Possibilities of Control of Reactive Power Flow in Polish Power System

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***Abstract*—Excessive reactive power flows are an important problem in a power system. Optimization of reactive power flows in the system allows reducing them. This paper deals with optimization of reactive power flows in the national power system. Effects of two variants of this optimization are presented. One of them is when voltage magnitudes at generation nodes, on-load tap changer positions, and reactive powers of compensators, which already exist in a power system, are control variables. In the second variant, one takes into account such control variables as in the first variant and also possibility of injection of reactive power at each node where it is possible. In that way, limit capabilities of modification of reactive power flows in the national power system are determined. In the paper, effects of optimization in each of the mentioned variants are analyzed. Particular attention is paid to comparison of those effects.**

Keywords—reactive power; optimization; active power losses; power system

I. INTRODUCTION

One of problems existing in a power system is a problem of excessive reactive power flows. Due to many negative consequences of those flows, as: increasing system active-power losses, increasing voltage drops in power-system branches, reduction of network capacity, deterioration of stability conditions, questions arise:

1. How much can be reduced excessive reactive power flows in a system by appropriate control of this system with the use of existing resources?
2. How much effect of reducing excessive reactive power flows in a system can be, locating additional reactive power sources in this system, compared with the effect of activities mentioned in point 1?

In the paper, answers to the mentioned questions are presented, when a part of Polish power system containing EHV and HV networks are taken into considerations. Further, acronym PPS will be used to the considered part of the Polish power system.

The paper presents analyses of results of original optimization calculations of reactive power flows in PPS [1] aimed on utilization of:

1) opportunities existing in PPS, i.e. control of: voltage magnitudes at generation nodes, on-load tap changer (OLTC) positions, and reactive powers of compensators, which already exist in a power system,
2) opportunities existing in PPS and additional reactive power sources installed in this system.

A task, which is considered in the paper, comprises of two parts. Optimization referring to point 1 (Opt-*O*1) is connected with one part, and optimization referring to point 2 (Opt-*O*2) is connected with second one. A solution of the mentioned task enables to establish how great part in finding an optimal state has installation of additional reactive power sources at nodes of PPS. In each of the optimization calculations, an objective function is system active-power loss [2]. Analysis of that loss is used for determination of effectiveness of reducing excessive reactive power flows after Opt-*O*1 and after Opt-*O*2.

In optimization calculations, tabu search is used [3].

In further part of the paper, in Section II, a definition of the considered task is presented. In Section III, the system active-power loss after Opt-*O*1 and after Opt-*O*2 is discussed, and in Section IV, results of the mentioned optimizations related to reduction of the system active-power loss in PPS are given. Recapitulation of the paper is in Section V.

II. A DEFINITION OF THE CONSIDERED TASK

The task, which is considered in the paper, is solved for distinguished hours of an one-year period, defining the observation period. For each hour from the observation period, optimization task Opt-*O*1 and optimization task Opt-*O*2 is solved.

A. Optimization Opt-O1

Task Opt-*O*1 is defined as follows:

$$\min \Delta P_s(\mathbf{x},\mathbf{u},\mathbf{s}), \tag{1}$$

under constraints:

$$P_i = \sum_{j=1, j\neq i}^{n} V_i V_j \left[G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij} \right], \tag{2}$$

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$$Q_i = \sum_{j=1, j\neq i}^{n} V_i V_j \left[G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \right], \tag{3}$$

$$V_{i\min} \leq V_i \leq V_{i\max}, \tag{4}$$

$$tap_{r\min} \leq tap_r \leq tap_{r\max}, \tag{5}$$

$$Q_{g\min}^{G} \leq Q_g^G \leq Q_{g\max}^{G}, , \tag{6}$$

$$, Q_{c\min}^{C} \leq Q_c^C \leq Q_{c\max}^{C}, \tag{7}$$

$$S_b^B \leq S_{b\max}^B . \tag{8}$$

where: ΔP_s – a system active-power loss; $\mathbf{x}$ – a state vector, $\mathbf{x}^{\mathrm{T}} = [\mathbf{V}^{\mathrm{T}}, \boldsymbol{\delta}^{\mathrm{T}}]$, $\mathbf{V}^{\mathrm{T}} = [V_1, V_2, \ldots, V_n]$, $\boldsymbol{\delta}^{\mathrm{T}} = [\delta_2, \delta_3, \ldots, \delta_n]$; V_k, δ_k – a magnitude and phase angle of the voltage at k-th node, respectively, $k \in \{i, j\}$, $i, j \in \{1, 2, \ldots, n\}$, n – a number of all nodes; $\mathbf{w}$ – an input vector, $\mathbf{w}^{\mathrm{T}} = [\mathbf{P}_L^{\mathrm{T}}, \mathbf{Q}_L^{\mathrm{T}}]$, $\mathbf{P}_L^{\mathrm{T}} = [P_{L1}, P_{L2}, \ldots, P_{L,L}]$, $\mathbf{Q}_L^{\mathrm{T}} = [Q_{L1}, Q_{L2}, \ldots, Q_{L,L}]$; P_{Ll}, Q_{Ll} – active and reactive powers of l-th load, respectively, $l \in I_L$, I_L – a set of numbers of load nodes, L – a number of load nodes; $\mathbf{s}$ – a control vector, $\mathbf{s}^{\mathrm{T}} = [\mathbf{V}_G^{\mathrm{T}}, \mathbf{T}^{\mathrm{T}}, \mathbf{Q}_C^{\mathrm{T}}]$; $\mathbf{V}_G^{\mathrm{T}} = \left[V_1^G, V_2^G, \ldots, V_G^G\right]$; V_g^G - a magnitude of the voltage at g-th generation node, $g \in I_g$, I_g – a set of numbers of generation nodes; G – a number of generation nodes; $\mathbf{T}^{\mathrm{T}} = \left[tap_1, tap_2, \ldots, tap_R\right]$; tap_r – a tap of r-th OLTC transformer, $r \in I_r$, I_r - a set of numbers of OLTC transformers; R – a number of OLTC transformers; $\mathbf{Q}_C^{\mathrm{T}} = \left[Q_1^{\mathrm{C}}, Q_2^{\mathrm{C}}, \ldots, Q_C^{\mathrm{C}}\right]$; Q_c^C - a reactive power of c-th compensator, existing in a power system; $c \in I_c$, I_c - a set of numbers of compensators; C - a number of compensators in a system; $\delta_{ij} = \delta_i - \delta_j$; P_i, Q_i – active and reactive injection power at i-th node, respectively; G_{ij}, B_{ij} – real and imaginary parts, respectively, of element of admittance matrix of PPS; Q_g^G - a reactive power of g-th generator; S_b^B - apparent power flow on b-th branch; $b \in I_b$, I_b – a set of numbers of branches in a system; min, max – stand for a minimum and a maximum of the specified quantity, respectively.

B. Optimization Opt-O2

Definition of optimization Opt-$O2$ differs from the definition of optimization Opt-$O1$ by the form of vector **s**. During Opt-$O2$, that vector is as follows:

$$\mathbf{s}^{\mathrm{T}} = \left[\mathbf{V}_G^{\mathrm{T}}, \mathbf{T}^{\mathrm{T}}, \mathbf{Q}_C^{\mathrm{T}}, \mathbf{Q}_A^{\mathrm{T}}\right], \tag{9}$$

where: $\mathbf{Q}_{\mathrm{A}}^{\mathrm{T}} = \left[Q_1^{\mathrm{A}}, Q_2^{\mathrm{A}}, \ldots, Q_A^{\mathrm{A}}\right]$; Q_a^{A} - a reactive power of a-th additional compensator in a system; $a \in I_a$, I_a - a set of numbers of additional compensators; A - a number of additional compensators in a system.

Opt-$O2$ is aimed to determine boundary capabilities of changes of reactive power flow in PPS. During that optimization, an assumption is made, that potentially, reactive power can be injected at each electrical node to be in a substation.

III. CHARACTERISTICS OF SYSTEM ACTIVE-POWER LOSS AFTER OPTIMISATION

General characteristics of system active-power loss before and after performing Opt-$O1$ and Opt-$O2$ for the considered observation period is in Tab. I. Fig. 1 presents system active-power loss in order of decreasing values before and after performing both optimizations.

TAB. I. SYSTEM ACTIVE-POWER LOSS BEFORE AND AFTER OPT-O1 AND AFTER OPT-O2

Parameter	**Before optimization MW**	**After optimization O1, MW**	**After optimization O2, MW**	**Change as an effect of optimization**			
				OPT-O1		**O2**	
				Value MW	**Relative Value %**	**Value MW**	**Relative Value %**
$\Delta P_{s\,min}$, MW	86.1	83.2	82.9	-2.9	-3.37	-3.2	-3.73
$\Delta P_{s\,max}$, MW	605.9	538.0	533.3	-67.9	-11.21	-72.6	-11.98
$\Delta P_{s\,av}$, MW	332.4	316.1	306.8	-16.3	-4.90	-25.6	-7.71
$\Delta P_{s\,max}$-$\Delta P_{s\,min}$, MW	519.8	454.8	450.4	-65.0	-12.50	-69.4	-13.35
$\frac{\Delta P_{s\max} - \Delta P_{s\min}}{\Delta P_{s\,av}}$	1.56	1.44	1.5	-0.12	-7.69	-0.1	-5.77

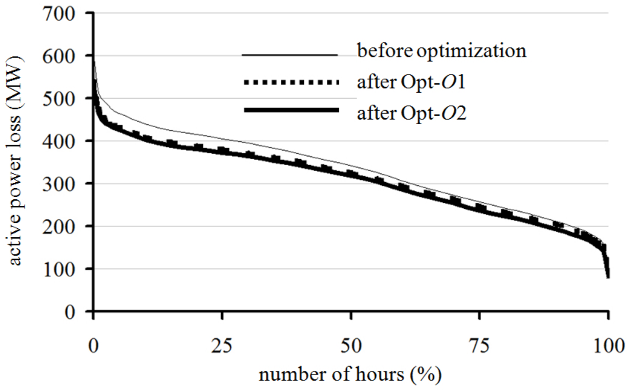

Fig. 1. System active-power loss before and after Opt-$O1$ and Opt-$O2$.

A. Optimization with the Use of Existing Resources

Results of calculations from Tab. I clearly show that Opt-$O1$ has favorable impact on PPS. After that optimization, all parameters, to be shown in Tab. I, are lower than before optimization.

After Opt-$O1$, there is decreasing the minimum and maximum values of system active-power loss. The maximum value of the system active-power loss decreases much more than the minimum value. Taking into account relative values, reduction of the maximum value is above three times more than reduction of the minimum value of the system active-power loss. Reduction of range of the system active-power loss is even larger (by 12.5 %). An average value is lower after optimization, but it decreases to a lesser degree than the maximum value of the system active-power loss. It should be noted, that variability of the system active-power loss decreases essentially. In relative values, that reduction is 7.69%.

Analyzing Fig. 1, it is easy to note, that in each of cases to be considered in Fig. 1, extreme values of the system active-power loss are a small number of hours. Before the optimization, in 98 % of the considered observation period, the system active-power loss is in range [158.83, 512.17] MW, whose width is equal to 353.35 MW and constitutes 67.98 % of the range of loss. Range [158.83, 512.17] MW is determined eliminating the largest values to occur in 1 % of the observation period and similarly eliminating the smallest values to occur also in 1 % of the observation period. Further, the so-defined time period is marked as $T_{98\%}$.

After Opt-$O1$ in time period $T_{98\%}$, values of the system active-power loss are in range [152.68, 473.98] MW having a width equal to 321.3 MW, to be 70.64 % of the range of all values of the system active-power loss.

Comparing width of the range of values of the system active-power loss for the time period $T_{98\%}$ before and after Opt-$O1$, one can ascertain that change is essential. The width of the considered range decreases by 9.07 %.

Fig. 1 shows that a time period, in which values of the system active-power loss are not less than a certain threshold value, is shorter after Opt-$O1$ than before this optimization. In relative terms, the larger the mentioned threshold value is, the larger difference of the considered time periods is observed.

B. *Optimization with the Use of Existing Resources and Additional Reactive Power Sources*

The subsection contains analysis of parameters describing the system active-power loss after optimization Opt-$O2$ under assumption that parameters describing the system active-power loss after optimization Opt-$O1$ are a base.

Results of calculation from Tab. I shows, that except the variation ratio ($(\Delta P_{s\,\max} - \Delta P_{s\,\min})/\Delta P_{s\,av}$) all other parameters describing the system active-power loss after optimization Opt-$O2$ are smaller than after optimization Opt-$O1$.

Utilization of additional reactive power sources apart from existing resources in PPS not very much affect such parameters of the system active-power loss as: minimum and maximum values, and a range. Those parameters decrease not more than 1 %.

Taking into account additional reactive power sources in optimization Opt-$O2$ have more impact on an average value and the variation ratio of values of the system active-power loss. A difference of the average values of the system active-power loss after optimization Opt-$O2$ and after optimization Opt-$O1$ is equal to almost 3 %. In the case of the variation ratios, a difference is equal to about 2 %. The change of the average value of the considered system loss after optimization Opt-$O2$ is more favorable than after optimization Opt-$O1$. A change of the variation ratio of values of the system active-power loss is less favorable after optimization Opt-$O2$.

After optimization Opt-$O2$ in time period $T_{98\%}$, values of the system active-power loss are in range [141.81, 464.87] MW, having a width equal to 323.06 MW, to be 71.73 % of the range of all values of the system active-power loss. Analyzing the mentioned range of values of the system active-power loss, one can note, that its width is slightly increased after optimization Opt-$O2$. Apart from that fact, the considered range is within smaller values of the system loss. After optimization Opt-$O2$, the endpoints of the range are less from the endpoints of corresponding range after optimization Opt-$O1$. The lower endpoint of the range is less by 7.12 %, and the upper endpoint is less by 1.92 %. It should be regarded as a positive.

It should be added that after optimization Opt-$O1$ as well as after optimization Opt-$O2$, values of the system active-power loss are more often in range [350, 400) MW. However, a number of hours, in which values of the system active-power loss are in that range, is larger after optimization Opt-$O2$ than after optimization Opt-$O1$.

IV. CHARACTERISTICS OF REDUCTION OF SYSTEM ACTIVE-POWER LOSS AFTER OPTIMISATION

General characteristics of reduction of the system active-power loss as a result of carrying out optimization Opt-$O1$ and optimization Opt-$O2$ for the assumed observation period is shown in Tab. II. The data from Tab. II show, that after each optimization there is large difference between extreme values of the system active-power loss to be observed in the observation period.

TAB. II. PARAMETERS DESCRIBING REDUCTION OF THE SYSTEM ACTIVE-POWER LOSS AS A RESULT OF CARRYING OUT OPTIMIZATION OPT-$O1$ AND OPTIMIZATION OPT-$O2$

Parameter	**After optimization**			
	OPT-O1		**OPT-O2**	
	Value MW	**Relative value %**	**Value MW**	**Relative value %**
$(\Delta(\Delta P_s))_{\min}$, MW	2.955	1.27	3.230	2.15
$(\Delta(\Delta P_s))_{\max}$, MW	70.778	12.95	77.360	13.88
$(\Delta(\Delta P_s))_{śr}$, MW	16.287	4.54	25.620	7.70
$(\Delta(\Delta P_s))_{\max}$-$(\Delta(\Delta P_s))_{\max}$, MW	67.823	11.68	74.130	11.73
$((\Delta(\Delta P_s))_{\max}$-$(\Delta(\Delta P_s))_{\max})/(\Delta(\Delta P_s))_{śr}$	4.164	2.57	2.893	1.52

Fig. 2 presents reduction of the system active-power loss in order of decreasing values after performing both optimizations. After each of the considered optimization, larger reduction of the system active-power loss (larger than 10 %) is in relatively small part of the observation period.

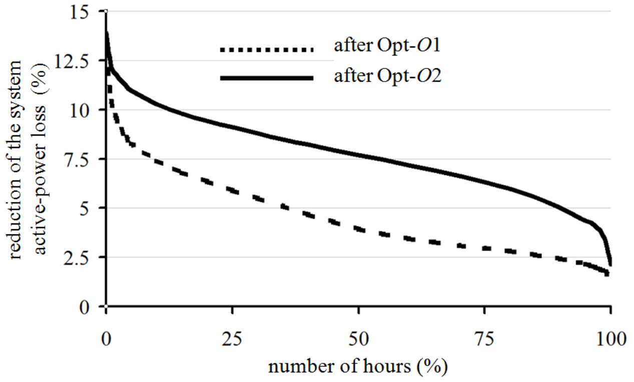

Fig. 2. Reduction of the system active-power loss after optimization *Opt-O*1 and after optimization *Opt-O*2.

A. *Optimization with the Use of Existing Resources*

Data from Tab. II reveal, that after optimization Opt-*O*1 there is no smaller reduction of the system active-power loss than 1.27 %.

In the largest number of hours, reduction of the system active-power loss is in interval [3, 4) %, and next in interval [2, 3) %. After optimization Opt-*O*1, reduction of the system active-power loss does not exceed 8, 10 and 12 %, respectively, in 93,55, 98.56 and 99.77 % of the observation period.

B. *Optimization with the Use of Existing Resources and Additional Reactive Power Sources*

After optimization Opt-*O*2 there is no smaller reduction of the system active-power loss than 2.15 %. After optimization Opt-*O*2, all general parameters describing reduction of the system active-power loss with the exception of the variation ratio are larger than these parameters after optimization *Opt-O*1. This fact indicates a favorable situation regarding reactive power flow after optimization *Opt-O*2. It should be noted, that after optimization *Opt-O*2, the minimum and maximum values and the range of reduction of the system active-power change the least with respect to the corresponding parameters after optimization *Opt-O*1. Changes of the mentioned parameters are not larger than 1 %. The most significant change is for the average value (by 3.16 %), and next for the variation ratio of reduction of the system active-power loss (by 1.05 %).

In the largest number of hours, reduction of the system active-power loss is in interval [7, 8) %, and next in interval [8, 9) % and [6, 7) % . After optimization Opt-*O*2, reduction of the system active-power loss does not exceed 8, 10 and 12 %, respectively, in 55,74, 87.48 and 98.61 % of the observation period.

V. Final Remarks

Optimization of PPS without utilization of additional reactive power sources (optimization Opt-O1) gives a noticeable change of system active-power loss. This fact can be regarded as an indicator of existing reserves in PPS, of which utilization enable achievement of a more favorable state than before optimization. Decreasing the mentioned loss during optimization is a consequence of changes in reactive power flows, i.e. is a consequence of reduction of reactive power flows, especially the largest ones.

The difference between impact of optimization Opt-O1 and impact of optimization with the use of additional reactive power sources (Opt-O2) on the system active-power loss is significant. This is evident when we analyze the average values of reduction of the mentioned loss, which are equal to 4.54 and 7.70 % (i.e. 1.7 times more), respectively, for optimization Opt-O1 and optimization Opt-*O*2. The difference between those average values can be regarded as the effect resulting from taking into account additional reactive power sources. That effect is smaller than the effect to be observed after optimization Opt-*O*1. It should be emphasize that effect to be obtained after optimization Opt-*O*2 is a boundary one. It is related with injecting relatively small reactive powers at many nodes of PPS, what cannot be economically acceptable. In practice, effect of reduction of the system active-power loss obtained after optimization Opt-*O*2 will be smaller. This would indicate that in the first place to reduce the excessive reactive power flows one should use resources existing in PPS.

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