REACTIVE CAPACITY COMPENSATION AND VOLTAGE REGULATION MULTI-PURPOSE OPTIMIZATION METHOD IN POWER DISTRIBUTION NETWORKS

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ABSTRACT

Using the most effective method of usefulness theory in multi-purpose optimization, algorithms and effective methods of reactive capacity compensations inside given technical restrictions of power network of electricity have been worked out.

Key words: power systems, electric network, reactive capacity compensation, voltage, optimization.

I. INSTRUCTION

With a big number of electric energy consumers and different characters electric energy quality depends on many factors in the modern power networks. It includes: power networks and working condition factors of consumers. One of them is the possibility of reactive power balances with an important reserve providing after emergency modes on the basic knots of the power system and voltage regulation on all networks.

As the length of networks of a power system increases in modern conditions, we can reduce the reactive power streams, as well as operational and capital expenses. Rational voltage mode brings to the front plan the technical – economic aspects of the power transmission EFFICIENCY. Analyses and economic calculations show that transferring the reactive power by short length lines means of a high voltage justifies. Therefore in most cases reduction of reactive power to the minimum is very effective for economically when the sources of reactive power settle down near the consumption centers.

The increase of consumer loading and its structure qualitative causes considerable increase of reactive power and constant reduction of a power factor in distributed power networks [1].

Thus, the tendency of modern power systems development is characterized by one side with the increase of reactive power consumption (in some systems to 1 kVAR/kVt), on the other side with decrease of power plant generators usage expediency and possibility for the reactive power compensation purpose [2-5]. In such conditions reactive power compensation attains a special urgency. Here the optimization's primary goal is optimum placing of reactive power sources and support of a necessary reserve of capacity Q_{rez} for voltage regulation on loading knot. For example, Polish power engineers consider that capacity of compensators should be 50% of the established capacity of generators in power plants. In France, Sweden and Germany the capacity of compensators is 35% of active peak loading, in the USA and Japan this volume is 70%. In different power systems of the USA the established capacity of compensators is 100% of generators capacities [6-11].

II. PROBLEM STATEMENT

Reactive power compensation problem is a multidimensional problem on the technical and economic aspects and consequently it is resulted with the finding of a global extremum of criterion function with the set of local extreme. In this article the voltage support within the technical restrictions and definition of optimal placing of the reactive power sources with a technique of multi-purpose optimization of reactive power in the power system is considered. By the problem consideration as one-target optimization within restrictions the criterion function is a linear combination from several factors. The problem decision is a unique optimum version and has lacks of alternative versions, and there is not dependency of an end result from the initial data.

Thus, the purpose of reactive power sources optimal placing in a power system consists of increase the quality of voltage in all central points of a network, control the stability of the system, reduce the power losses and capacities in networks. As a result these will increase the economic efficiency in the power system. From the economic efficiency point of view the new compensating units intended for installation should be proved and given corresponding optimum recommendations.

Considering the aforesaid as conditions of technical restriction of optimization it is possible to accept the followings:

1. Voltage support in the set limits of the technical restrictions on considered knots of loading of a power system:

$$U_{i\min} \le U_i \le U_{i\max}$$
$$PF_{\min} \le PF \le PF_{\max}$$
$$F(x,u) = 0$$

where, U_{imin}, U_{imax} – is respectively, admissible minimum and maximum values of voltage on ith knot; *PF*- power factor; *F(...)* -

2. Voltage deviation should be minimum:

$$\delta U = \sqrt{\sum \left(\frac{U_i - U_{i\,nom}}{U_{i\,nom}} \right)^{\mathbf{2}}} \rightarrow \mathbf{min}$$

3. Power loss reduction maximization in power system networks

$$\Delta\Delta W_{il} = \left(\Delta\Delta \mathrm{P} \cdot \tau\right) = \left(\Delta \mathrm{P}_{b,c} - \Delta \mathrm{P}_{a,c}\right) \cdot \tau \rightarrow \max$$

where, $\Delta\Delta \mathrm{P}$, $\Delta \mathrm{P}_{b,c}$, $\Delta \mathrm{P}_{a,c}$ - respectively, the change (reduction) by loss of active power in the maximum loading mode, losses of active power before and after compensation, τ - the loss time of maximum power.

4. Maximization of annual economic efficiency

$$\mathrm{E} = \left(\Delta\Delta W_{il} \cdot \beta - \frac{C_k}{n_k} \right) \rightarrow \mathbf{max}$$

where, β - the cost price of electric energy, for a power system; C_k -general expense of compensating devices; n_k - operating time of compensating devices.

5. Compensating devices expense outlay recovery time minimization:

$$T_0 = \frac{C_k - C_t - C_x}{\Delta\Delta W_{il} \cdot \beta} \to \min$$

where, C_t and C_X -incomes formed from increase of throughput of transformers and lines as a result of compensation:

$$C_{t,i} = K_{t,i} \frac{S_{i,\mathbf{1}} - S_{i,\mathbf{2}}}{S_{nom}}$$

$$C_{x,i} = K_{xi} \frac{I_{i,\mathbf{1}} - I_{i,\mathbf{2}}}{I_{b,i}}$$

$S_{i,1}$, $S_{i,2}$ – total power of transformers before and after compensation respectively; $\dot{I}_{i,1}$, $\dot{I}_{i,2}$ - currents proceeding through lines before and after compensation; S_{nom} - full rated power of the transformer; $\dot{I}_{a,i}$ - an admissible current of a line; k_t and k_X-costs of lines and transformers.

For voltage regulation on loading knot the necessary reactive power reserve should be provided:

$$Q_{rez} = (0{,}1 \div 0{,}15) Q_{\text{y}}$$

In this case capacity of the compensating device on consumer balance border belonging and power supplying organization should satisfy the below-mentioned condition:

$$Q_k \geq (1{,}1 \div 1{,}15) Q_{\text{y}} - Q_{ekv}$$

where, $Q_{ekv} = \sum Q_{\text{y}} - q$ is equivalent reactive power which is defined on the basis of the report; $\sum Q_{\text{y}}$ - the sum of reactive power demanded by the consumer; q - reactive power loss in a network.

The most effective method of efficiency for multi-purpose optimization is used. According to this method efficiency of each analyzed version is defined as below:

$$B_k = \sum l_{il} \cdot N_i \to \mathbf{max}$$

where N_i - is coefficients of purposes importance, their sum should be equal to one; l_{ik} - the standardized values of optimization criteria.

For minimization purpose

$$l_{il} = \frac{Y_{k\max} - Y_{ik}}{Y_{k\max} - Y_{k\min}}$$

For maximization purpose

$$l_{il} = \frac{Y_{ik} - Y_{k\mathbf{min}}}{Y_{k\mathbf{max}} - Y_{k\mathbf{min}}}$$

In this problem decision the acceptance of N_i creates uncertainty and consequently its use creates difficulty. In the offered algorithm coefficients N_i are accepted in the below-mentioned form:

$$N_1 > N_2 > N_k$$

$$N_1 > \left(N_2 + N_3 + \dots N_k\right) = m_i \sum_{i=2}^{k} N_i$$

$$N_1 > \left(N_{j+1} + N_{j+2} + \dots N_k\right) = m_j \sum_{j+1}^{k} N_j$$

In the first case N_i is given by the researcher. And in the second case the change step is defined, and coefficients N_i are accepted as the least usage N_i $\left(N_k \approx 0{,}01 - 0{,}05\right)$:

$$a = \frac{1 + kN_k}{1 + 2 + \dots (k-1)}$$

k - number of criterion functions.

For this case

$$N_{k-1} = N_k + a; \qquad N_{k-2} = N_{k-1} + a = N_k + 2a; \qquad N_1 = N_k + (k-1)a.$$

After definition N_i condition $\sum N_i = 1$ is checked and updating of coefficients to accuracy 0,001 is conducted.

In the third case for definition of N_i k number linear equations systems are constituted and from their decision N_i is found. For example, к=4 the following equation turns out

$$\begin{cases} N_1 + N_2 + N_4 = 1 \\ m_1 N_1 = \left(N_2 + N_3 + N_4\right) \\ m_2 N_2 = \left(N_3 + N_4\right) \\ m_3 N_3 = N_4 \end{cases} \qquad \text{or} \qquad \begin{cases} N_1 + N_2 + N_3 + N_4 = 1 \\ m_1 N_1 - N_2 - N_3 - N_4 = 0 \\ m_2 N_2 - N_3 - N_4 = 0 \\ m_3 N_3 - N_4 = 0 \end{cases}$$

The problem decision in the matrix form is as following:

$$\left|\begin{array}{cccc} 1 & 1 & 1 & 1 \\ m_1 & -1 & -1 & -1 \\ 0 & m_2 & -1 & -1 \\ 0 & 0 & m_3 & -1 \end{array}\right|^{-1} x \left|\begin{array}{c} 1 \\ 0 \\ 0 \\ 0 \end{array}\right| = \left|\begin{array}{c} N_1 \\ N_2 \\ N_3 \\ N_4 \end{array}\right|$$

If coefficients m_1, m_2, m_3 are not given $m_1 = m_2 = \cdots = m_{k-1} = 1$ is accepted

III. PRACTICAL RESULTS

For defining of reactive power sources optimal voltages V_i values of coefficients efficiency for problem of four criterion optimizing have been accepted as V_i =0, 526; V_2 =0, 263; V_3=0, 158;

V_4=0, 053. Criteria report values are given at the table 1 and optimal variants have been given at the table 2.

As caan be seen from the tables 1 (0,789), 10 (0,7084) və 11-ci (0,7037) versions are much more optimal with the maximal efficiency point of view. For the optimal versions selfpeyment terms are 3,9; 3,4; 3,4 yerars.

As an example a distribution power network which has sixteen nodes has given. Before the installation of the capacitor banks in the electric network the power flow and power losses for the maximum load case has been calculated and given in the table 3 and table 4. As can be seen from the voltage graphic (Fig.1) in the most of the nodes voltage values are lower than the permittable minimum level (85 – 89%). The total losses of the network are 4, 37%.

Table 1

Standardizing and general efficiency

Variants	F1(0,526)	F2(0,263)	F3(0,158)	F4(0,053)	General effeciency
1	2	3	4	5	6
1	1	1	0	0	0,789
2	0,311	0,3162	0,6735	0,5714	0,3834
3	0,3484	0,3959	0,5102	0,1429	0,3756
4	0,7097	0,6427	0,4898	0,7143	0,6576
5	0,6503	0,5964	0,5102	0,5714	0,6098
6	0,4271	0,455	0,4898	0,1429	0,4293
7	0,3806	0,4242	0,4898	0,1429	0,3967
8	0,6968	0,6272	0,5102	0,7143	0,6499
9	0,4142	0,4396	0,5102	0,1429	0,4217
10	0,7794	0,6889	0,4898	0,7143	0,7064
11	0,7755	0,6864	0,4898	0,7143	0,7037
12	0,4103	0,437	0,5102	0,1429	0,4189
13	0,5226	0,491	0,5714	0,5714	0,5246
14	0,6748	0,6401	0,4286	0,4286	0,6137
15	0,5406	0,4961	0,5918	0,7143	0,5462
16	0,3226	0,3033	0,7347	0,7143	0,4034
17	0	0	0	1	0,211
18	0,6413	0,5938	0,5	0,5714	0,6028

Table 2

Optimal variants

№	Variants	General efficiency	F1 (man)	F2(MVt)	F3 (man)	F4 (year)
1	1	0,789	1758333	9,54	9400000	3,9
2	10	0,7084	1615833	8,33	7000000	3,4
3	11	0,7037	1613333	8,32	7000000	3,4

With the application of genetic algorithm eight nodes has been chosen for the optimal placement of the static capacitor banks.

The studied network with the allocation of capacitor banks (CB) in the nodes has been shown in fig.2. The voltage deviation from the nominal value has been given in the table 5. Also according to the power losses values of the static capacitor banks for which the electric network is considered as an optimal has been given in this table. After the allocation of the static capacitor banks the improvement of voltage quality and the decrease of power losses can be observed from the table 6. As can be seen the losses are decreased from 5,28% to 3,7%.

Table 3

The results of the flow distribution

Node	**Voltage**			**Generation**		**Power**		**Node**	**Power Flow**		**Current**	**cos**
Name	**кV**	**%**	**Angle**	**MW**	**MVAr**	**MW**	**MVAr**	**Name**	**MW**	**MVAr**	**A**	**Power faktor. %**
404	35	96,56	-1,2	0	0	6,178	2,682	**405**	-11,34	-5,818	217,8	89
								403	5,169	3,136	103,3	85,5
405	35	98,67	-0,6	0	0	2,434	1,46	**Dubendi**	-13,964	-7,53	265,2	88,0
								404	11,53	6,07	217,8	88,5
Buzovna	35	85,46	-5,2	0	0	0,454	0,272	**TS3**	-0,454	-0,272	10,2	85,8
								405	14,071	7,779	265,2	87,5
Dubendi	35	100,0	0,0	49,74	32,11	0	0	**N432**	8,511	5,385	166,1	84,5
								TS1	27,154	18,941	546,1	82,0
N406	35	89,79	-3,8	0	0	4,031	2,419	**TurkenII**	3,298	2,007	70,9	85,4
								N408	-16,894	-10,456	365	85
N407	35	85,69	-5,2	0	0	2,754	1,653	**TS2**	-3,665	-2,200	82,3	85,7
								TS3	0,911	0,547	20,4	85,7
N408	35	91,75	-3,0	0	0	2,104	1,263	**TS1**	-19,222	-12,178	409,1	84,5
								N406	17,118	10,915	365,0	84,3
N432	35	97,71	-0,5	0	0	8,365	5,184	**Dubendi**	-8,365	-5,184	166,1	85,0
N403	35	95,44	-1,5	0	0	5,124	3,074	**404**	-5,124	-3,074	103,3	85,8
TS1	35	95,59	-1,6	0	0	0	0	**Dubendi**	-26,439	-17,395	546,1	83,5
								Zire	6,744	4,197	137,1	84,9
								N408	19,694	13,197	409,1	83,1
TS2	35	87,13	-4,9	0	0	0	0	**N406**	-9,396	-5,667	207,7	85,6
								N407	3,717	2,252	82,3	85,5
								TurkenI	5,679	3,415	125,4	85,7
TS3	35	85,57	-5,2	0	0	0	0	**Buzovna**	0,455	0,273	10,2	85,7
								N407	-0,910	-0,546	20,4	85,7
								Seysm/st	0,455	0,273	10,2	85,7
Seysm/st	35	85,51	-5,2	0	0	0,455	0,273	**TS3**	-0,455	-0,273	10,2	85,8
TurkenI	35	86,94	-5,0	0	0	5,670	3,402	**TS2**	-5,670	-3,402	125,4	85,8
TurkenII	35	89,13	-3,9	0	0	3,278	1,987	**N406**	-3,278	-1,987	70,9	85,5
Zire	35	95,04	-1,7	0	0	6,716	4,162	**TS1**	-6,716	-4,162	137,1	85

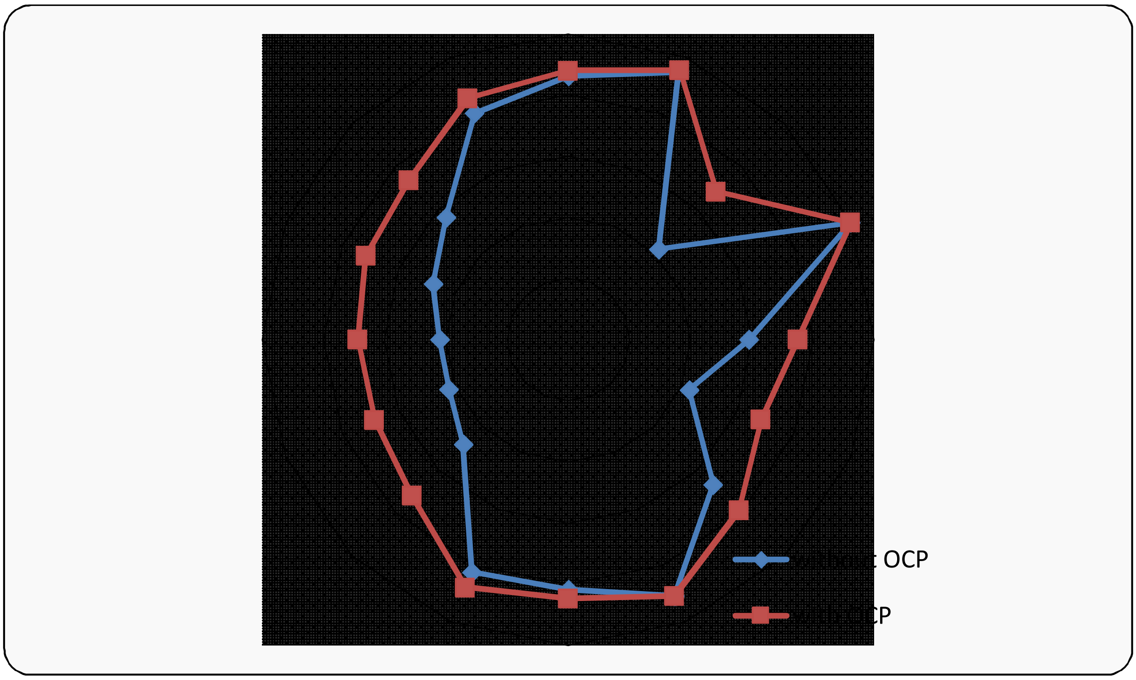

Fig.1. The voltage profile in the nodes

Table 4

The losses in the branches

Line	Flow -To		Flow- From		Losses		Node Voltage , %		Voltage drop %
Name	MW	MVAr	MW	MVAr	кW	кVAr	To	From	
Line 5	-11,347	-5,818	11,530	6,070	183,3	252,1	96,6	98,7	2,11
Line 6	5,169	3,136	-5,124	-3,074	44,8	61,6	96,6	95,4	1,12
Line 2	-13,964	-7,530	14,071	7,779	106,7	248,5	98,7	100,0	1,32
Line51	-0,454	-0,272	0,455	0,273	0,5	0,5	85,5	85,6	0,12
Line 8	8,511	5,358	-8,365	-5,184	146,1	200,8	100,0	97,7	2,29
Line18	27,154	18,941	-26,439	-17,395	715,8	1546,2	100,0	95,6	4,41
Line41	9,565	6,030	-9,396	-5,667	168,3	363,5	89,8	87,1	2,65
Line44	3,298	2,007	-3,278	-1,897	20,3	20,5	89,8	89,1	0,65
Line58	-16,894	-10,456	17,118	10,915	223,8	458,8	89,8	91,8	1,96
Line47	-3,665	-2,200	3,717	2,252	52,2	52,6	85,7	87,1	1,44
Line52	0,911	0,547	-0,910	-0,546	1,1	1,1	85,7	85,6	0,12
Line56	19,222	-12,178	19,694	13,197	472,0	1019,5	91,8	95,6	3,84
Line19	6,744	4,197	-6,716	-4,162	27,9	35,1	95,6	95,0	0,54
Line48	5,679	3,415	-5,670	-3,402	9,3	12,7	87,1	86,9	0,19
Line54	0,455	0,273	-0,455	-0,273	0,3	0,3	85,6	85,5	0,06
Total					2172,4	4273,9			

Table 5

The results of the optimal placement of capacitors

Node-Candidat	**Voltage**			**Power Factor %**	**Information on the capacitors**				**Cost, ($)**		
Name	**kV**	**%**	**Angle**		**Nom. кВАр/ bank**	**Rate, кV**	**Number of banks**	**Total кVAr**	**Installation costs**	**Pursache,** *thousand*	**Service/year**
404	35	96,998	-1,39	91,7							
405	35	98,850	-0,65	85,8							
Buzovna	35	92,124	-7,96	-70,4	1000	37	1	1000	1000	30	300
Dubendi	35	100,00	0,00	100,0	1000	37	1	1000	1000	30	300
N406	35	93,780	-5,35	85,8							
N407	35	92,057	-7,71	85,8							
N408	35	94,763	-4,21	85,8							
N432	35	97,712	-0,53	85,0							
N403	35	96,169	-1,80	97,1	1000	37	2	2000	1000	60	600
TS1	35	96,934	-2,11	100,0							
TS2	35	93,028	-7,11	100,0	1000	37	4	4000	1000	120	1200
TS3	35	92,123	-7,86	100,0							
Seysm/st	35	92,188	-7,95	-35,7	1000	37	2	2000	1000	60	900
TurkenI	35	92,885	-7,19	98,1	1000	37	3	3000	1000	90	900
TurkenII	35	93,406	-5,64	-99,3	1000	37	3	3000	1000	90	
Zire	35	96,385	-2,25	85,0							
Total							16	16000	7000	480	4200

Table 6

Summary results of losses in the nodes (at maximum load)

Node	**Flow-To**		**Flow-From**		**Losses**		**Node Voltage,%**		**Voltage drop %**
Name	**MW**	**MVAr**	**MW**	**MVAr**	**кW**	**кVAr**	**From**	**To**	
Line 5	-11,471	-4,026	11,636	4,253	165,2	227,1	97,0	98,8	1,85
Line 6	5,238	1,320	-5,202	-1,272	35,4	48,7	97,0	96,2	0,83
Line 2	-14,079	-5,719	14,176	5,946	97,5	227,2	98,8	100,0	1,15
Line51	-0,528	0,532	0,529	-0,531	0,9	0,9	92,1	92,1	0,00
Line 8	8,511	5,385	-8,365	-5,184	146,1	200,8	100,0	97,7	2,29
Line18	29,294	8,636	-28,685	-7,320	609,1	1315,7	100,0	96,9	3,07
Line41	10,912	-1,794	-10,764	2,113	147,6	318,7	93,8	93,0	0,75
Line 44	3,616	-0,419	-3,599	0,436	16,6	16,7	93,8	93,4	0,37
Line 58	-18,925	-0,425	19,111	0,807	186,3	381,8	93,8	94,8	0,98
Line 47	-4,241	0,001	4,285	0,044	44,5	44,9	92,1	93,0	0,97
Line 52	1,063	-1,908	-1,059	1,912	3,9	4,0	92,1	92,1	0,07
Line 56	-21,356	-2,154	21,750	3,004	393,7	850,4	94,8	96,9	2,17
Line 19	6,935	4,316	-6,907	-4,280	28,7	36,1	96,9	96,4	0,55
Line 48	6,479	1,305	-6,471	-1,294	8,1	11,1	93,0	92,9	0,14
Line 54	0,530	-1,381	-0,528	1,383	1,8	1,8	92,1	92,2	0,07
Total					1885,4	3686,1			

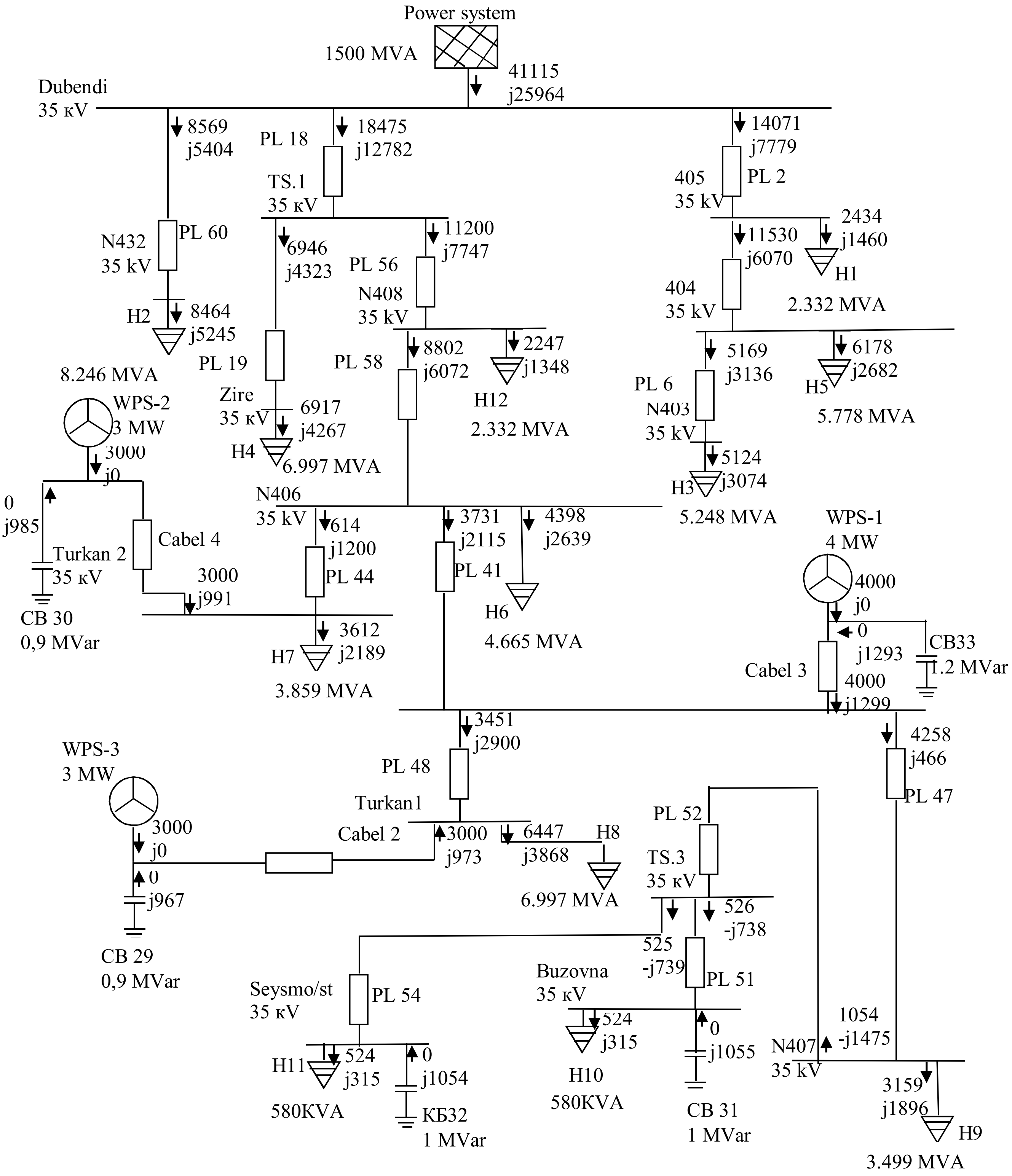

Fig. 2. The circuit of the network with the static capacitor banks

CONCLUSIONS

1. Methods and multi-purpose optimization compensations algorithms have been developed with support of a necessary reserve for preservation of normal level of voltage taking into account technical restrictions in knots of an electric network of a power system. Results of computerization to realization have shown speed and high efficiency the developed algorithm providing minimization of losses of active capacity in a net.

2. Based on genetic algorithm the power and installation locations of the static capacitor banks with the multicriteria optimization technique has given. In this case, as a criterion of optimality the minimum expenses for the installation and exploitation, the minimization of power losses during the required values of voltage and power factor and maximum saving and the minimum self-payment term are accepted.

3. The report of the real electricity network is given for two cases: operation without the CB; with optimal placement of CB. The application of the proposed method can reduce the average power losses approximately 13-14% in the electric network.

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