Aleksander KOT, Wiesław NOWAK, Waldemar SZPYRA, Rafał TARKO

AGH University of Science and Technology

Efficiency Improvement of Reactive Power Compensation in Power Distribution Networks

***Abstract**. The paper presents the idea of improving the economic efficiency of reactive power compensation in distribution networks. This idea is based on the installation low voltage capacitors with higher rated power in selected MV/LV substations, instead of installing new medium voltage capacitors in HV/MV stations and capacitors for compensation of magnetizing power of MV/LV transformers. Presented idea is illustrated by calculation example for real distribution network.*

***Streszczenie.** Referat przedstawia ideę poprawy ekonomicznej efektywności kompensacji mocy biernej w sieciach dystrybucyjnych. Idea ta polega na instalowaniu, w wybranych stacjach SN/nn, kondensatorów niskiego napięcia o większej mocy znamionowej zamiast instalowania nowych kondensatorów średniego napięcia w stacjach WN/SN oraz kondensatorów niskiego napięcia do kompensacji mocy magnesującej transformatorów SN/nn. Prezentowana idea jest zilustrowana przykładem obliczeń dla rzeczywistej sieci. (**Poprawa efektywności kompensacji mocy biernej w elektroenergetycznych sieciach rozdzielczych**).*

Keywords: reactive power compensation, power distribution networks, energy loss reduction.
Słowa kluczowe: kompensacja mocy biernej, elektroenergetyczne sieci rozdzielcze, ograniczanie strat energii.

Introduction

The issue of reactive power in power distribution networks has been subject of numerous publications and studies, where the issues of negative consequences of reactive power flow, methods and devices to reduce the reactive power demand as well as optimization methods of reactive power sources placement in industrial, distribution and transmission networks are broadly addressed. The first publications on economic efficiency of reactive power compensation appeared in the third decade of the 20th century [1]. The recent papers are mainly focused on new methods for finding optimum location of compensation devices and selection of their parameters [2, 3, 4] or problems that occurred with the dynamic development of renewable energy sources connected to distribution networks [5, 6, 7]. This article relates the economic efficiency of reactive power compensation in distribution networks in Poland and the possibilities of its improvement.

Reactive power compensation in power distribution networks is used for reducing energy losses, improving voltage profile in medium and low voltage networks and improving reactive power balance in 110 kV distribution network.

In Poland the capacitors are most frequently installed in:
- high voltage/medium voltage (HV/MV) stations, being the Main Feeding Point (MFP) of the medium voltage network,
- network switchboards (NS),
- medium voltage/low voltage (MV/LV) stations on the low voltage terminals of transformer.

The total power of capacitors installed in MFP in Poland is about 1 430 Mvar. The main task of capacitors installed in the MFP is reducing the reactive power demanded from the 110 kV networks, with the additional effect of reducing energy losses (mainly in the transformers).

Capacitors in the network switchboards are installed to improve the voltage profile in the network fed by the switchboards. Also in this case, the reduction of energy losses in lines feeding the switchboards, is an additional effect.

Capacitors connected directly to the low voltage terminals of the MV/LV transformers are used for compensating of magnetizing (idle state) reactive power of these transformers. The aim of such an installation is to reduce the energy losses in medium voltage lines feeding the MV/LV stations. It is estimated that the capacitors for compensation of idle state reactive power of transformers are installed in about 70% of MV/LV stations. Next capacitors are installed in new stations and when the transformers are replaced in the existing stations.

Effect of reactive power compensation

The effect of reactive power compensation can be presented with the example of the network branch connecting nodes i and j. Capacitors connected to the nodes j, $j+1$, …n will reduce the reactive power flowing through the branch ij as shown in Fig. 1b.

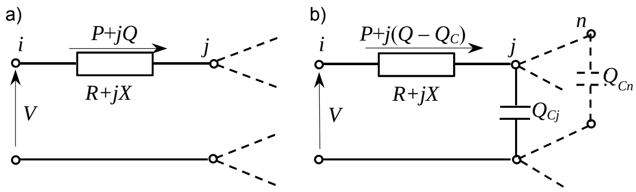

Fig.1. Power flow in the network branch: a) without power factor correction: b) with the capacitors installed at nodes j, $j+1$,…,n. Designations: P, Q – respectively, active and reactive power that flow thru the branch ij before installing capacitors, Q_C – sum of reactive power of capacitors installed in those nodes to which the power flows through the branch ij, V – network voltage, R, X – respectively, resistance and reactance of branch ij.

Active power losses in the branch, whose resistance is R, can be calculated from the formulas:
a) without power factor correction (Fig. 1a):

$$\Delta P = \frac{P^2 + Q^2}{V^2} R \tag{1}$$

b) after installing capacitors with a total reactive power Q_C in nodes powered by branch ij (Fig. 1b):

$$\Delta P_C = \frac{P^2 + \left(Q - Q_C\right)^2}{V^2} R \tag{2}$$

Reduction of active power losses in branch ij is equal to the difference of losses before and after installation of capacitors:

$$\delta P = \Delta P - \Delta P_C = \frac{Q_C^2 - 2\,Q\,Q_C}{V^2} R \tag{3}$$

Relationship (3) shows that the reduction of the active power losses depends on both: the reactive power Q_C supplied by the capacitor, and the reactive power Q flowing through the branch before the compensation.

Since the load of the network changes over time, the amount by which the active energy losses will decrease due to compensation requires knowledge of the 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_w as result of reactive power compensation with a fixed value of Q_C can be calculated according to:

(4) $$\delta E_a = \int_{t=0}^{t=T_w} \delta P(t)\,dt = \frac{R}{V^2}\int_{t=0}^{t=T_w}\left(Q_C^2 - 2Q(t)Q_C\right)dt$$

After the integration we obtain:

(5) $$\delta E_a = \frac{2RQ_C}{V^2}\int_{t=0}^{t=T_w} Q(t)\,dt - \frac{RQ_C^2 T_w}{V^2}$$

Where $Q(t)$ is the instantaneous reactive power flowing through the branch, and T_w is the period of time during which the capacitor is switched on.

It should be noted that $\int_{t=0}^{t=T_w} Q(t)\,dt$ is equal to the amount of reactive energy E_r that has flown through the branch during time T_w. Thus, equation (5) that allows to calculate the active energy losses, takes the form:

(6) $$\delta E_a = \frac{R}{V^2}\left(2E_r\,Q_C - Q_C^2\,T_w\right)$$

where: E_r is reactive energy that flows through the branch in time T_w.

The maximum energy loss reduction can be obtained when the reactive power of capacitor will be equal to:

(7) $$Q_C^{opt} = \frac{E_r}{T_w}$$

If the capacitor is connected to the transformer on the receiver side terminals, part of the reactive power supplied by the capacitor will be used to produce magnetizing flux. In this case, the reactive power of the capacitor Q_c in the formulas (3) and (6) should be reduced by the magnetizing reactive power of the transformer Q_0. Reduction of losses will occur only if a condition: $Q_C > Q_0$, is met. Calculations can be done by using the formulas (3) and (6), however, it is convenient to use the formulas using the rated parameters of the transformer. Suitable formulas are as follows:

- active power loss reduction:

(8) $$\delta P_{Tr} = \left\{\left(Q_C - Q_0\right)^2 - 2Q\left(Q_C - Q_0\right)\right\}\frac{P_k}{S_n^2}$$

- active energy loss reduction:

(9) $$\delta E_{aTr} = \left\{2E_r\left(Q_C - Q_0\right) - T_w\left(Q_C - Q_0\right)^2\right\}\frac{P_k}{S_n^2}$$

where: Q_0 is magnetizing reactive power of transformer, P_k is rated load losses of transformer, and S_n is rated power of transformer.

If calculations are performed for a distribution network consisting of a large number of branches, we need to know the resistances of individual branches and the value of reactive power and reactive energy flowing through the branches. It is therefore necessary to use the program to calculate load flows. Loss reduction in the network is the sum of the reduction of losses in the individual branches of this network.

Annual profit from the installation of capacitors Z_a is the difference between annual savings from reducing losses O_a and operating costs of capacitors K_a:

(10) $$Z_a = O_a - K_a$$

Annual savings resulting from the reduction of losses are equal to:

(11) $$O_a = \delta P\,k_P + \delta E_a\,k_{Ea}$$

Where δP is reduction of active power losses in peak load, δE_a is annual reduction of active energy losses, k_P is the unit cost of power losses, k_{Ea} is the unit cost of active energy.

The annual cost of the capacitor is calculated from the formula [8]:

(12) $$K_a = \delta P_Q\,Q_C\left(k_P + k_{Ea}\,T_w\right) + K_I\left(k_{es} + k_{rr}\right)$$

Where δP_Q is active power losses per unit of reactive power capacitor, K_I is capital expenditures incurred for the installation of capacitors, k_{es} is the fixed operating costs factor, and k_{rr} is extended reproduction rate.

Active power losses in currently manufactured capacitors are small ($\delta P_Q \approx$ 1 W/kvar) and can be skipped.

As a measure of profitability is often used net present value ratio ($NPVR$) that informs how much is the cumulative net income achieved during the assumed period of operation per one unit of capital invested [9]. As a measure of the effectiveness of compensation can also be used [8]:

- an equivalent unit costs of loss reduction (k_{Eekw}), i.e. the cost of 1 kWh of saved energy.
- and the discounted payback period (DPP), i.e. the period after which the cumulative net profit will be equal to the investment outlays.

After omitting the power losses in the capacitors, $NPVR$ can be calculated using the dependence given in [10], [11]:

(13) $$NPVR = \frac{O_a}{K_I}SD - \left(1 + k_{es}SD\right)$$

Where SD is the sum of discount factors:

(14) $$SD = \sum_{k=1}^{N}(1+i)^{-k}$$

Where N is expected life of the capacitors, and i is interest rate.

Efficiency of reactive power compensation in HV/MV stations

The effectiveness of reactive power compensation is illustrated on the example of a typical 110/15 kV station, which feeds a small town and nearby villages. Station is powered by two transformers with a rated power of 25 MVA each. Calculations were performed for one of the two transformers that are installed in the station.

Calculations were performed in two variants:

- Variant W1 – assuming successively, that the rated power of connected capacitor is: Q_C = {0.6, 1.2, 1.8, 2.4, 3.0, 3.6} Mvar (Fig. 2a);

– Variant W2 – assuming that the connected capacitor with a rated power Q_C = 2.4 Mvar, is divided into two banks, each with the capacity of 1.2 Mvar (Fig. 2b). For both of variants, the calculations were performed assuming that the rated power of the transformer installed in the stations is: S_n = 25 MVA and S_n = 16 MVA.

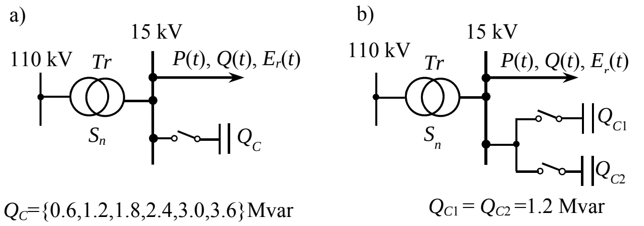

Fig. 2. Simplified scheme connecting the capacitors in the analyzed example: a) Variant W1; b) Variant W2

In each of the examined cases, it was assumed that the capacitor is switched on during the time, when the reactive power, which flows through the transformer, is equal to or larger than the supplied by the capacitor, i.e. when the condition: $Q_{Tr} \geq Q_C$ is fulfilled. Operating time for each rated power of capacitors and the amount of reactive energy, that flows through the transformer at that time are given in Table 1 and 2.

Graph of apparent power and reactive power that flows through that transformer during particular hours of the year is shown in Fig. 3. The transformer load was sorted according to descending the reactive power.

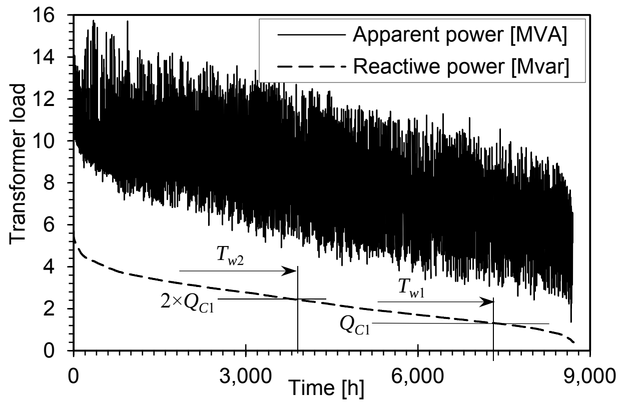

Fig. 3. Chart of the transformer load at particular hours of the year: T_{w1}, T_{w2} – operating time of capacitor bank Q_{C1}, and $2{\times}Q_{C1}$ respectively

The results of calculations performed according to a variant W1 are summarized in Table 1.

Table 1. Input data and calculation results for Variant W1

Q_C	[Mvar]	0.6	1.2	1.8	2.4	3	3.6
T_w	[h/a]	8 620	7 680	5 720	3 790	2 370	1 060
E_r	[Mvar·h]	20 500	19 600	16 660	13 010	8 670	4 380
S_n = 25 MVA, i_0 = 0.5%, Q_0 = 125 kvar, P_k = 127 kW							
δP_{Tr}	[kW]	0.6	1.3	1.8	2.2	2.4	2.5
δE_{aTr}	[MW·h]	3.6	6.8	8.1	8.0	6.1	3.6
S_n =16 MVA, i_0 = 0,5%, Q_0 = 80 kvar, P_k = 87.5 kW							
δP_{Tr}	[kW]	1.15	2.25	3.10	3.71	4.07	4.19
δE_{aTr}	[MW·h]	6.49	11.71	13.80	13.66	10.40	6.05

The table contains value of reduction of active power losses at maximal reactive load and the amount of reduction of active energy losses during the year for different power of capacitors. Volume reduction of active energy loss depending on the capacitor power is also shown in Fig. 4.

The results of calculations performed according to a variant W2 are summarized in Table 2. Total volume of active energy loss reduction is also shown in Fig. 4.

Table 2. Input data and calculation results for variant W2

Q_C	[Mvar]	1.2	2×1.2	Total
T_w	[h/a]	3 690	3 790	7 680
E_r	[Mvar·h]	6 590	13 010	19 600
S_n = 25 MVA, i_0 = 0.5%, Q_0 = 125 kvar, P_k = 127 kW				
δE_{aTr}	[MW·h]	2.0	7.8	9.8
S_n =16 MVA, i_0 = 0.5%, Q_0 = 80 kvar, P_k = 87.5 kW				
δE_{aTr}	[MW·h]	3.2	13.2	16.4

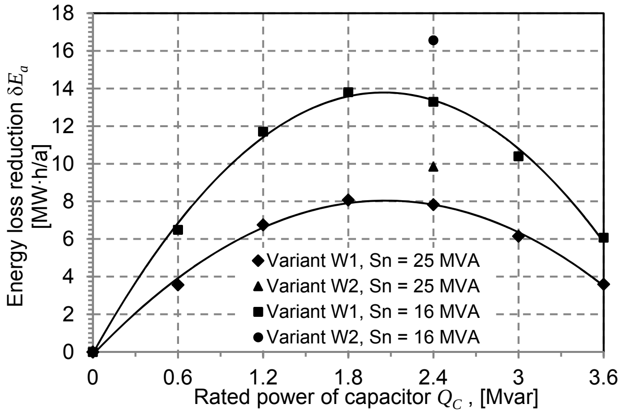

Fig. 4. Energy loss reduction in 110/15 kV transformer of 16 MVA and 25 MVA vs. power of capacitor connected to 15 kV switchboard

The reduction of energy losses in transformers due to the operation of capacitor installed in the HV/MV stations are small.

The cost of a capacitor of rated power 2,4 Mvar for 15,75 kV ranges between PLN 77 000 and PLN 90 000. There should be also added the cost of medium voltage switch box, which is PLN 60 000 to PLN 80 000. The total cost of installation of such a capacitor can be about PLN 137 000 to PLN 170 000. Assuming that the fixed operating costs factor k_{es} is = 0,02 (2% of capital cost of installation), the yearly fixed operating cost will be about PLN 3 400 to 4 250. Assuming that the unit price of active energy k_{Ea} is PLN 250 per MWh, the annual savings on energy loss reduction due to the operation of a 2,4 Mvar capacitor would be about PLN 2 450 for 25 MVA transformer, therefore less than the annual cost of its operation.

Above example shows that the savings in reduced energy losses (as a result of working capacitors installed in the MFP) are less than their operation cost.

Efficiency of compensation magnetizing reactive power in MV/LV transformers

Installation of capacitors in MV/LV stations reduces reactive power supplied to the stations from medium voltage networks. Capacitors are chosen so that the reactive power supplied by them is equal to or slightly less than the magnetizing reactive power of the transformer installed in the station. These capacitors are permanently connected directly to the low voltage terminals of the MV/LV transformers. Reduction of reactive power flowing through the branches of the medium voltage network decreases power and energy losses in these branches, according to the equations (3) and (6). Due to the fact, that the power of installed capacitors are small (for example reactive power of idle state of typical transformers with a capacity of 63 ÷ 630 kVA, is in the range 1.6 ÷ 6.5 kvar [8]), the reduction of energy losses is also small. This is confirmed by the results of calculations made for one of the Distribution Network Operators in Poland [12]. Calculations were performed for 10 medium voltage feeders that supply MV/LV stations with capacitors installed for idle state reactive power compensation of transformers. Selected results of these calculations are presented in Table 3. For each of feeders the table shows:

- data characterizing the feeder, i.e.: the length of the main line (L_m), the amount of reactive energy demanded from the feeder during the year (E_r), the number of installed capacitors (NC), the total installed rated power of capacitors (ΣQ_C), capital expenditures for capacitors installation (K_I);
- and the calculation results , i.e.: amount of active energy saved per year (δE_a), the annual net profit (Z_a), and net present value ratio ($NPVR$) calculated assuming 10-year life of the capacitors.

Table 3. Data characterizing analyzed circuits and selected calculation results

Line No.	L_m [km]	E_r [Mvar·h]	N_C [pc]	ΣQ_C [kvar]	K_I [PLN]	δE_a [MW·h]	Z_a [PLN/a]	$NPVR$ [PLN/PLN]
1	9.95	1.935	9	27.8	1 546	0.742	-55	-
2	6.13	4.084	8	56.0	1 668	1.317	90	0.36
3	12.60	6.242	23	63.5	3 879	6.458	1 193	2.06
4	14.41	5.521	28	105.6	4 989	11.774	2 501	3.36
5	4.95	0.939	10	24.8	1 660	0.221	-230	-
6	10.84	3.496	21	51.0	3 476	2.848	147	0.28
7	11.73	2.243	20	47.8	3 303	1.983	-49	-
8	9.94	2.600	22	55.9	3 665	3.179	273	0.50
9	5.00	1.495	18	46.3	3 004	0.988	-246	-
10	4.25	1.242	11	34.2	1 891	0.624	-148	-

The analysis of the results listed in Table 3 shows that the profit resulting from the reduction of energy loss is positive for 5 circuits, but only for circuit No. 3 and 4, the profit is large enough to request capital expenditures on the installation of capacitors.

The above results show that, in a majority of cases, the capacitors to compensation magnetizing reactive power of MV/LV transformers are not efficient from an economic point of view.

This does not mean that the reactive power compensation should not be used for reducing the energy losses in the distribution network, only the compensation method has to be changed.

Possibility of efficiency improvement for reactive power compensation in medium voltage distribution networks

The reason for low profitability of idle state reactive power compensation of MV/LV transformers is high unit cost of low-voltage capacitors with small rating power. Prices of low-voltage capacitors with different rated power are summarized in Table 4. This table also contains prices of contactors, that are suitable for switching the capacitors (all prices were taken from the producer's price lists).

The relationship of unit cost of reactive power versus rated power of low-voltage capacitors has been presented in Fig. 4. Unit costs of reactive power supplied by the capacitors have been calculated taking into account the installation cost of capacitors. For capacitors mounted directly to terminals of the transformer was adopted cost PLN 50 per piece, and for capacitors with contactors PLN 250 per piece plus the cost of the appropriate contactor.

Table 4. Price for low-voltage capacitors and contactors

Rated power [kvar]	Price of capacitor [PLN/pc.]	Price of contactor [PLN/pc.]
1.5	119	193
2.0	123	
2.5	124	
3.0	125	
4,2	133	
6.3	135	
7.5	150	
10	175	
12.5	190	
15	220	240
18.3	240	275
20	320	
25	340	490
30	380	

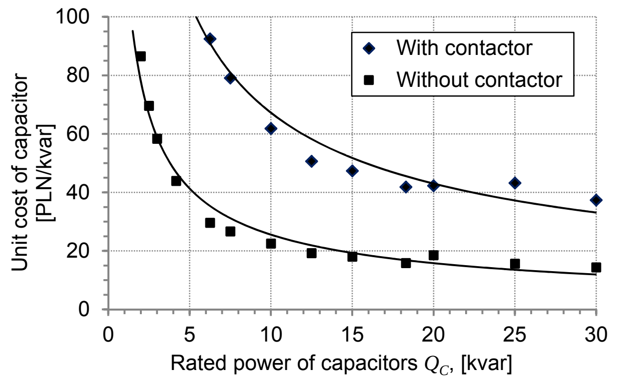

Fig. 4. Unit cost of low voltage capacitors as a function of rated power

The analysis of the plots presented in Fig. 4 reveals that with the increase of rated power of the capacitor, the unit capital expenditure decrease. Taking into account that the magnitude of reducing energy losses depends, among others, on the reactive power of capacitor, the economic efficiency of reactive power compensation in distribution networks can be improved by installing a smaller number of capacitors with a much higher power rating. Capacitors should be connected to the low voltage terminals of transformers in selected MV/LV stations. The capacitors could be switched on permanently or with the use of contactors.

The effectiveness of the proposed manner of reactive power compensation illustrates an calculation example for a real medium voltage circuit. This is a typical circuit with a voltage of 15 kV power supply in suburban areas. Circuit consists of 22,86 km of overhead lines (including 7,76 km main line), and 34 stations 15/0,4 kV of total rated power of transformers ΣS_n = 5 791 kVA. The power supplying the circuit at peak load is S_s = (3 776 + j1 460) kVA, and the annual reactive energy supplying the circuit is E_r = 4 765 Mvar·h. A simplified scheme of the analyzed circuit has been shown in Fig. 5.

For this circuit were analyzed following variants of reactive power compensation using low-voltage capacitors:

- Variant W0 – using capacitors for compensation of idle reactive power of transformers, permanently connected to all MV/LV stations (T_w = 8760 h);
- Variant W1 – using capacitors of rated power 30 kvar, permanently connected to selected MV/LV stations (T_w = 8760 h);

- Variant W2 – using capacitors of rated power 30 kvar with contactors, connected at selected MV/LV stations, assuming that the they are switched on all year long (T_w = 8760 h);
- Variant W3 – using capacitors of rated power 30 kvar with contactors, connected at selected MV/LV stations, assuming that the they are switched on 6000 hours per year (T_w = 6000 h).

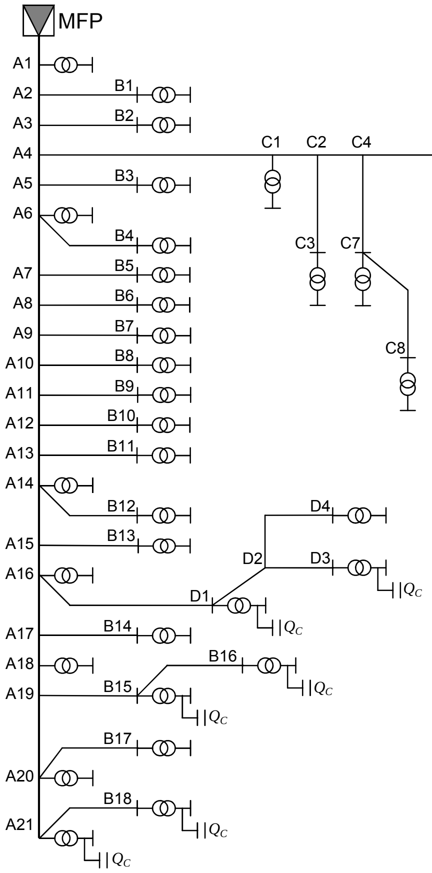

Fig. 5. Simplified scheme of 15 kV circuit: Q_c – location of 30 kvar capacitors

The following cost capacitors were adopted for calculation: for variant W0: the cost of suitable capacitor according to table 2 + PLN 50 assembly cost per unit; for variant W1: PLN 430 per unit (PLN 380 cost of capacitor + PLN 50 assembly cost); for variants W2 and W3: PLN 1120 per unit (PLN 380 cost of capacitor + PLN 490 cost of contactor + PLN 250 assembly cost). In addition, for calculations were adopted: the unit cost of active power: k_P = 100 [PLN/kW/a]; the cost per unit of active energy to cover losses: k_{Ea}= 0.25 [PLN/kW·h]; interest rate: i = 0.08 (8%), the rate of operating costs of capacitor with contactor: k_{es} = 0.025 (2.5%), and for capacitor without contactor: k_{es} = = 0.005 (0.5%) from investment costs, the period of analysis N_a = 10 years.

The order of the station, in which next capacitors were connected in variants W1, W2 and W3 was determined on the ranking based on diminishing values of $NPVR$. To determine the ranking of stations, value of $NPVR$ was calculated after connecting a capacitor rated at 30 kvar successively to each station. The compensation efficiency was calculated by connecting the capacitor in the successive stations (starting from the highest $NPVR$ value) till the moment the energy loss reduction started to decrease.

The selected results of calculations have been presented in Table 5 and in Figs 6 ÷ 9 where have been presented: capital costs K_I, magnitude of loss reduction $\Sigma\delta E_a$, profit from reducing losses Z_a, and $NPVR$ as a function of power of installed capacitors. Individual points on the graphs correspond to the total power of connected capacitors after connecting capacitor to successive station.

Table 5. Selected results of calculation of efficiency of reactive power compensation for circuit shown in Fig. 6

Category [unit of measure]	Variant			
	W0	W1	W2	W3
Number of capacitors, [pc.]	34	6	6	6
Sum of rated power of installed capacitors ΣQ_C, [kvar]	86.51	180	180	180
Capital expenditure K_I, [PLN]	5 924	3 780	6 720	6 720
Annual energy loss reduction $\Sigma\delta E_a$, [kW·h]	6 017	11 582	11 582	10 292
Annual profit Z_a, [PLN]	806	2 881	2 369	2 047
Net Present Value NPV, [PLN]	4 616	19 330	15 897	13 733
Net Present Value Ratio $NPVR$, [PLN/PLN]	0.78	5.11	2.37	2.04
Equivalent per unit costs of energy loss reduction k_{Eekw} [PLN/kW·h]	0.1713	0,0568	0.1010	0.1136
Discounted Payback Period DPP [year]	11.5	1.4	3.3	4.0

For the variants W1, W2 and W3 in above table, the values are calculated for total power of connected capacitors, at which the profit reaches a maximum value

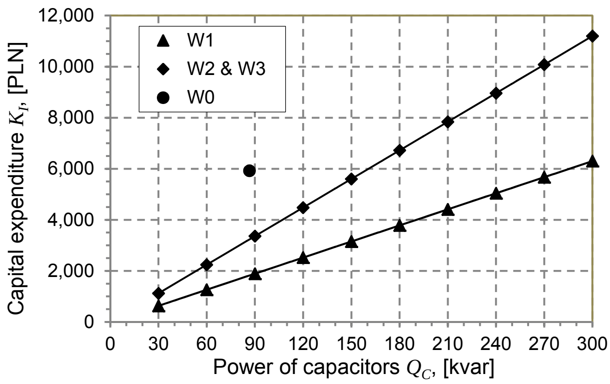

Fig. 6. Capital expenditure as function the total power of connected capacitors

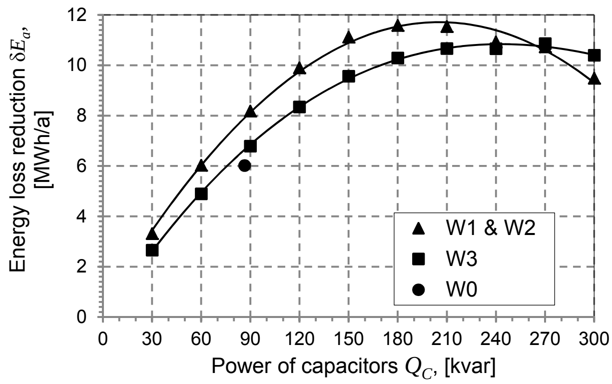

Fig. 7.Energy loss reduction as a function the total power of connected capacitors

The analysis of the graphs in Figure 6 shows that the expenditures needed for installation of capacitors in variant W0 would be sufficient to install 9 capacitors as in variant W1 or 5 capacitors with contactors as in variants W2 and

W3. By contrast, Fig. 7 shows that as a result of installing 5 capacitors rated at 30 kvar each, the energy loss in variant W1 and W2 will be reduced by more than 1.8 times, and in variant W3 almost 1.6 times more than in variant W0. In turn, from the graphs in Fig. 8 follows that the profit from the reduction of energy losses in the variants W1, W2 and W3 would have been respectively 3.4, 2.9 and 2.4 times higher than in variant W0.

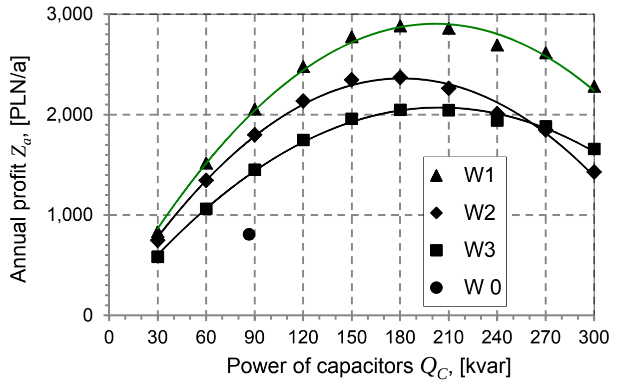

Fig. 8 Annual profit as a function the total power of connected capacitors

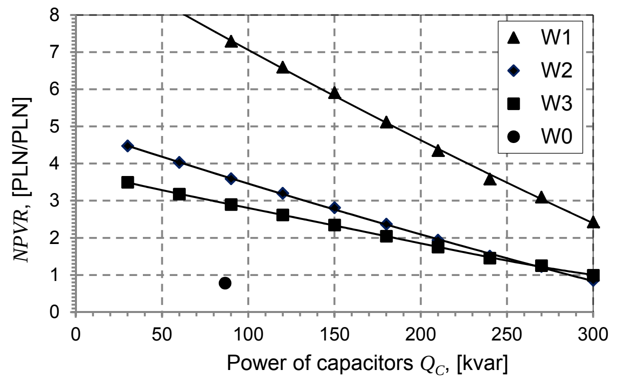

Fig. 9. Net Present Value Ratio as function the total power of connected capacitors

Concluding remarks

The above presented results show that the capacitors installed in HV/MV stations, as well in a majority of cases, the capacitors to compensation of magnetizing reactive power of MV/LV transformers are not efficient from an economic point of view. Nevertheless, so far installed capacitors should be used to improve the balance of reactive power in the transmission network. Work schedule those capacitors should be agreed with the operator of the transmission network. Also, rated power and selection of HV/MV stations to install new capacitors should be agreed with the Transmission System Operator.

Installation of capacitors in selected MV/LV stations may be efficient and effective way for reducing energy losses in distribution networks. This, however, requires installing capacitors of much higher rated power than magnetizing reactive power of transformers in those stations. In these stations may occur periodically surplus of reactive power. However, the results of studies presented in [8] and [13] indicate that periodical overcompensation of reactive power of MV/LV transformers did not cause technical problems.

In many circuits of medium voltage networks the capacitors can be switched on permanently, and the total power of the capacitors should not exceed the minimum reactive power fed by the HV/MV transformers from 110 kV network.

The capacitors with contactors will help switch off the capacitor, to disable the flow of reactive power to the 110 kV network. By the time a remote control of the capacitor is available, the capacitor could be switched on/off with the use of timers, according to the previously prepared schedules.

Such a solutions would greatly improve the efficiency of reactive power compensation and energy losses reduction.

REFERENCES

[1] Marsteller G. F.: Analytical notes on the economics of power-factor correction, *Journal of the Institution of Electrical Engineers*, 66, (1928), 975-983.

[2] Seifi A. R.: A New Hybrid Optimization Method for Optimum Distribution Capacitor Planning, *Modern Applied Science*, Vol. 3, No. 4 (2009), 196-202

[3] Subhash G.V., More S.S.: Reactive Power Loss & Efficiency Calculation Using Load Flow Technique In Distribution System For Pune City, *International Journal of Computer Science and Informatics* Vol-1, Iss-4, (2012), 49-52,

[4] Manglani T., Shishodia Y.S.: Reduction in Power Losses on Distribution Lines using Bionic Random Search Plant growth Simulation Algorithm, *International Journal of Recent Research and Review*, Vol. III, No. 9 (2012), 8-14.

[5] Cagnano A., De Tuglie E., Liserre M., Mastromauro R.: On-line optimal reactive power control strategy of PV-inverters, *IEEE Transactions on Industrial Electronics*, vol. 58, No. 10, (2011) 4549–4558

[6] Tengku Hashim T.J., Mohamed A. Shareef H.: A review on voltage control methods for active distribution networks, Electrical Review, R. 88 No. 6 (2012), 304-312.

[7] Majumder R.: Reactive Power Compensation in Single-Phase Operation of Microgrid, *IEEE Transactions on Industrial Electronics*, Vol. 60 , No. 4, (2013), 1403 – 1416.

[8] Szpyra W.: Efficiency of compensation of no load reactive power loses of MV/LV transformers. *Przegląd elektrotechniczny* (*Electrical Review*), No. 2, (2011) 144–147 (in Polish).

[9] Paska J.: *Ekonomika w elektroenergetyce*. Wydawnictwa Politechniki Warszawskiej. Warszawa 2007 (in Polish).

[10] Hanzelka Z., Szpyra W., Piątek K.: Reactive power compensation, in *Electrical energy efficiency: technologies and applications,* edited by Sumper A. & Baggini A., John Willey & Sons, Chichester 2012, 371–398.

[11] Szpyra W., Nowak W., Bąchorek W., Moskwa Sz., Tarko R., Benesz M.: Compensation of reactive power in MV/LV substations. *Energia elektryczna*, No.12 (2010), 18-23 (in Polish).

[12] Szpyra W., Nowak W., Moskwa Sz., Tarko R., Bąchorek W., Benesz M.: Technical and economic analysis installing LV capacitors for reactive power compensation in MV/LV stations - Phase II. Research report No. 5.5.120.968, AGH University of Science and Technology in Cracow, September 2010 (in Polish).

[13] Szpyra W., Tarko R., Nowak W.,: Analysis of the impact of nonlinear loads in terms of selection and operation of capacitors for reactive power compensation in MV/LV substations. Proceedings of Conference: Reactive Power Problems in Distribution and Transmission Networks, PTPiREE, 7–8 December 2010, 08.1- 08.10 (in Polish).

***Authors**: dr inż. Aleksander Kot, e-mail: akot@agh.edu.pl;*
dr hab. inż. Wiesław Nowak, e-mail: wieslaw.nowak@agh.edu.pl;
dr inż. Waldemar Szpyra, e-mail: wszpyra@agh.edu.pl;
dr inż. Rafał Tarko, E-mail: e-mail: rtarko@agh.edu.pl
AGH University of Science and Technology in Cracow, Department of Electrical Engineering and Electrical Power Engineering, Al. Mickiewicza 30, 30-059 Cracow, Poland