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CONTROL OF THE REACTIVE POWER COMPENSATORS IN INDUSTRY POWER GRID

Summary. The problem of the control of reactive power compensators in multilevel industry power grid is analysed in the paper. The minimisation of active power losses caused by reactive power flows in the grid is taken as the main criterion of optimisation. Additional criterions and restrictions resulting from maintenance of the power factor in desired limits, different voltage levels in grid nodes, limited range of reactive power of compensators, discrete (step) operation of some compensators, capacitors banks for example, are taken into account in the control algorithm. Chosen results of the simulation research and obtained in industrial control system are presented in the paper.

STEROWANIE KOMPENSATORAMI MOCY BIERNEJ W SIECI PRZEMYSŁOWEJ

Streszczenie. W artykule przedstawiono problem kompensacji mocy biernej w sieci przemysłowej. Jako główne kryterium optymalizacyjne przyjęto minimalizację strat mocy czynnej spowodowanych przepływem mocy biernej. Uwzględniono również dodatkowe kryteria i ograniczenia, jak: utrzymanie współczynnika mocy w punkcie zasilania w zadanym zakresie, różne wartości napięć w węzłach sieci, skończone zakresy regulacji mocy biernej kompensatorów, dyskretne wartości mocy biernej niektórych kompensatorów, np. baterii kondensatorów. Zaprezentowano wybrane wyniki badań symulacyjnych oraz pomiary uzyskane w przemysłowym systemie kompensacji mocy biernej.

1. INTRODUCTION

The power grid in large industrial plants except main switching station (stations) can contains departments switching stations. All of these create multilevel industry power grid. A scheme of example three-level power grid is presented in fig. 1.

The flows of reactive power in power transmission lines are reason of:

- additional active power losses in resistance of the lines,
- voltage drops in the power transmission lines,
- change for the worse of the power quality.

Therefore compensators of reactive power, such capacitors, filters of harmonics, synchronous motors, are applied. They can be installed by large reactive power receivers or in switching stations on different levels of industrial power grid.

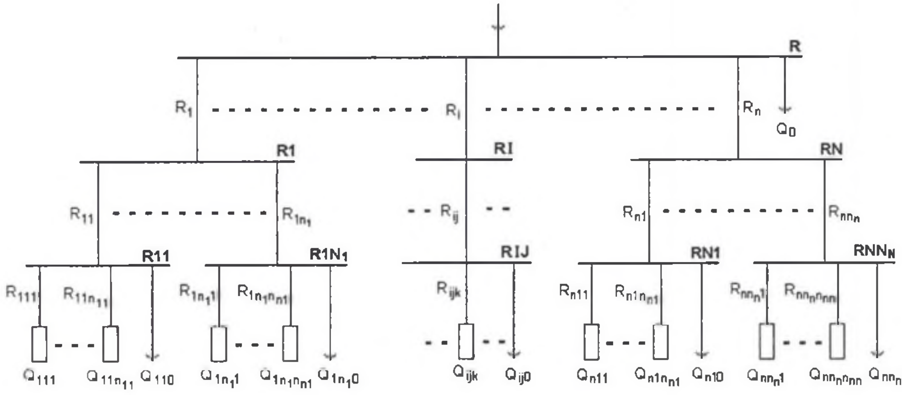

Fig. 1. Scheme of the three-level industry power grid
Rys. 1. Schemat trójpoziomowej sieci przemysłowej

The paper deals of the compensators control for the purpose of optimization of reactive power flow in industrial power grid. The minimization of active power losses caused by reactive power flows in the grid is taken as the main criterion of optimization. Additional criterions and restrictions resulting from:

- maintenance of the power factor in main supply in desired limits,
- different voltage levels in grid nodes,
- limited range of reactive power of compensators,
- discrete (step) operation of some compensators, capacitors banks for example,

are taken into account in the control algorithm.

2. THE BASIC METHOD OF THE CONTROL OF REACTIVE POWER COMPENSATORS

It was assume that active power flows in the grid are independent of reactive power of compensators. Then for minimization of the active power losses the minimization of the losses produced by the reactive current is enough. For the three-level industry power grid (fig. 1) the power loses produced in the lines by reactive power flows are given by equation:

$$\begin{aligned}\Delta P(Q) &= \sum_{i=1}^{n}\left(\Delta P(Q)_i+\sum_{j=1}^{n_i}\left(\Delta P(Q)_{ij}+\sum_{k=1}^{n_{ij}}\Delta P(Q)_{ijk}\right)\right)= \\ &=\frac{1}{U^2}\left(\sum_{i=1}^{n}\left(R_i\left(\sum_{j=1}^{n_i}\left(Q_{ij0}+\sum_{k=1}^{n_{ij}}Q_{ijk}\right)\right)^2+\sum_{j=1}^{n_i}\left(R_{ij}\left(Q_{ij0}+\sum_{k=1}^{n_{ij}}Q_{ijk}\right)^2+\sum_{k=1}^{n_{ij}}R_{ijk}Q_{ijk}^2\right)\right)\right),\end{aligned} \tag{1}$$

where:

Q_{ijk} - reactive power of *ijk*-compensator,
Q_{ij0} - reactive power of other loads supplied from *ij*-switching station,
R_i, R_{ij}, R_{ijk}, - resistance of *i, ij, ijk*-lines,
U - grid voltage.

Newton-Raphson method, which enables to obtain the extreme of quadratic form:

$$F(\mathbf{x}) = \mathbf{x}^T \mathbf{A}\mathbf{x} + \mathbf{b}^T \mathbf{x} + c \tag{2}$$

in one calculation step, was applied for calculation of the optimal values of the reactive power of each compensator.

The co-ordinates of extreme point are defined as:

$$\mathbf{x}^o = -\left(\frac{\partial^2 F(\mathbf{x})}{\partial \mathbf{x}^2}\right)^{-1} \mathbf{b}\,. \tag{3}$$

Solving the problem of optimization of the compensators controls with regard on minimization of power loses with none limits, we can obtain from eqns (1-3) the optimal value of reactive power of each compensator:

$$Q_{xyz} = \frac{1}{R_{xyz}} \cdot \frac{R_{xy}}{1 + R_{xy} S_{xy}} Q_{xy0} - \frac{1}{R_{xyz}} \cdot \frac{1}{1 + R_{xy} S_{xy}} \cdot \frac{R_x}{1 + R_x K_x} \sum_{j=1}^{n_x} \left(\frac{1}{1 + R_{xj} S_{xj}} Q_{xj0} \right), \tag{4}$$

where:

$$S_{ij} = \sum_{k=1}^{n_{ij}} \frac{1}{R_{ijk}}, \tag{5}$$

$$K_i = \sum_{j=1}^{n_i} \frac{S_{ij}}{1 + R_{ij} S_{ij}}\,. \tag{6}$$

If the summary reactive power Q_z of all compensators:

$$Q_z = \sum_{i=1}^{n} \left(\sum_{j=1}^{n_i} \left(\sum_{k=1}^{n_{ij}} Q_{ijk} \right) \right), \tag{7}$$

is definite by preferred value of the power factor in main switching station R (fig. 1), we should to solve the problem of compensators control optimization with limit given by eqn (7). In this case the optimal value of reactive power of each compensator is determined by equation:

$$\begin{aligned} Q_{xyz} = {} & \frac{1}{R_{xyz}} \cdot \frac{1}{1 + R_{xy} S_{xy}} \Bigg(R_{xy} Q_{xy0} - \frac{1}{1 + R_x K_x} \Bigg(\sum_{j=1}^{n_x} \bigg(\frac{1}{1 + R_{xj} S_{xj}} R_x Q_{xj0} \bigg) - \\ & - \frac{1}{L} \Bigg(Q_z + \sum_{i=1}^{n} \bigg(\frac{1}{1 + R_i K_i} \sum_{j=1}^{n_i} \bigg(\frac{R_{ij} S_{ij}}{1 + R_{ij} S_{ij}} Q_{ij0} \bigg)\bigg) + \sum_{i=1}^{n} \bigg(\frac{R_i}{1 + R_i K_i} \bigg(\sum_{j=1}^{n_i} \frac{S_{ij}}{1 + R_{ij} S_{ij}} \bigg) \sum_{j=1}^{n_i} Q_{ij0} \bigg)\Bigg)\Bigg)\Bigg), \end{aligned} \tag{8}$$

where K_i and S_{ij} are given by eqns (5) and (6), and:

$$L = \sum_{i=1}^{n} \frac{K_i}{1 + R_i K_i}\,. \tag{9}$$

The optimization is carried out for three level industry power grid, which general scheme is presented in fig. 1, but its results may be applied for double or single level industry grids, and for compensators located in different levels of the grid. For example, fragments of the grid presented in fig. 2a and fig. 2b are identical from the point of view of presented optimization method.

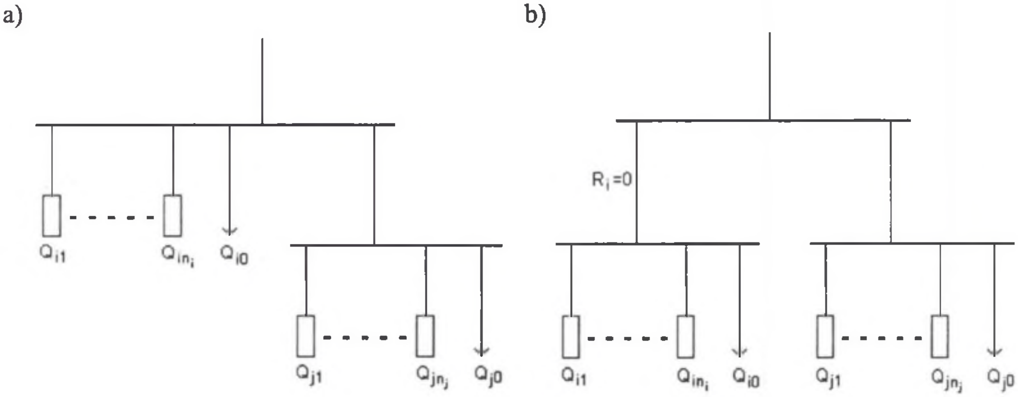

Fig. 2. Illustration of the power grid transformation method
Rys. 2. Ilustracja metody transformacji fragmentów sieci do wspólnego poziomu

3. OPTIMIZATION OF THE REACTIVE POWER FLOWS IN THE CASE OF ADDITIONAL LIMITS

Equations presented above are obtained with assumption of identical voltage in all points of power grid. Taking into consideration:

- changes of the voltage in the grid nodes causes by active and reactive power flow,
- limits of the voltage differences in the grid nodes,

application of iteration procedures for calculation of the optimal reactive power values for each compensator is necessary.

The voltage drop in supply line is expressed by equation:

$$\Delta U_i = I_i(R_i \cos\varphi_i + X_i \sin\varphi_i) = \frac{R_i P_i + X_i Q_i}{\sqrt{3}U}, \tag{10}$$

where:

ΔU_i, I_i - voltage drop and current in i-supply line,
$\cos\varphi_i$ - power factor in the i-supply line,
P_i, Q_i - active and reactive power transmitted by the i-supply line,
U - voltage in supply point of i-supply line.

Assuming permissible increase and decrease voltage level in grid node, the minimum Q_{imin} and maximum Q_{imax} values of reactive power, which is allowed to transmit by i-line supplying this node, are expressed by equation:

$$Q_{i\min} = \frac{\sqrt{3}U\Delta U_{i\min} - R_i P_i}{X_i}, \tag{11}$$

$$Q_{i\max} = \frac{\sqrt{3}U\Delta U_{i\max} - R_i P_i}{X_i}, \tag{12}$$

where:

$\Delta U_{i\min}$ - minimum acceptable voltage drop in *i*-supply line ($\Delta U_{i\min} < 0$),

$\Delta U_{i\max}$ - maximum acceptable voltage drop in *i*-supply line.

Reactive power transmitted by *i*-supply line need to fulfil the following condition:

$$Q_{i\min} \le Q_i \le Q_{i\max}\,. \tag{13}$$

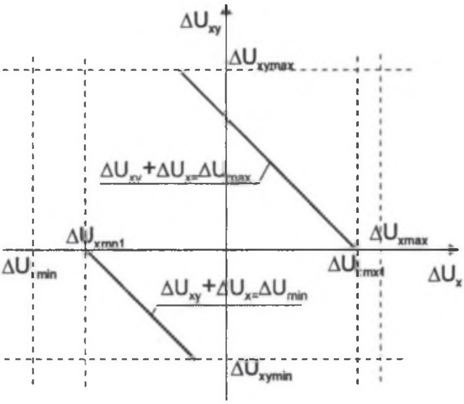

Fig. 3. Graphical interpretation of the method of reactive power flow calculation for the limited voltage changes in the grid nodes

Rys. 3. Interpretacja graficzna metody poszukiwań optymalnego rozpływu mocy biernych przy ograniczeniu zmian napięcia w węzłach sieci

In multilevel grid a change of reactive power transmitted by the *xy*-supply line provoke change of the voltage drop in this line and simultaneously change of the reactive power transmitted by the *x*-supply line. The effect of this is change of the voltage drop in this line, and as consequence voltage change of *XY*-switching station. So if summary voltage drops in several dependent supply lines are limited, application of simple control procedure based on eqns (11) and (12) is not possible.

If the optimal reactive power of compensators evaluated from eqn (4) or (8), causes inadmissible voltage change of *XY*-switching station:

$$\Delta U_{RXY} = \Delta U_x + \Delta U_{xy} > \Delta U_{\max} \tag{14}$$

or

$$\Delta U_{RXY} = \Delta U_x + \Delta U_{xy} < \Delta U_{\min}, \tag{15}$$

the minimum of objective function is out of the acceptable range of solution, so optimal solution is searched on the boundary of this region, i.e.:

$$\Delta U_{RXY} = \Delta U_x + \Delta U_{xy} = \Delta U_{acc}, \tag{16}$$

where:

$$\Delta U_{acc} = \Delta U_{\max}, \tag{17}$$

or

$$\Delta U_{acc} = \Delta U_{\min}, \tag{18}$$

depending if (14) or (15) restriction was exceeded.

The algorithm of the compensators' control takes into consideration also the limitations resulted from:

- discrete values of the reactive power of capacitors banks
- admissible frequency of capacitors banks connection.

4. SIMULATION AND INDUSTRY TESTS

Simulation tests of the presented algorithms were carried out for the model of the grid presented in fig. 4. The 3-level model of the grid contains synchronous motors, capacitors banks and others loads. The investigations were carried out for various control algorithms, number of the synchronous motors, admissible levels of voltage drops, desired values of the power factor. Chosen simulation test results are presented in fig. 5.

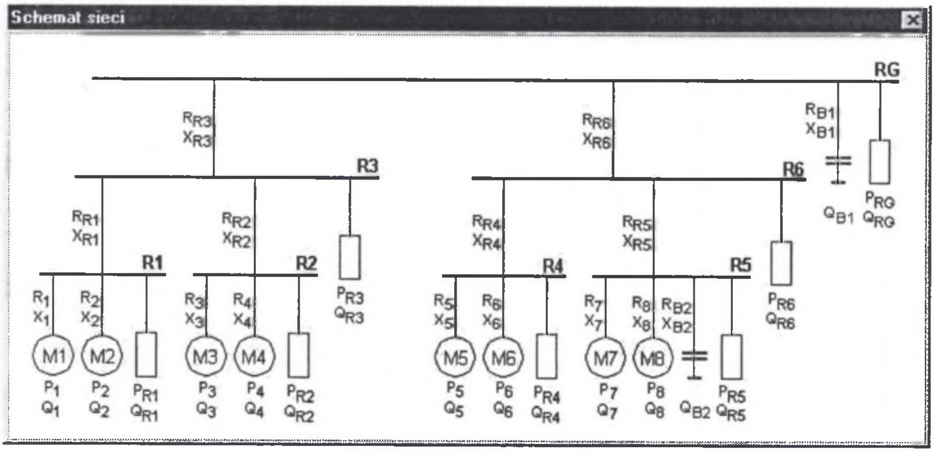

Fig. 4. Model of the tested industry power grid
Rys. 4. Model badanej sieci przemysłowej

Fig. 5 presents effect of the algorithm taking into consideration the admissible voltage change of the *R3* and *R6* (fig. 4) switching stations. After change of the algorithm of equal desire reactive power of synchronous machines to algorithm of equal desire reactive power with limitation of the voltage drops, the distribution of the reactive power in the system has changed this way, that the limitations of voltage change in the *R3* and *R6* (fig. 4) switching stations and power factor are kept. Application of the algorithm minimizing the line power loses causes changes of the reactive power of synchronous machines and decrease of the line power loses, but voltage of switching stations and input power factor remain unchanging.

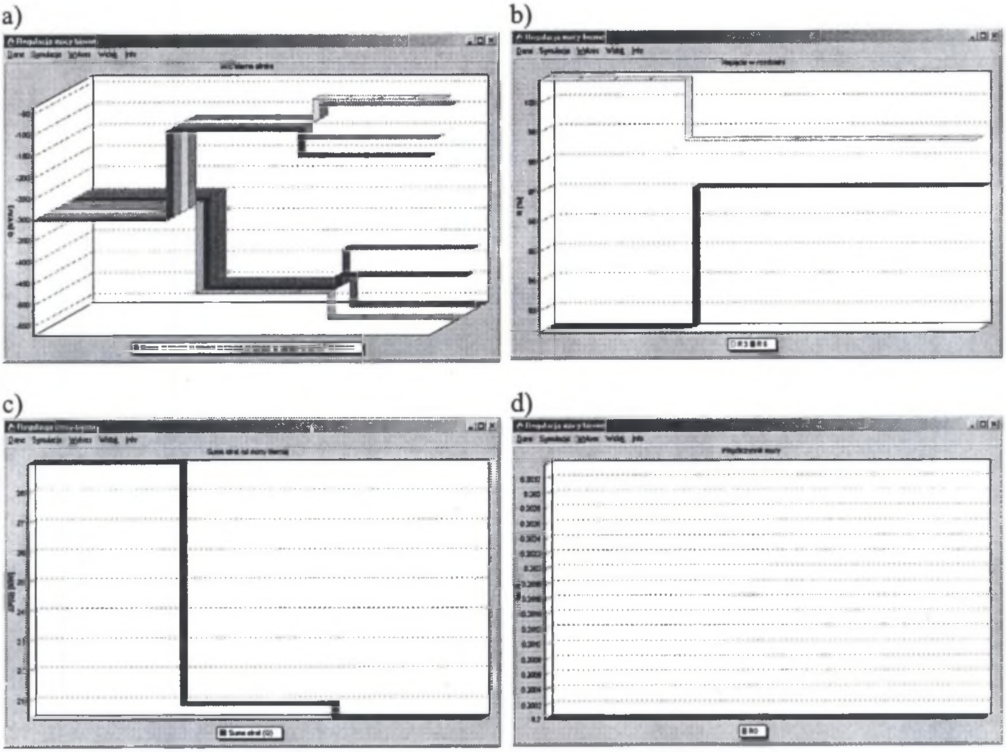

Fig. 5. The change of the algorithm of equal desire reactive power of synchronous machines to algorithm of equal desire reactive power with limitation of the voltage drops and then algorithm minimizing the line power loses for desired value of power factor *tgφ* =0,2 and with limitation of the voltage drops:
a) reactive power of synchronous machines,
b) percent voltage values in *R3* and *R6* (fig. 4) switching stations,
c) line power loses produced by the reactive current,
d) power factor *tgφ* on the input of main switching station

Rys. 5. Zmiana algorytmu równych mocy zadanych silników synchronicznych na algorytm równych mocy zadanych z ograniczaniem zmian napięcia w węzłach sieci, a następnie na algorytm minimalizacji strat mocy w liniach zasilających dla stałej wartości zadanej współczynnika mocy *tgφ* =0,2 z ograniczaniem zmian napięcia w węzłach sieci:
a) moce bierne silników synchronicznych,
b) procentowa wartość napięcia rozdzielni zasilających *R3* i *R6* (rys. 4),
c) sumaryczne straty mocy w liniach zasilających,
d) współczynnik mocy *tgφ* na dopływie rozdzielni *RG*

Some of prepared algorithms verified by computing simulations were applied in industrial control systems of the reactive power compensation. Its scheme is presented in fig. 6 and waveforms of the active and reactive power and power factor in the main switching station are presented in fig. 7 and fig. 8.

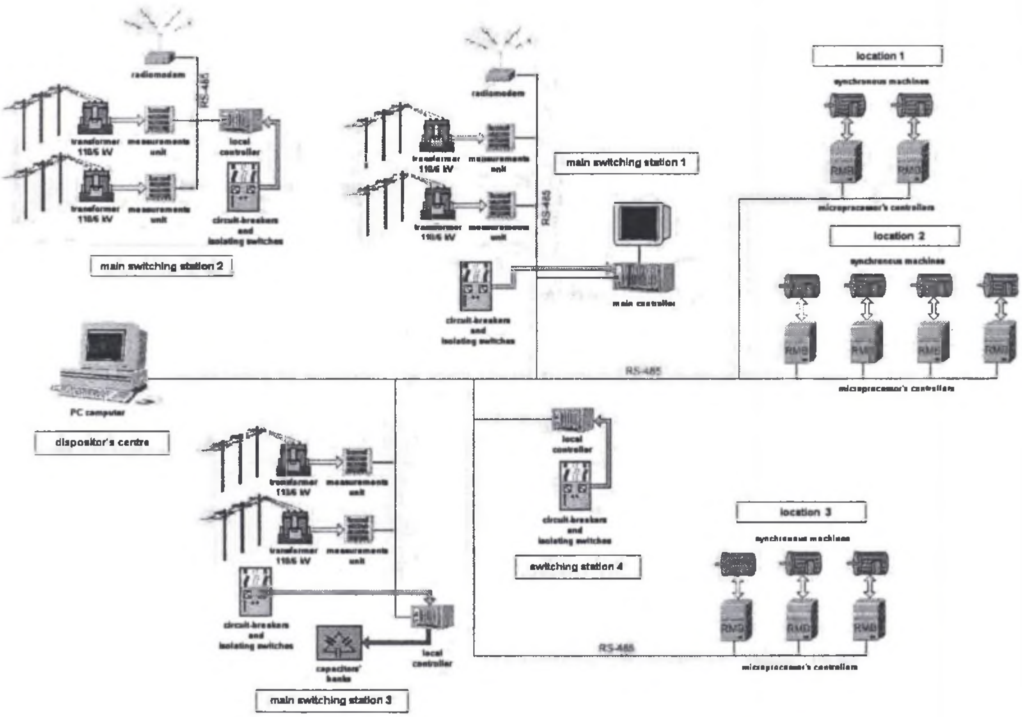

Fig. 6. Scheme of the industrial reactive power compensation system
Rys. 6. Schemat ogólny przemysłowego systemu kompensacji mocy biernej

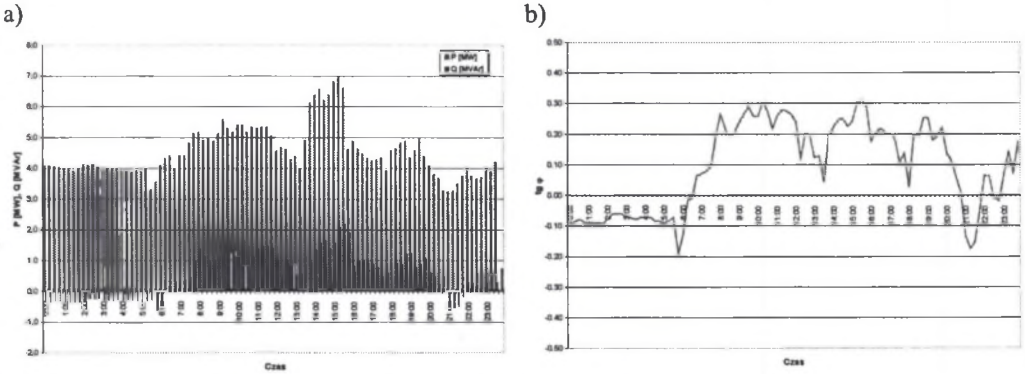

Fig. 7. Average 15 min. measurements values in one of the supply points before installation of compensation system:
a) active and reactive power,
b) power factor *tgφ*

Rys. 7. Pomiary średnich 15-minutowych w jednym z punktów zasilających przed zainstalowaniem systemu kompensacji:
a) moc czynna i bierna,
b) współczynnik mocy *tgφ*

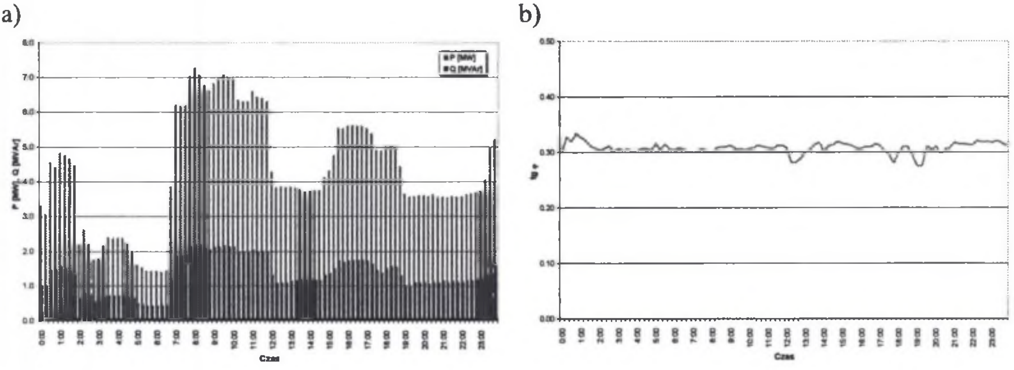

Fig. 8. Average 15 min. measurements values in one of the supply points after installation of compensation system:
a) active and reactive power,
b) power factor *tgφ*

Rys. 8. Pomiary średnich 15-minutowych w jednym z punktów zasilających po zainstalowaniu systemu kompensacji:
a) moc czynna i bierna,
b) współczynnik mocy *tgφ*

5. CONCLUSIONS

Many enterprises bear the additional expenses of the electrical energy purchase caused by improper management of the reactive power in spite of sufficient quantity and control possibilities of compensators. Application of the control system of compensators and presented control algorithms makes possible the better utilization of the compensators.

The minimization of the active power loses caused by reactive power flows in the grid is the main optimization criterion of the compensators control method presented in the paper. Simulation and industry tests demonstrate, that application of this method makes possible considerable reduction of the power loses in the grid.

If effect of the voltage changes on active power loses caused by reactive power flows is neglected and any limitations don't appear, then determination of the optimal values of the compensators reactive power executes in one step.

In industry application of the central compensator control system it is required the identification of the grid configuration.

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