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The influence of control strategy choice on effectiveness of reactive power compensation in distribution network

Streszczenie. *Kompensacja mocy biernej to jedna z podstawowych metod poprawy warunków pracy sieci elektroenergetycznej. Zastosowanie tej metody przyczynia się do zwiększenia zdolności przesyłu mocy czynnej. Prawidłowo stosowana kompensacja mocy biernej skutkuje poprawą warunków napięciowych w sieci elektroenergetycznej a także zmniejszeniem przesyłowych strat mocy czynnej. W artykule przedstawiono wszechstronną analizę skuteczności kompensacji mocy biernej pod kątem strat mocy w sieci dystrybucyjnej, w zależności od przyjętego kryterium sterowania.* ***(Wpływ wyboru strategii sterowania na skuteczność kompensacji mocy biernej w elektroenergetycznej sieci rozdzielczej)****.*

Abstract*. Reactive Power compensation is the one of the basic methods of improvement of power network operating conditions. Application of this method contributes to transmission capacity improvement of active power. Correctly applied compensation of reactive power leads to improvement of voltage conditions in the power network and reduction of power losses transmission. Following paper describes the effectiveness of reactive power compensation as its influence on the transmission power losses level in distribution network depending on control strategy. The influence of control strategy choice on effectiveness of reactive power compensation in distribution network.*

Słowa kluczowe: kompensacja mocy biernej, straty mocy czynnej, elektroenergetyczna sieć rozdzielcza.
Keywords: reactive power compensation, active power losses, distribution network.

Introduction

This study aims to review the issue of reactive power flow which is one of the major concerns in the power transmission and distribution networks [1-7]. Reactive power flow is adversely affecting the electrical power quality. The solution is reactive power compensation, which is also one of the major methods to reduce power losses. Due to the fast development of new technologies (e.g. DFACTS), such analysis gives an opportunity to find a new way to control reactive power flow. There are different methods of compensation, depending on the place of installation and type of controlled parameter. In industry practice, there are applied four methods of reactive power compensation [6]:

(a) individual compensation - compensation device connected directly to the terminals of the consumer;
(b) group compensation - compensation device connected to a distribution network that feeds a number of individual loads;
(c) central compensation - compensation device connected to the main busbar in large installations where many individual loads operate;
(d) mixed compensation - consists in simultaneous application of two or three of the previously mentioned methods of compensation.

In distribution parts of network, which do not include industrial consumers, the central compensation of reactive power are met, where compensation devices are connected to the middle voltage busbars (Main Power Supply Station – GPZ).

In this research a central compensation with different types of control strategy are presented and analysed. In this research a few of them are presented and analysed. The quality of compensation is being investigated on the basis of power loses. In the analysis two types of power network are used. First, one which reflects the distribution network in a large city where most of the lines are cables and the second one which represents the rural network with cable and overhead lines.

Strategies of reactive power flow compensation

In general the following strategies are used for reactive power compensation [2, 6]

- Power factor control

Power factor control is one of the most popular strategies of compensation. In this strategy, the controller keeps the power factor cosφ or tgφ at the set level. It means that the controller keeps the reactive to active power ratio constant. This is realized by connecting the appropriate amount of reactive power (capacitive or inductive depending on the character of the compensated power) to the busbar. In this method the power factor can be controlled independently from the active power consumed by the load (in the distributed compensation) or flowing through the busbars (in the central compensation).

- C/K parameter control

In this strategy of compensation, the controller does not control one value of the power factor in whole range. The C/K parameter decides about the non-active zone, inside which the controller does not compensate. The C/K parameter is related to the reactive power of the first (the smallest) capacitor in reactive power compensation devices.

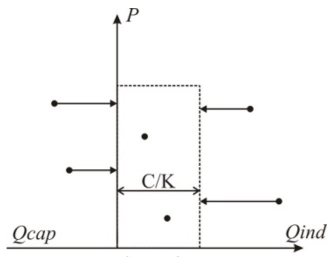

Fig. 1. Control characteristics of the C/K controller

The controller starts the compensation if the amount of reactive power flowing through the busbars (central compensation) or consume by the load is higher than the set value (C/K) – outside the non-active zone. In the analysis it is assumed that the capacitive reactive power is compensated to the set value and the inductive reactive power is compensated to zero (Fig. 1). During the compensation, the power factor changes depend only on the amount of active power flowing in the network.

- Voltage control

Higher power demand increases the active and reactive power flows in the network. Increased flows increase the voltage drops. Thus the voltages in the nodes decrease. On the other hand, the voltage is changing with the character of the load. The way to keep the voltages at a constant level despite changes in the demand, is to change the character of the demand. The main idea of this control strategy is to keep voltage constant on the defined level (U=const.). This is realised by inserting or consuming reactive power. It is made by compensators with voltage control which by adding additional reactive power demand (inductive or capacitive), controls the power factor in the point of installation. Voltage control strategy can be realised by FACTS device of the STATCOM type.

General characteristic of the test system

The test system used in the analysis is a distribution network of nominal voltage 15 kV (Fig. 2). The distribution network is supplied by two main substations 110/15 kV (GPZ - Main Power Supply Station). In the first substation (GPZ 1) two transformers of power 40 MVA connect the transmission network with two main 15 kV feeders: S1 and S2. In the second substation, (GPZ 2) networks are connected by one transformer of 40 MVA where one main 15 kV feeder: S36 supplies energy to the distribution network. All three main busbars (S1, S2 and S36) are not connected together (radial open loop topology). Each main busbar connects 6 radial power lines of different lengths.

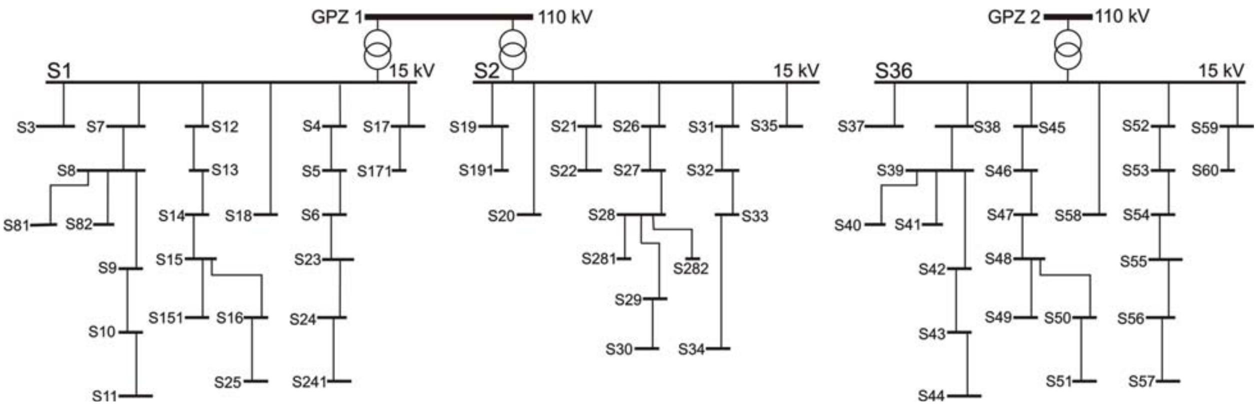

Fig. 2. Diagram of the test system

Most of the loads supplied from busbars S1 and S2 have an inductive character (cosφ<1). However, some of the loads supplied from busbar S36, draw capacitive reactive power. This causes the power factor cosφ in that part of the network to be close to one.

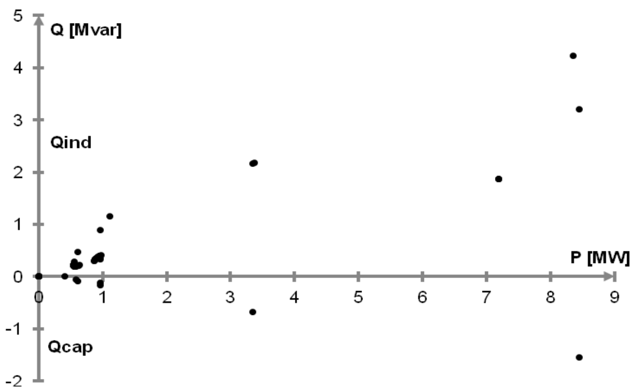

Fig. 3. Active and reactive demand in all 15 kV nodes

Two types of power network have been considered:

- Variant 1

Urban network where all lines connected to the feeders S1 and S2 are cable lines. Lines connected to the feeder S36 are overhead lines.

- Variant 2

Rural network where most of the lines are overhead lines. Only a few lines directly connected to feeders S1 and S2 are cable lines.

Introduction to the analysis

For each variant of the power network a central compensation is made. In the central compensation, reactive power compensation devices are installed in the main nodes: S1, S2, S36 and they compensate the reactive power flowing into the nodes.

For both variants of the power network three control strategies are considered:

- Strategy 1 - Power Factor Control,
- Strategy 3 - C/K Control.
- Strategy 2 - Voltage Control,

In power factor control strategy, the reactive power compensation device is set to keep given tgφ (tgφ=0,4 and tgφ=0,3) in the node.

In the C/K control strategy, the controller keeps the reactive power demand on level of 50 and 100 kvar for inductive load and 0 kvar for capacitive load.

In the voltage control strategy, the control parameter is voltage in the bus. It is kept at the set level, which is: $0{,}95U_N$, $1{,}00U_N$ and $1{,}05U_N$.

All three control strategies are based on controlling the reactive power flow in the network. The power factor and C/K control are implemented as the additional loads with zero active demand and controlled reactive demand. The compensators with voltage control are modelled as reactive power sources which, by injecting the proper amount of reactive power, keep the voltage at reference levels. All simulations are made in Plans program.

The efficiency of each compensation strategy has been compared using two criteria: sum of active power losses and the cost factor.

The active power losses are calculated along all branches connected to the each feeder (S1, S2 and S36). Then the total active power losses in 15 kV network is calculated:

$$\Delta P_{total} = \Delta P_{S1} + \Delta P_{S2} + \Delta P_{S36} \quad (1)$$

Where:

ΔP_{total} - total active power losses in the 15 kV network,

ΔP_{S1} - active power losses along all line branches connected to main busbar S1,

ΔP_{S2} - active power losses along all line branches connected to main busbar S2,

ΔP_{S36} - active power losses along all line branches connected to main busbar S36.

To compare the performance of the compensation, the cost factor C_{comp} is used. The cost factor is the ratio of the active power losses reduction to the compensation power:

$$C_{comp} = \frac{\Delta(\Delta P)}{Q_{comp}} \quad (2)$$

where:
$\Delta(\Delta P)$ is the difference between power losses in the network with compensation and without it,
Q_{comp} is the reactive power (either capacitive or inductive) used in the compensation.

This ratio is calculated separately:
- for the networks supplied from the main feeders: S1, S2, S36: $\Delta(\Delta P)S1/Q$, $\Delta(\Delta P)S2/Q$, $\Delta(\Delta P)S36/Q$;
- for the networks connected together to the nodes S1 and S2: $\Delta(\Delta P)S1S2/Q$;
- as the total cost of the compensation in the 15 kV power network: $(\Delta(\Delta P)/Q)$.

A positive value of the cost factor C_{comp} means reduction in power loses. The higher the value of the ratio, the unity cost of compensation is smaller.

Active power losses and cost factors are shown for each control strategy and for each variant of the power network.

Results

Results of the comprehensive power flow simulations are shown in Tables 1 and 2 as well as on Figures 4, 5, 6.

Table 1 Active power losses ΔP for different control strategies

Accumulated active power losses ΔP [MW]						
Control Strategy	ΔP_{S1}	ΔP_{S2}	$\Delta P_{S1} + \Delta P_{S2}$	ΔP_{S36}	ΔP_{total}	$\Delta P_{\%}$
Variant 1						
without compensation	0,694	0,693	1,387	0,887	2,274	100,00
tg(φ)=0,4	0,688	0,689	1,377	0,942	2,319	101,99
tg(φ)=0,3	0,671	0,675	1,345	0,919	2,265	99,59
C/K=50 kvar	0,625	0,635	1,260	0,860	2,120	93,22
C/K=100 kvar	0,625	0,635	1,260	0,860	2,120	93,24
U=0.95Un	0,774	0,791	1,565	1,078	2,643	116,24
U=1.00Un	0,687	0,701	1,389	0,954	2,343	103,03
U=1.05Un	0,615	0,627	1,242	0,852	2,094	92,07
Variant 2						
without compensation	1,289	1,357	2,646	0,907	3,553	100,00
tg(φ)=0,4	1,255	1,326	2,581	0,964	3,545	99,77
tg(φ)=0,3	1,214	1,287	2,501	0,940	3,441	96,85
C/K=50 kvar	1,109	1,186	2,295	0,878	3,173	89,31
C/K=100 kvar	1,110	1,186	2,296	0,878	3,174	89,35
U=0.95Un	1,413	1,544	2,956	1,078	4,035	113,57
U=1.00Un	1,214	1,312	2,526	0,954	3,480	97,96
U=1.05 Un	1,060	1,136	2,196	0,852	3,048	85,80

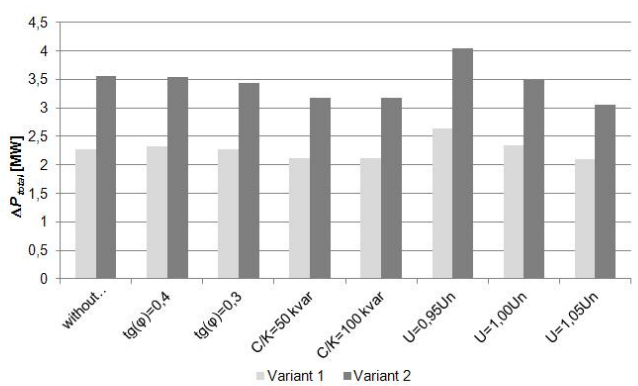

Fig. 4. Total power loses in the network for different strategies of compensation. Variant 1 and Variant 2 of the distribution network

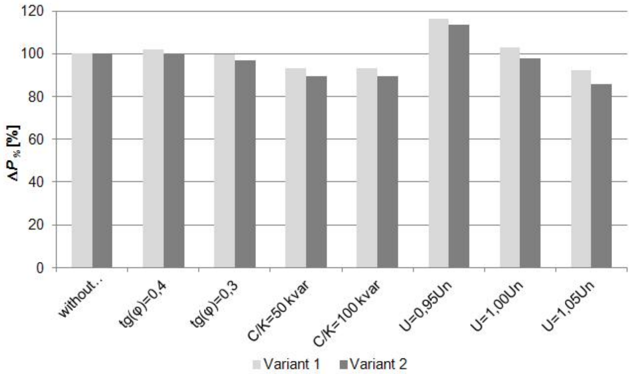

Fig. 5. Total power loses in the network (relative to the total power losses in the network without compensation) for different strategies of compensation. Variant 1 and Variant 2 of the power distribution network

Table 2 Cost factors for different control strategies

Control Strategy	Feeder S1	Feeder S2	sum of S1 and S2	Feeder S36	Total
	$\Delta(\Delta P)S1/Q$	$\Delta(\Delta P)S2/Q$	$\Delta(\Delta P)S1S2/Q$	$\Delta(\Delta P)S36/Q$	$(\Delta(\Delta P)/Q)$
Variant 1					
tg(φ)=0,4	0,0050	0,0050	0,0050	-0,0068	-0,0046
tg(φ)=0,3	0,0071	0,0043	0,0055	-0,0066	0,0007
C/K=50 kvar	0,0054	0,0056	0,0055	0,0072	0,0057
C/K=100 kvar	0,0054	0,0056	0,0055	0,0072	0,0057
U=0.95Un	-0,0051	-0,0056	-0,0054	-0,0101	-0,0071
U=1.00Un	0,0024	-0,0018	-0,0002	-0,0139	-0,0055
U=1.05Un	0,0070	0,0070	0,0070	0,0032	0,0057
Variant 2					
tg(φ)=0,4	0,0129	0,0144	0,0136	-0,0070	0,0006
tg(φ)=0,3	0,0131	0,0147	0,0138	-0,0067	0,0072
C/K=50 kvar	0,0313	0,0359	0,0334	0,0058	0,0246
C/K=100 kvar	0,0126	0,0142	0,0134	0,0075	0,0126
U=0.95Un	-0,0173	-0,0186	-0,0181	-0,0083	-0,0127
U=1.00Un	0,0128	0,0152	0,0136	-0,0069	0,0046
U=1.05Un	0,0112	0,0126	0,0118	0,0065	0,0109

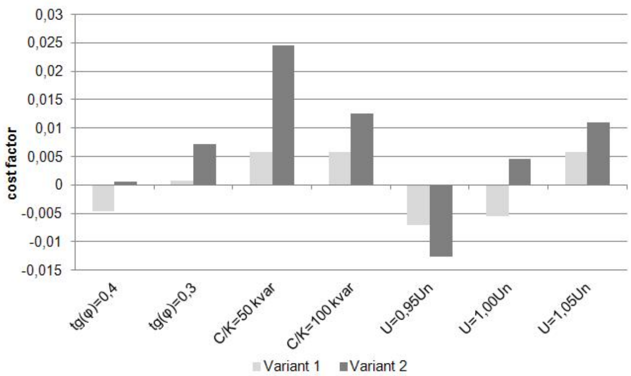

Fig. 6. Values of total cost factor for three strategies of compensation. Variant 1 and Variant 2 of the power distribution network

The results obtained shows that the quality of compensation (including the power losses) strongly depend on the line type (cable or overhead) of the compensated network. Compensation of a cable line network supplied from nodes S1 and S2, in most cases, reduces the transmission losses. This is because, in accordance with previous considerations, the flow of inductive reactive power is reduced (by forcing the flow of capacitive reactive power), hence the active power losses. Compensation has the opposite effect if the power network, before switching on the compensation device, has the capacitive character (feeder S36). In such case, compensation involving constant power factor or voltage level, increases the inductive reactive power in the network, and thereby also increase active losses. Therefore, the strategy of compensation must be determined by the line type of the network. The type of strategy which is least dependent on the type of network is the compensation which maintains reactive power demand within a range (regardless of active power demand) – C/K method. For the entire network, this method gives the best results, including the smallest unity cost of compensation for both cable and overhead lines network. For other methods, the total cost factor (for the 15 kV power network) are either negative or close to zero. It means that the C/K strategy of compensation can be used in any type of network without the threat of increased losses.

The reactive power compensation also improves the voltage profiles along the radial lines. Only the compensation with voltage control strategy U=0,95Un decreases the voltage levels, what was intended. As it can be seen in Figures 7 and 8, both variants of the C/K control strategy (C/K=50 kvar and C/K=100 kvar) keep the voltage at similar levels. Increases (or decrease) of voltage levels depends on selected control strategy and the type of the line (overhead or cable line), thus the type of the power network (urban or rural).

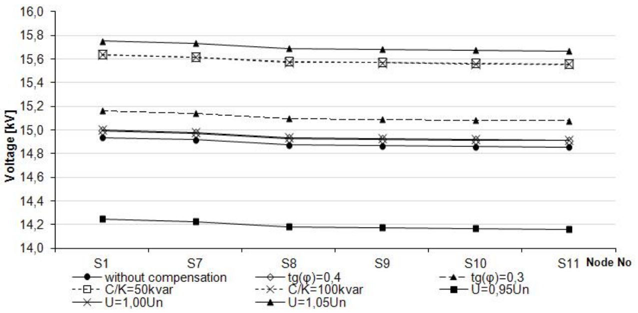

Fig. 7. Voltage profile along the radial line between nodes S1 and S11 for different control strategies. Variant 1 of the power distribution network

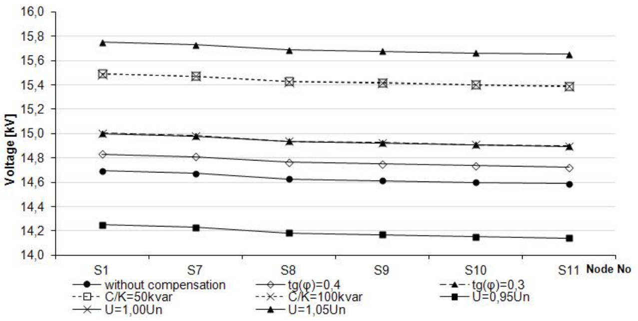

Fig. 8. Voltage profile along the radial line between nodes S1 and S11 for different control strategies. Variant 2 of the power distribution network

Conclusions

In this paper different control strategies of reactive power compensation were analysed. Two types of distribution power network (urban and rural) where used. Only central compensation, where compensators where connected to the middle voltage busbars (Main Power Supply Station – GPZ), were investigated. The efficiency of each control strategy was analysed using two criteria: total power losses in 15 kV distribution network and cost factor. The obtained results show the influence of controller parameters and the type of the network on the effectiveness of the compensation. Also the place of installation has a large impact on the performance of the compensation which wasn't investigate in this paper. The results obtained show that the reactive power compensation improves voltage conditions of the electric network and its effectiveness depends on the control strategy.

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