficient operation of supply network, giving rise to the possibility of interference between loads belonging to different consumers. Compensating devices have an essential role to play in maintaining supply voltages within the intended limits [9–13].

In most industrial harmonics networks, the primary objective for installing capacitor banks is to meet the utility power factor requirements. Additional benefits are better voltage regulation and lower losses. Any capacitor banks can be a source of parallel resonance with the system inductance. The best approach to avoid resonance problems is to install large capacitor banks at the main bus. This solution offers the following advantages: (i) more available reactive power to the network as a whole, (ii) easier control of harmonic voltages and currents, (iii) lower capital costs, as large banks are more economical in terms of purchase cost and (iv) reactors can be added to shift the resonant frequency away from the characteristic harmonic frequency of the plant [3].

For reactive power control in distribution and industrial networks mainly used capacitor bank configurations realized through changing the connection scheme certain number of capacitor sections according reactive load requirements. In these applications mechanically switched capacitor banks [14–16] are the most economical reactive power compensation resources. They are a simple, no effect on the short-circuit power and low-cost, but low-speed solution for voltage control and network stabilization

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under heavy load conditions. Newer solutions enable change of reactive power from capacitor banks as smooth output or output in very small blocks. These solutions contain a minimal number of switches and become very rational.

One of the most important problems related to the planning of electrical distribution and industrial networks is selection of the optimal size and allocation of capacitor banks. In the recent literature a numerous techniques for solving this problem have been used. For example, the works presented in [17,18] search the optimal location of capacitor banks and voltage regulators in distribution networks. The strategy proposed in [17] involves the allocation of capacitor banks with specification for the type of bank (fixed or automatic) and reactive power, as well as the allocation of voltage regulators with adjustment of their secondary voltage. For allocating voltage regulators and fixed or switched capacitor banks in radial distribution systems, the proposed model in [18] evaluates the set of equipments most appropriate to be installed. In [19] optimal capacitor bank sizes are determined using an efficient heuristic method, while appropriate capacitor bank locations are identified using nodes stability-indices. The proposed technique in [20] finds optimal locations for shunt capacitor banks from the daily load curve and it determines the suitable values of fixed and switched capacitors. A dynamic model considering multiperiod capacitor banks allocation problem of the primary radial distribution system is proposed in [21]. In reference [22] a new dynamic reactive power control method for the micro grid that is designed for small scale unbalanced distribution systems is presented. This method dynamically coordinates between voltage and reactive power generation and consumption to keep the bus voltages close to their nominal value.

The static VAr compensator is one of the modern power electronics equipment that ensures fast and continuous capacitive and inductive power supply to the electric power system. Generally, there are two approaches to the realization of power electronics based on VAr compensators: the first one that uses thyristor-switched capacitors and reactors and the second that uses self-commutated static converters [13]. Different configurations and arrangements thyristor-switched capacitors (TSC), binary thyristor-diode-switcher capacitors, thyristor-controlled reactors (TCR), thyristor-controlled reactor with shunt capacitor are used depending on application. All these arrangements have their own advantages and disadvantages especially when it comes to a continuous range of reactive power control, generation of harmonics components during the control process, sometimes uneconomical construction, etc. Static compensators combined with TSC and TCR are more advanced configurations characterized by a continuous control, practically no transients, low generation of harmonics and flexibility in control and operation. Significant progress of gate commutated semiconductor devices has attracted attention on self-commutated VAr compensators, capable of generating or absorbing reactive power without requiring large banks of capacitors or reactors.

While searching for solutions that would ensure continuous range of reactive power control, we have investigated a design of compensator that is presented in this paper. The design is based on the arrangement of the capacitor bank composed of 9 sections and the reactor. With this arrangement it is possible to ensure smooth control of reactive power by using change of reactor reactance, which is the main contribution of the paper. The proposed solution has an attractive theoretical simplicity and represents motivation for further researches (behavior of compensator in dynamic simulations, analyses of harmonics and flickers, etc.). It seems to us that thyristor-controlled reactor would be a good solution. This compensator would be installed on MV buses like a shunt compensator.

Notation

The notation used throughout the paper is stated below:

U	applied line voltage in the network
m, n	positive real numbers
C_1, C_2, C_3	capacitances of individual capacitor units
X_1	impedance of the capacitor C_1
R, X	resistance and reactance of the connected reactor
X_0, X_P	reactance that represent zero and reactance that represent pole of function $Q = f(X)$
$X_{\min}$, $X_{\max}$	minimum and maximum value of reactance of the reactor
Q	reactive power of the capacitor bank with connected reactor (reactive power of the compensator)
Q_∞	reactive power of the capacitor bank with disconnected reactor
$Q_{\min}$, $Q_{\max}$	minimum and maximum value of reactive power of the compensator

Design and performance of compensator

The capacitor banks consist of several capacitors per phase, each of that is connected or disconnected, as needed, by mechanical (thyristor) switches. This capacitor arrangement has a control system that monitors the voltage. When the voltage deviates from the desired value by some preset error in either direction, the control switches in (or out) one or more capacitors until the voltage returns inside the defined range, provided that not all capacitors have been switched in (out). It is very important to note that because of the on/off nature of the capacitor banks control, the compensating current can change only in discrete steps as a result of control action. In medium voltage applications (distribution and industrial networks) the number of capacitor banks is limited to a small number (for example, three or four) because of the expense of the thyristor (or mechanical) switches. As a result, the discrete steps in compensating current may be quite large, giving somewhat coarse control.

The solution that provides a change of reactive power of capacitor banks continuously or in very small discrete steps and which should be economical rational, is presented in Fig. 1.

For analyzed bank arrangement, $C_2 = C_1/m$ and $C_3 = C_1/n$, where, in the general case, m and n are positive real numbers. For this connection, with $\underline{Z} = R + jX$ and $X = const$, it is not difficult to show that the condition:

$$\frac{1}{\omega C_1} = \frac{2}{3}\frac{1+m+3n}{m+n+mn}X$$

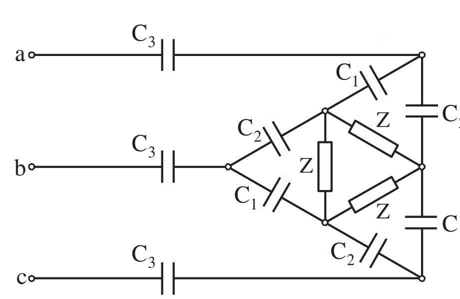

Fig. 1. The capacitor bank arrangement composed of 9 sections and reactor.

resulting in the fact that the rated voltage on impedance $\underline{Z}$ is independent of changes in its resistance R. Then the voltage on impedance has the form:

$$U_Z = U\frac{\sqrt{1-m+m^2}}{1+m+3n}$$

where U is the applied line voltage in the network shown in Fig. 1.

Let $\underline{Z}_1 = -jX_1$, $\underline{Z}_2 = m\underline{Z}_1$, $\underline{Z}_3 = n\underline{Z}_1$ and $\underline{Z} = R + jX$ represent the impedances of capacitors C_1, C_2, C_3 and reactor, respectively. System illustrated in Fig. 1 is symmetrical and it is easy to show that equivalent admittance per phase is given as follows:

$$\underline{Y}_e = \frac{1}{\underline{Z}_e} = \frac{3(\underline{Z}_1+\underline{Z}_2+\underline{Z})}{3(\underline{Z}_1\underline{Z}_2+\underline{Z}_2\underline{Z}_3+\underline{Z}_1\underline{Z}_3)+\underline{Z}(\underline{Z}_1+\underline{Z}_2+3\underline{Z}_3)}$$

or in the form:

$$\underline{Y}_e = \frac{3}{X_1}\frac{(1+m)X_1 - X + jR}{(1+m+3n)R + j((1+m+3n)X - 3(m+n+mn)X_1)}$$

Apparent power injected by the network to the capacitor bank arrangement (with reactor) is given as follows:

$$\underline{S} = P + jQ = \underline{Y}_e^* U^2$$

where after substitution active and reactive power become:

$$P = 3RU^2\frac{1-m+m^2}{(1+m+3n)^2R^2 + ((1+m+3n)X - 3(m+n+mn)X_1)^2}$$

$$Q = -\frac{3U^2}{X_1}\frac{(1+m+3n)R^2 - ((1+m)X_1 - X)((1+m+3n)X - 3(m+n+mn)X_1)}{(1+m+3n)^2R^2 + ((1+m+3n)X - 3(m+n+mn)X_1)^2}$$

In the case when the resistance R can be neglected compared to the reactance X and reactance X_1 (this is a case that is of interest to us), reactive power have simpler form:

$$Q = -\frac{3U^2}{X_1}\frac{X-(1+m)X_1}{(1+m+3n)X - 3(m+n+mn)X_1} \quad (1)$$

If only the reactance X on the right hand side of Eq. (1) changes, then the derivative of Q with respect to X is written as:

$$\frac{dQ}{dX} = -3U^2\frac{1-m+m^2}{((1+m+3n)X - 3(m+n+mn)X_1)^2}$$

Since

$$1 - m + m^2 > 0, \quad \forall m \in \mathbb{R}^+$$

it follows:

$$\frac{dQ}{dX} < 0$$

The function $Q = f(X)$ is decreasing on the interval $(-\infty, +\infty)$. Several characteristic values of this function, with the respect on corresponding values of reactance X, are given below:

$X = 0$	→	$Q = -\frac{U^2}{X_1}\frac{1+m}{m+(1+m)n}$
$X = 3\frac{m+n+mn}{1+m+3n}X_1$	→	$Q = \infty$
$X = (1+m)X_1$	→	$Q = 0$
$X = \infty$	→	$Q = -\frac{3U^2}{X_1}\frac{1}{1+m+3n}$

Denote with X_P and X_0 pole and zero of function $Q = f(X)$, respectively:

$$X_P = 3\frac{m+n+mn}{1+m+3n}X_1 \quad (2)$$

$$X_0 = (1+m)X_1 \quad (3)$$

Since m and n are positive real numbers, then:

$$3\frac{m+n+mn}{1+m+3n} = 1 + m\left[1 - \frac{1}{m}\frac{1-m+m^2}{1+m+3n}\right] < 1+m$$

it can be concluded that $X_P < X_0$. The graph of function $Q = f(X)$ is shown in Fig. 2.Introducing

$$Q_\infty = -\frac{3U^2}{X_1}\frac{1}{1+m+3n} \quad (4)$$

then Eq. (1) can be written as:

$$Q = Q_\infty\frac{X_0 - X}{X_P - X} \quad (5)$$

where Q_∞ is reactive power of the capacitor bank with disconnected reactor.

In the case of known parameters: U, m and n, the problem is reduced to determining the reactance X_1 and the interval within that is need to change the reactance of reactor X from $X_{\min}$ to $X_{\max}$, to the reactive power Q changed from $Q_{\min}$ to $Q_{\max}$. In this $Q_{\min}$ and $Q_{\max}$ are parameters specified in advance. Since it is usually necessary to $Q_{\max}$ is (3–4) times greater than $Q_{\min}$, from Fig. 2 it is obvious that the reactance of reactor X needed to change in the interval $0 \leqslant X \leqslant X_P$, while ensuring that the voltage in any section of capacitor bank is not above the allowed values.

In accordance with Eq. (5), for boundary values of reactance of reactor $X_{\min}$ and $X_{\max}$ there is:

$$Q_{\min} = Q_\infty\frac{X_0 - X_{\min}}{X_P - X_{\min}} \quad (6)$$

$$Q_{\max} = Q_\infty\frac{X_0 - X_{\max}}{X_P - X_{\max}} \quad (7)$$

so that:

$$X_{\min} = \frac{X_0Q_\infty - X_PQ_{\min}}{Q_\infty - Q_{\min}} \quad (8)$$

$$X_{\max} = \frac{X_0Q_\infty - X_PQ_{\max}}{Q_\infty - Q_{\max}} \quad (9)$$

From Eqs. (6) and (7) follows:

$$k = \frac{Q_{\max}}{Q_{\min}} = \frac{X_0 - X_{\max}}{X_P - X_{\max}}\frac{X_P - X_{\min}}{X_0 - X_{\min}} \quad (10)$$

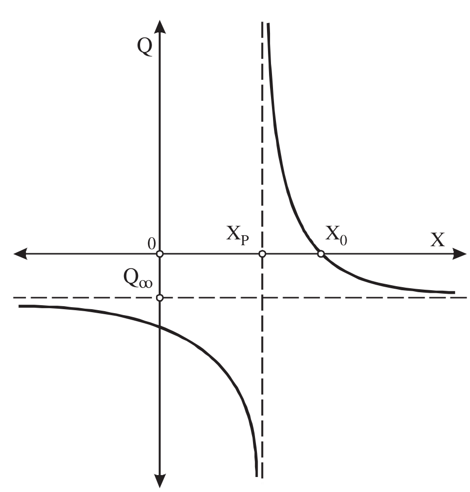

Fig. 2. The graph of function $Q = f(X)$.

Table 1
Results for test case #1.

Known values	Calculated values
$U = 10$ kV	$X_P = 212.80\ \Omega$
$m = 7.983$	$X_0 = 614.44\ \Omega$
$n = 0.227$	$Q_\infty = -0.45$ MVAr
$X_1 = 68.4\ \Omega$	$X_{min} = 94.91\ \Omega$
$Q_{min} = -2$ MVAr	$X_{max} = 179.94\ \Omega$
$Q_{max} = -6$ MVAr	

Table 2
Results for test case #2.

Known values	Calculated values
$U = 10$ kV	$X_P = 212.80\ \Omega$
$m = 7.983$	$X_0 = 614.44\ \Omega$
$n = 0.227$	$Q_\infty = -0.45$ MVAr
$X_{min} = 94.91\ \Omega$	$X_1 = 68.4\ \Omega$
$Q_{min} = -2$ MVAr	$X_{max} = 179.94\ \Omega$
$Q_{max} = -6$ MVAr	$\alpha = -37.661$

Table 3
Results for test case #3.

Known values	Calculated values
$U = 10$ kV	$X_P = 212.80\ \Omega$
$X_{min} = 94.91\ \Omega$	$X_0 = 614.29\ \Omega$
$X_{max} = 179.94\ \Omega$	$Q_\infty = -0.45$ MVAr
$Q_{min} = -2$ MVAr	$X_1 = 68.42\ \Omega$
$Q_{max} = -6$ MVAr	$m = 7.978$
	$n = 0.227$

In solving this problem from the total of 8 parameters: U, m, n, X_1, X_{min}, X_{max}, Q_{min} and Q_{max}, if assumed 6 of them as known values, the other two can be determined analytically. The simplest case is when the values U, m, n, X_1, Q_{min} and Q_{max} are known. Then using the Eqs. (2)–(4) can be determined X_P, X_0 and Q_∞, and using Eqs. (8) and (9) can be determined values X_{min} and X_{max}. Complicated case is that of the known values U, m, n, X_{min}, Q_{min} and Q_{max}, and then substitute Eqs. (2)–(4) into Eq. (8) and solving for X_1 we get:

$$X_1 = -\alpha + \sqrt{\alpha^2 + \frac{X_{min}U^2}{(m+n+mn)Q_{min}}}$$

where:

$$\alpha = \frac{3(1+m)U^2 - (1+m+3n)X_{min}Q_{min}}{6(m+n+mn)Q_{min}}$$

Next, with the known parameter X_1 and using of Eqs. (2)–(4) can be determined values X_P, X_0 and Q_∞, and after that, from Eq. (9) can be determined value X_{max}.

The problem is most interesting if are known values U, X_{min}, X_{max}, Q_{min} and Q_{max} and it is necessary to determine the values m, n, X_1. It is obvious that, in the general case, there exist several possible solutions. In order to choose the optimal solution, it is necessary to first define the criteria for finding solution. One approach to solving is as follows. Solving the Eq. (10) for X_0 we get:

$$X_0 = \frac{X_P - X_{min} - k\frac{X_{min}}{X_{max}}(X_P - X_{max})}{X_P - X_{min} - k(X_P - X_{max})}X_{max} \tag{11}$$

To numerator and denominator of a fraction in Eq. (11) were positive, it is necessary to satisfy the condition:

$$X_P < \frac{kX_{max} - X_{min}}{k-1} \tag{12}$$

Therefore, the value of X_P should be chosen within the interval:

$$X_{max} < X_P < \frac{kX_{max} - X_{min}}{k-1} \tag{13}$$

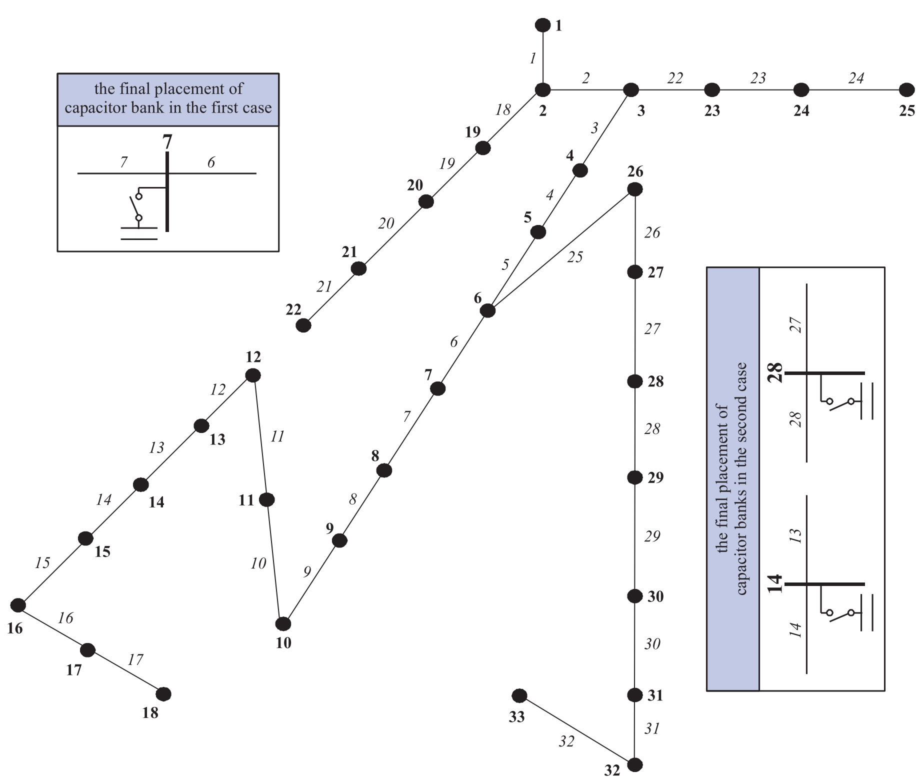

Fig. 3. Single-line diagram of radial IEEE-33 bus distribution network.

Table 4
Details in the study distribution network.

Branch No.	Sending node	Receiving node	Resistance Ω	Reactance Ω	Active power of receiving node kW	Reactive power of receiving node kVAr
1	1	2	0.0922	0.0470	100	60
2	2	3	0.4930	0.2511	90	40
3	3	4	0.3660	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.8190	0.7070	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.0300	0.7400	60	20
9	9	10	1.0440	0.7400	60	20
10	10	11	0.1966	0.6500	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.4680	1.1550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5740	90	40
18	2	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	6	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5302	60	40

With the chosen value of X_P from Eq. (11) can be determined value of X_0, and after that value of Q_∞ using Eqs. (6), (7). Values m and n will be positive if the following condition is satisfied:

$$-\frac{3U^2}{X_0} \leqslant Q_\infty \leqslant -\frac{3U^2}{X_0^2}(X_0 - X_P) \tag{14}$$

If this condition is not satisfied, it is necessary to correct the value of X_P and repeat the process. When the obtained value of Q_∞ satisfies the condition (14), then solving Eqs. (2)–(4) we get:

Table 5
Results with single capacitor bank.

Case	Bank site (node)	Bank size (MVAr)	Network losses (kW)
Without capacitor bank	–	–	318.21
With one capacitor bank	7	−1.897	241.66

$$X_1 = \frac{X_0}{2} \pm \sqrt{-\frac{U^2}{Q_\infty}(X_0 - X_P) - \frac{X_0^2}{12}} \tag{15}$$

$$m = \frac{X_0}{X_1} - 1 \tag{16}$$

$$n = \frac{1}{X_1}\left(-\frac{U^2}{Q_\infty} - \frac{X_0}{3}\right) \tag{17}$$

In order to avoid approaching the reactor reactance value X_P, it is necessary to work in a slightly different conditions, for example with $X > X_0$. It is obvious from Fig. 2 that for $X_P < X < X_0$ whole system works as consumer of reactive power and for $X > X_0$ system works as producer of reactive power.

Numerical results

Parameters for the design of capacitor bank

In accordance with presented mathematical model of reactive power control, several test cases and obtained results will be illustrated depending on the parameters which are known. Let's consider a distribution supply system at 10 kV line voltage. Three test cases whose results are illustrated in Tables 1–3, are analyzed.

In test case #1 capacitances of the capacitors C_1, C_2, C_3 or parameters X_1, m, n are known. An interval of change in reactive power from $Q_{\min}$ to $Q_{\max}$ is also known. In this case the values for X_P, X_0 and Q_∞ can be obtained, and then interval for changing reactance of reactor from $X_{\min}$ to $X_{\max}$ can be determined.

In test case #2 the parameters m, n and $X_{\min}$ are known. An interval of change in reactive power from $Q_{\min}$ to $Q_{\max}$ is known. In this case the values for X_P, X_0 and Q_∞ can be obtained, and then the values for reactance X_1 and $X_{\max}$ can be determined.

Test case #3 is the most interesting. In this case an interval of change in reactance of the reactor from $X_{\min}$ to $X_{\max}$ is known. Here

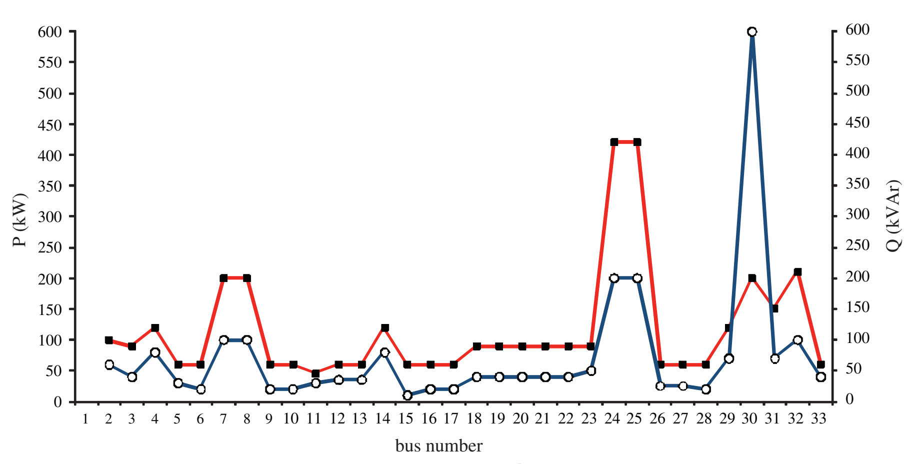

Fig. 4. Load profile in distribution network.

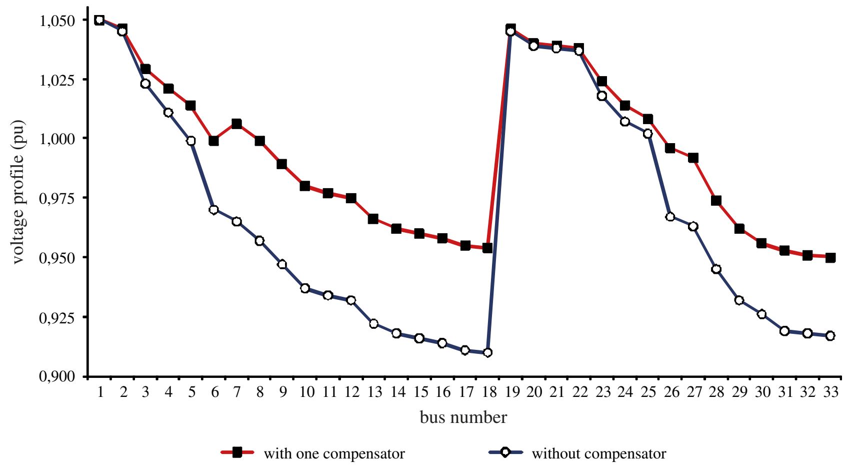

Fig. 5. Voltage profile in distribution network without and with one compensator.

Table 6
The design parameters of the proposed compensator that will be installed at node 7.

Known values	Calculated values
$m = 3.243$	$X_P = 249.97\ \Omega$
$n = 0.634$	$X_0 = 366.17\ \Omega$
$X_1 = 86.3\ \Omega$	$Q_\infty = -0.57$ MVAr
$Q_{min} = -0.85$ MVAr	$X_{min} = 18.75\ \Omega$
$Q_{max} = -2$ MVAr	$X_{max} = 204.14\ \Omega$

Table 7
Results with two capacitor banks.

Case	Bank site (node)	Bank size (MVAr)	Network losses (kW)
Without capacitor bank	–	–	318.21
With two capacitor banks	14; 28	−1.062; −1.039	223.74

it is necessary to design capacitances for capacitor bank – values for parameters X_1, m and n. The interval of change in reactive power from Q_{min} to Q_{max} is known. In accordance with the model presented by Eqs. (11)–(17), the values for X_P, X_0 and Q_∞ can be obtained, and then the parameters X_1, m and n can be determined.

Application on the distribution network

In order to determine parameters of capacitor banks and their influence on the effects of compensation of reactive power, 10 kV radial IEEE-33 bus distribution network, as shown in Fig. 3, has been analyzed. The parameters for this network are given in Table 4. The total loads for this network are 3715 kW and 2300 kVAr, and load profile is shown in Fig. 4. The minimum and maximum voltages are set on 0.95 and 1.05 pu, respectively. The optimal locations and size of capacitor banks with an objective of improving the voltage profile and reduction of power losses are obtained by mathematical model from [23] and using genetic algorithm from [24].

At first, we analyzed that one capacitor bank of size varying between −0.85 MVAr and −2 MVAr. The results of this study are shown in Table 5 and Fig. 5. Table 5 shows the network losses with and without compensator. As can be seen, the capacitor bank is effective in power loss reduction in the network. Fig. 5 illustrates buses voltage in two cases, where the voltage profile with capacitor bank is better than without capacitor bank. Generally, the voltages are varying because the voltage module at the node depends on topological position this node in the network, the network parameters and load (P, Q) at this node (as well as loads at all other nodes).

Design capacitor bank illustrated in Fig. 1 might be with parameters shown in Table 6. Here it is necessary to point out that selection of parameters should enable usage of standard capacitor

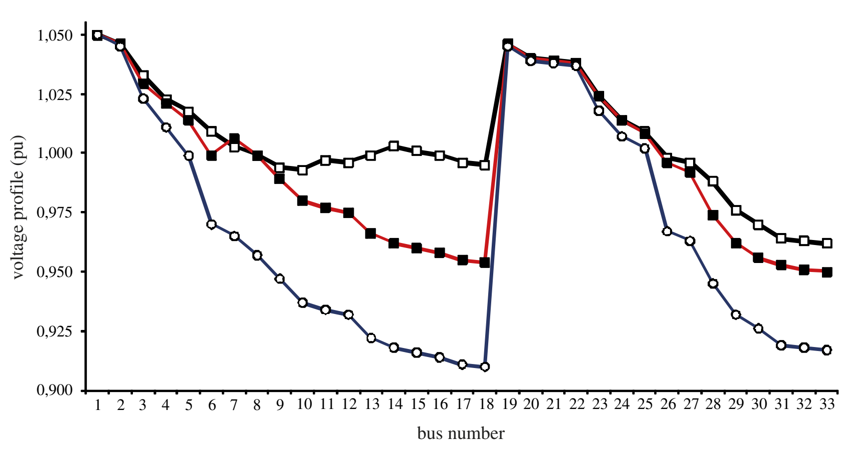

Fig. 6. Voltage profile in distribution network without and with (one and two) compensator.

units and reactors with sufficient range of change of the reactance. Economical aspect had significant influence on the final design.

In other case, two capacitor banks are of size varying between −0.85 MVAr and −2 MVAr. Results of this case are presented in Table 7 and in Fig. 6. In this figure the voltage profiles of three cases (without compensator, one compensator and two compensators) are presented. As can be seen, it is clear that the two capacitor banks result in less power losses and better voltage profile in comparison with one capacitor bank and without compensator in study network.

In this case two capacitor banks can be used at nodes 14 and 28 with parameters given in Table 6.

Conclusions

Reactive power compensation devices, especially capacitor banks, have increased their presence in the power utilities, large industrial and commercial consumer environments during the last years. The main reason for this increase is the need to maintain voltage profile at acceptable levels and to compensate reactive power in distribution and industrial networks. Significant increase of supply capacity, environment friendly integration in existing substations, easy supply of reactive power wherever needed and quick amortization of investment are some of the reasons why the capacitor banks represent an essential element in the design of these networks. In this paper the reactive power control of compensator consisting of appropriate number of capacitor sections and reactor is considered. This compensator can either absorb or supply reactive power inside distribution and industrial networks, providing a smooth control of reactive power at particular bus as much as possible to ensure a change of reactance of reactor.

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