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Algorithm for Complex Optimization of Short-term Modes of Electric Power Systems

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ABSTRACT: One of the main problems solved during planning of short-term modes of electric power systems (EPS) is the optimization of their modes, which involves for determining for each time interval of the period the optimal values of all adjustable parameters, taking into account the established constraints. It is a complex nonlinear mathematical programming problem with many variables of different scales, simple and functional constraints in the form of equalities and inequalities. Therefore, the methods and algorithms currently used in practice provide for solving this problem by decomposing it into two subtasks. As a result, in some cases, the results are obtained with some errors that reduce the effect of optimization. This article provides a mathematical model and an effective algorithm for complex optimization of EPS modes, which are free from the shortcomings, which took place for existing methods for solving it. They involve the use and minimization of a generalized objective function, which includes, in addition to the original objective function, components that take into account constraints in the form of equalities using indefinite Lagrange multipliers and penalty functions that take into account functional constraints in the form of inequalities. The results of a study of the effectiveness of the proposed model and algorithm for complex optimization of EPS modes are presented using a specific example.

KEY WORDS: electric power systems, power plant, optimization, constraints, mode planning, Lagrange multiplier, penalty function.

I. INTRODUCTION

Solving the problem of planning of short-term modes of EPS involves, in particular, optimization their modes. It consists in determining, for each moment or time interval of the planned period, the optimal values of all adjustable parameters, at which all consumers are reliably provided with high-quality electricity at minimal economic costs and fulfilled technical and technological limitations. The regulated parameters are usually the active and reactive powers of regulated stations, reactive powers of regulated compensators, voltages of reference nodes and transformation ratios of regulated transformers. The problem of simultaneous complex optimization of modes on all the adjustable parameters, in general cases, is mathematically complex nonlinear programming problem with many variables of different scales, simple and functional constraints in the form of equality and inequality. Accordingly, its solution for modern complex EPS is sometimes associated with significant difficulties, determined by the unreliability of convergence of the iterative calculation process, and in some cases, the relatively low accuracy of optimization.

Currently, there are a number of methods and algorithms for solving the problem under consideration [1-13]. The approaches used in them can be divided into two groups. The first group of approaches involves solving the problem in one step, performing optimization simultaneously for all variables [1]. The main advantage of this approach is the high accuracy of optimization, which achieves the maximum effect through optimization. The main disadvantage here is the relatively low reliability of convergence of the iterative calculation process due to the different scale of variables and the presence of a large number of simple and functional constraints in the form of inequalities. In addition, in optimization algorithms based on the reduced gradient method, some difficulties arise in determining the optimal EPS mode with minimal violations of some restrictions in conditions of their incompatibility.

In the second group of approaches, the problem under consideration is solved on the basis of its decomposition into two subtasks - the problem of optimization of power system mode on active power [1-6, 8, 9] and optimization the modes of electrical networks [1, 2, 10-13]. At the same time, at each step of the iterative calculation process, these two subtasks are solved in turn. When solving one subtask, the parameters of another are taken into account accordingly as in [2-4]. The main advantage of the second approach is the simplicity of the algorithm and the relatively high reliability of convergence of iterative process. Therefore, at present, programs that implement optimization methods and algorithms using this approach are used in many power systems, where the first and second subtasks are often solved once each. At

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the same time, decomposition of the original problem in these methods, under conditions of complex EPS with heavy duty conditions, can lead to solutions with noticeable errors that reduce the effect of optimization.

In connection with the circumstances described above, the issue of improving methods and algorithms for complex optimization of EPS modes remains an urgent task. This paper proposes a mathematical model and algorithm for complex optimization of EPS modes, which effectively overcomes a number of disadvantages, which took place for existing methods.

II. OPTIMIZATION ALGORITHM

To explain the formulation and algorithm for solving the problem, it is enough to consider an EPS containing only thermal power plants (TPPs) participating in the optimization. Since the described algorithm involves taking into account hydroelectric stations participating in optimization, introducing indefinite Lagrange multipliers, which represent the fuel equivalent of water consumption in the corresponding hydroelectric power stations and are determined by the methods given in the works of author of this work [2]. In this case, after determining the values of these factors, by multiplying them whith the energy characteristics of the corresponding hydroelectric power plants, in a calculated sense they are reduced to fictitious thermal power plants. And power plants that do not participate in optimization, in particular plants operating on renewable energy resources, participate with their capacities, determined in advance on the basis of appropriate forecasting. In this case, solving the problem of optimal planning of a short-term mode of EPS is reduced to a separate optimization of the power system mode for each time interval of the period under consideration.

Thus, the economic costs associated with the production, transmission and distribution of electricity in each time interval of the planning period are determined by the fuel consumption in thermal power plant. Therefore, in the described mathematical model of the problem under consideration, the function of total fuel costs in thermal power plants for a time interval is taken as an objective function. Accordingly, the problem is mathematically formulated as follows:
minimize the function of total fuel costs in thermal power plants

$$B = \sum_{i \in T} B_i(P_i) \rightarrow \min ; \tag{1}$$

taking into account constraints on the balance of active and reactive powers in all generating G and load L nodes

$$W_0' = P_0 - \overline{P}_0 = 0 , \tag{2}$$

$$W_i' = P_i - \overline{P}_i = 0, \quad i \in G + L , \tag{3}$$

$$W_i'' = Q_i - \overline{Q}_i = 0, \quad i \in G_1 + L ; \tag{4}$$

minimum and maximum permissible voltage values of all nodes, active and reactive powers of thermal power plants involved in optimization, reactive powers of adjustable compensators, as well as real and imaginary components of complex (in general case) transformation ratios of adjustable transformers

$$U_i^{\min} \le U_i \le U_i^{\max}, \quad i \in G + L , \tag{5}$$

$$P_i^{\min} \le P_i \le P_i^{\max}, \quad i \in T , \tag{6}$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max}, \quad i \in G\text{-}G_1 , \tag{7}$$

$$\left. \begin{aligned} K_l^{'\min} \le K_l' \le K_l^{'\max} \\ K_l^{''\min} \le K_l'' \le K_l^{''\max} \end{aligned} \right\}, \quad l \in T_K , \tag{8}$$

minimum and maximum permissible active power flows and currents of some controlled power transmission lines (PTL)

$$P_l^{\min} \le P_l \le P_l^{\max}, \quad l \in L_P , \tag{9}$$

$$I_l^{\min} \le I_l \le I_l^{\max}, \quad l \in L_I , \tag{10}$$

where T is the set of thermal power plants participating in optimization; G, L are the set of generating and load nodes in the EPS; G_1 is a set of generating units with adjustable reactive powers (except power plants, participating in optimization); T_k is a set of adjustable transformers; L_p, L_I are the set of branches in which active power flows and currents are controlled; $U_i, P_i, Q_i, P_i^{\min}, Q_i^{\min}, U_i^{\min}$, $P_i^{\max}, Q_i^{\max}, U_i^{\max}$ are calculated and specified limit values of active and reactive powers, as well as voltage of node i; $\overline{P}_0, \overline{P}_i, \overline{Q}_i$ are specified (but for calculated thermal power plants and compensators - optimized) active and reactive powers of generating and load nodes; $K_l^{'\min}, K_l^{''\min}, K_l^{'\min}, K_l^{''\max}$ are calculated and specified limit values of the real and imaginary components of adjustable transformation ratio of the l-th branch transformer; $P_l^{\min}, I_l^{\min}$, $P_l^{\max}, I_l^{\max}$ are calculated and specified limit values of the active power flow and current of the l-th controlled branch.

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Currently existing methods for optimization of EPS modes can be divided into classical (accurate) such as [1-7], artificial intelligence [8] and heuristic [9-13] methods. These methods have their own characteristic advantages and disadvantages. In particular, many classical methods require the continuity of the objective function and the constraint function, as well as the one-extremal nature of the problem in the area of finding the optimal solution. When these conditions are met, these methods allow to obtain the solution with high accuracy. Artificial intelligence methods and heuristic methods are free from general disadvantages which took place for classical methods. However, in general case, they do not allow to obtain a solution of the problem with high accuracy. Therefore, it is advisable to use them in conditions where it is not possible to use classical methods, as well as when the initial information about the state of the EPS is probabilistic and partially uncertain. This paper discusses the issues of solving the problem of complex optimization of EPS modes based on the use of classical optimization methods.

In the proposed algorithm for solving the problem under consideration, constraints in the form of power balance (3)-(4) are taken into account using indefinite Lagrange multipliers, functional constraints in the form of inequality (9)-(10) are taken into account by penalty functions in quadratic form as in [1-4] . Simple constraints imposed on controllable parameters that are independent variables are taken into account on a verification basis before performing each iteration of the calculation process and fixing the variables that are outside the limits to the corresponding violated limit values. The limitation in the form of the active power balance in the balancing node (2) can be taken into account using an indefinite Lagrange multiplier or by penalty function based on the allocation of the balancing station power P_0 as a dependent variable (not an adjustable parameter) [3]. This paper presents an optimization algorithm taking into account this constraint using the first way.

Thus, the problem under consideration comes down to minimization the following generalized objective function:

$$F=\sum_{i\in G}B_i(P_i)+\mu_0^{'}W_0^{'}+\sum_{i\in G+L}\mu_i^{'}W_i^{'}+\sum_{i\in G_1+L}\mu_i^{''}W_i^{''}+\sum_{l\in L_P}PF_l+\sum_{l\in L_I}PF_l\to\min\,, \tag{11}$$

where $\mu_0^{'}, \mu_i^{'}, \mu_i^{''}$ are the indeterminate Lagrange multipliers, which take into account the conditions for the balance of active power of the balancing, as well as active and reactive powers of the i-th node; PF_l are penalty functions for taking into account the functional constrain in the form of inequality on the active power flow and the current of the l-th PTL. The penalty function for taking into account the inequality constraint $x\le x^{\max}$ has the following form:

$$PF=\alpha\left(x-x^{\max}\right)^2, \tag{12}$$

where α is the penalty coefficient, the value of which is taken as a positive number based on the experience of taking into account the specific limitation for the EPS under consideration. Taking into account the constraint in this form of the penalty function involves checking the fulfillment of the constraint before performing the next iteration. If the constraint is violated, it is taken into account at the next iteration by this penalty function, and if it is fulfilled, the penalty taking into account this constraint for the next iterations will be artificially equaled to zero [1-4].

Determination of the optimal values of all parameters at each iteration is carried out based on the use of the first partial derivatives of the generalized function (11). In the proposed algorithm, optimization of the reactive power of a node is carried out through optimization of its voltage. In addition, to improve the convergence of the iterative process, the optimal components of the complex transformation coefficients of adjustable transformers at each step are found by determining their optimal increments and solving the equations obtained as a result of equating the partial derivatives of function (11) on them to zero.

Thus, according to the proposed complex optimization algorithm, the calculation process is performed iteratively, in each k-th step of which computational operations are performed in the following sequence:

1) based on solving a system of nodal equations obtained by equating to zero the partial derivatives of function (11) on undetermined Lagrange multipliers

$$\begin{cases}\dfrac{\partial F}{\partial\mu_0^{'}}=P_0-\overline{P}_0=0;\\[2mm]\dfrac{\partial F}{\partial\mu_i^{'}}=P_i-\overline{P}_i=0,\quad i\in G+L;\\[2mm]\dfrac{\partial L}{\partial\mu_i^{''}}=Q_i-\overline{Q}_i=0;\qquad i\in G_1+L\end{cases} \tag{13}$$

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using the Newton-Raphson method, they calculate the steady state of the EPS, as a result they find the phase angles and modules of the complex voltages of all nodes $\delta_i^{(k)}, U_i^{(k)}, i \in G+L$, power flows and losses in electrical networks;

2) solving a system of linear algebraic equations obtained by equating to zero the first partial derivatives of function (11) on phase angles δ and modules U of complex voltages of nodes

$$\begin{cases} \dfrac{\partial F}{\partial \delta_0} = \mu_0^{'} \dfrac{\partial W_0^{'}}{\partial \delta_0} + \sum\limits_{j \in \Gamma + H} \mu_j^{'} \dfrac{\partial W_j^{'}}{\partial \delta_0} + \sum\limits_{j \in \Gamma_1 + H} \mu_j^{"} \dfrac{\partial W_j^{"}}{\partial \delta_0} + \sum\limits_{l \in L_P} \dfrac{\partial Ш_l}{\partial \delta_0} + \sum\limits_{l \in L_I} \dfrac{\partial Ш_l}{\partial \delta_0} = 0, \\ \dfrac{\partial F}{\partial \delta_i} = \mu_0^{'} \dfrac{\partial W_0^{'}}{\partial \delta_i} + \sum\limits_{j \in \Gamma + H} \mu_j^{'} \dfrac{\partial W_j^{'}}{\partial \delta_i} + \sum\limits_{j \in \Gamma_1 + H} \mu_j^{"} \dfrac{\partial W_j^{"}}{\partial \delta_i} + \sum\limits_{l \in L_P} \dfrac{\partial Ш_l}{\partial \delta_i} + \sum\limits_{l \in L_I} \dfrac{\partial Ш_l}{\partial \delta_i} = 0, \quad i \in G+L; \\ \dfrac{\partial F}{\partial U_i} = \mu_0^{'} \dfrac{\partial W_0^{'}}{\partial U_i} + \sum\limits_{j \in \Gamma + H} \mu_j^{'} \dfrac{\partial W_j^{'}}{\partial U_i} + \sum\limits_{j \in \Gamma_1 + H} \mu_j^{"} \dfrac{\partial W_j^{"}}{\partial U_i} + \sum\limits_{l \in L_P} \dfrac{\partial Ш_l}{\partial U_i} + \sum\limits_{l \in L_I} \dfrac{\partial Ш_l}{\partial U_i} = 0, \quad i \in G_1 + L \end{cases} \qquad (14)$$

determine the values of the undetermined Lagrange multipliers $\mu_0^{'(k)}, \mu_i^{'(k)}, \mu_i^{"(k)}, i \in G+L$;

3) the optimal values of the active power of all stations participating in optimization and the voltages of nodes with controlled reactive powers and reference nodes $U_t^{(k)}, t \in G - G_1$ are found using partial derivatives of function (11)

$$\frac{\partial F}{\partial P_i} = \frac{\partial B_i}{\partial P_i} + \mu_i^{'} \frac{\partial W_i^{'}}{\partial P_i} = b_i + \mu_i^{'}, \quad i \in T$$

(15)

$$\frac{\partial F}{\partial U_t} = \mu_0^{'} \frac{\partial W_0^{'}}{\partial U_t} + \sum_{j \in \Gamma + H} \mu_j^{'} \frac{\partial W_j^{'}}{\partial U_t} + \sum_{j \in \Gamma_1 + H} \mu_j^{"} \frac{\partial W_j^{"}}{\partial U_t} + \sum_{l \in L_P} \frac{\partial Ш_l}{\partial U_t} + \sum_{l \in L_I} \frac{\partial Ш_l}{\partial U_t}, \quad t \in G - G_1;$$

(16)

according to the following formulas:

$$P_i^{(k)} = P_i^{(k-1)} - h_i^{(k)} \cdot \frac{\partial F}{\partial P_i}^{(k-1)}, \quad i \in T.$$

(17)

$$U_t^{(k)} = U_t^{(k-1)} - h_t^{(k)} \cdot \frac{\partial F}{\partial U_t}^{(k-1)}, \quad t \in \Gamma - \Gamma_1; \qquad (18)$$

4) based on solving a system of equations obtained as a result of equating to zero the partial derivatives of function (11) on real and imaginary components of complex transformation coefficients of adjustable transformers $\Delta K_l^{'}, \Delta K_l^{"}, l \in T_K$

$$\left.\begin{aligned} \frac{\partial F}{\partial \Delta K_l^{'}} &= \mu_0^{'} \frac{\partial W_0^{'}}{\partial \Delta K_l^{'}} + \sum_{j \in \Gamma + H} \mu_j^{'} \frac{\partial W_j^{'}}{\partial \Delta K_l^{'}} + \sum_{j \in \Gamma_1 + H} \mu_j^{"} \frac{\partial W_j^{"}}{\partial \Delta K_l^{'}} + \sum_{l \in L_P} \frac{\partial Ш_l}{\partial \Delta K_l^{'}} + \sum_{l \in L_I} \frac{\partial Ш_l}{\partial \Delta K_l^{'}}, \\ \frac{\partial F}{\partial \Delta K_l^{"}} &= \mu_0^{'} \frac{\partial W_0^{'}}{\partial \Delta K_l^{"}} + \sum_{j \in \Gamma + H} \mu_j^{'} \frac{\partial W_j^{'}}{\partial \Delta K_l^{'''}} + \sum_{j \in \Gamma_1 + H} \mu_j^{"} \frac{\partial W_j^{"}}{\partial \Delta K_l^{"}} + \sum_{l \in L_P} \frac{\partial Ш_l}{\partial \Delta K_l^{"}} + \sum_{l \in L_I} \frac{\partial Ш_l}{\partial \Delta K_l^{"}} \end{aligned}\right\}, \quad t \in T_K; \qquad (19)$$

the optimal values of the components of the transformation coefficients are determined as

$$\left.\begin{aligned} K_l^{'(k)} &= K_l^{'(k-1)} + h_l^{'(k)} \cdot \Delta K_l^{'(k)}, \\ K_l^{"(k)} &= K_l^{"(k-1)} + h_l^{"(k)} \cdot \Delta K_l^{"(k)} \end{aligned}\right\}, \quad l \in T_K. \qquad (20)$$

where $h_i^{(k)}, h_t^{(k)}, h_l^{'(k)}, h_l^{"(k)}$ are the steps in the direction of descending to the minimum of function (11) according to the corresponding optimized parameters at the k-th iteration. Its value for the optimized parameter x at each k-th iteration is determined by the following condition:

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$$h^{(k)} = \begin{cases} \alpha_1 h^{(k-1)} & \text{if} \quad \dfrac{\partial F}{\partial x}^{(k-1)} \cdot \dfrac{\partial F}{\partial x}^{(k-2)} > 0, \\ \alpha_2 h^{(k-1)} & \text{if} \quad \dfrac{\partial F}{\partial x}^{(k-1)} \cdot \dfrac{\partial F}{\partial x}^{(k-2)} < 0, \end{cases} \tag{21}$$

where α_1, α_2 are acceleration coefficients, the values of which are selected in the ranges 1< α_1≤2 и 0< α_2<1;

5) checking the convergence of the iterative process based on the condition that the change in the total fuel costs in the TPPs participating in the optimization is insignificant at the fulfilled constraints:

$$\left| B^{(k-1)} - B^{(k)} \right| \le \varepsilon_B . \tag{22}$$

If the last condition is met, the calculation process stops and the result obtained at the last iteration is accepted as optimal. Otherwise, the next iteration of the calculation process is performed starting from point 1.

III. RESULTS AND DISCUSSIONS

The effectiveness of the proposed model and algorithm for complex optimization of EPS modes, taking into account limiting conditions, was studied, in particular, using the example of optimization of the EPS mode, the circuit of which is shown in Fig. 1, on the active power of the thermal power plant in nodes 1, 6, 7 and 8, the reactive power of thermal power plants in nodes 1 and 7, the transformation ratio of the transformer in branch 5-6, taking into account operating and technological constraints. Node 8 and, accordingly, the thermal power plant in this node are balancing.

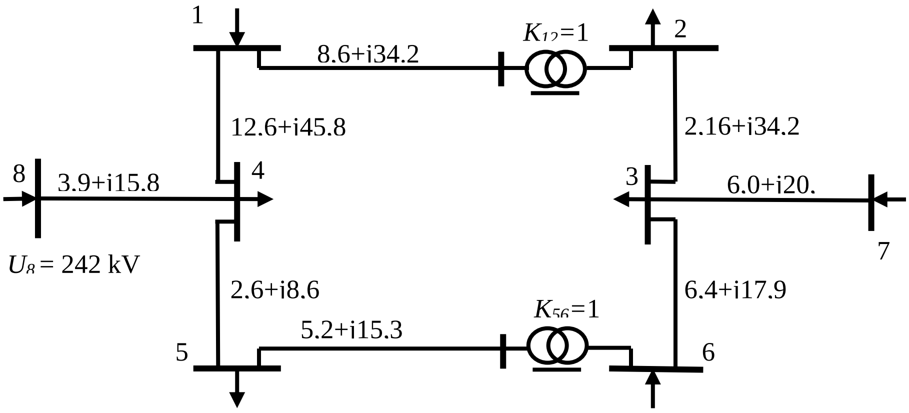

Fig. 1. Electrical network diagram of EPS.

The values of resistances of branches, voltage of the balancing node U_8 and the initial transformation ratios of transformers are shown in the circuit.

The active (in MW) and reactive (in MVAr) powers of nodes (and for generating nodes - the initial generated ones) are given below:

P_1= -450; P_2= 350; P_3= 550; P_4= 230; P_5= 470; P_6= -450; P_7= -450.
Q_1= -228.7 ; Q_2= 169.5 ; Q_3= 266.4 ; Q_4= 111.4 ; Q_5= 227.6 ;
Q_6= -358.6 ; Q_7= -246.8 .

TPPs have the following fuel equivalent consumption characteristics, t.f.e./h.:

$B_1 = 90 + 0.1P_1 + 0.0007\,P_1^2$, $B_6 = 70 + 0.11P_6 + 0.0004\,P_6^2$,

$B_7 = 80 + 0.15P_7 + 0.0005\,P_7^2$, $B_8 = 60 + 0.12\,P_8 + 0.00055\,P_8^2$.

Minimum and maximum permissible active power of thermal power plants, MW:

$200 \le P_1 \le 800$, $150 \le P_6 \le 700$, $100 \le P_7 \le 900$, $100 \le P_8 \le 1000$.

Minimum and maximum permissible reactive power of thermal power plants, MVAr:

$100 \le Q_1 \le 400$, $50 \le Q_7 \le 450$, $50 \le Q_8 \le 600$.

Range of regulation of components of complex transformation ratio of the transformer in the branch 5-6:

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$0.8 \le K'_{56} \le 1.2$; $-0.2 \le K''_{56} \le 0.2$.

Maximum permissible active power flow along a controlled PTL 6-3:

$P_{63} \le 250$ MВт .

Since in this example the consumption characteristics of equivalent fuel in thermal power plants are specified, the function of the total consumption of equivalent fuel in them is taken as the objective function.

To assess the efficiency of optimization, the initial steady-state mode of the EPS was first calculated. The results of this calculation are shown in Table 1.

Table 1. Parameters of the initial steady state of EPS.

№	U_i , [kV]	δ_i, [rad]	P_i, [MW]	Q_i, [MVAr]
1	232.22	0.0390	-450.00	-228.70
2	195.40	-0.1564	350.00	169.50
3	206.23	-0.1052	550.00	266.40
4	220.03	-0.0816	230.00	111.40
5	212.90	-0.1183	470.00	227.60
6	228.12	-0.0564	-450.00	-358.60
7	236.63	0.0570	-450.00	-246.80
8	242.00	0.0000	-339.71	-263.84
Total active power losses: π = 89.71 MW, Active power flow in controlled PTL: P_{63} = 203.01 MW				

Objective function - the total consumption of equivalent fuel in TPP of EPS in the initial mode is
B= 890.24 t.f.e./h.

As a result of complex optimization of the EPS mode on all the adjustable parameters using the proposed mathematical model and calculation algorithm, taking into account all specified constraints, the following result was obtained:

optimal transformation ratio of the transformer in branches 5-6:

$\dot{K}_{56} = 1.0038 + j0.0641$;

optimal voltages and reactive powers of stations in nodes 1 and 7:

$U_1 = 242.0$ kV, Q_1 = -282.124 MVAr ;

$U_7 = 242.0$ kV, Q_7 = -234.874 MVAr ;

optimal active powers of thermal power plants and equivalent fuel consumption in them:

P_1 = 330.95 MW, B_1 = 199.764 t.f.e./h. ;
P_6 = 550.42 MW, B_6 = 251.731 t.f.e./h. ;
P_7 = 416.298 MW, B_7 = 229.097 t.f.e./h. ;
P_8 = 382.95 MW. B_8 = 186.613 t.f.e./h. ;
total equivalent fuel consumption B= 867,21 t.f.e./h.

Table 2 shows the parameters of optimal steady-state mode of EPS, obtained by the use of proposed mathematical model and algorithm for complex optimization of mode, taking into account operating, technological and network constraints.

Table 2. Parameters of the optimal steady-state mode of EPS.

№	U_i , [kV]	δ_i, [rad]	P_i, [MW]	Q_i, [MVAr]
1	242.00	-0.0796	-330.95	-282.12
2	205.88	-0.2425	350.00	169.50
3	213.60	-0.1814	550.00	266.40
4	224.72	-0.0980	230.00	111.40
5	218.88	-0.1248	470.00	227.60
6	234.50	-0.1164	-550.42	-358.60
7	242.00	-0.0407	-416.30	-234.87
8	242.00	0.0000	-382.95	-186.63
Total active power losses: π = 80.62 MW, Active power flow in controlled PTL: P_{63} = 249.95 MW				

Thus, as a result of complex optimization of the mode of the EPS under consideration, the total hourly consumption of equivalent fuel decreases from 890.24 t.f.e./h. up to 867.21 t.f.e./h., i.e. at 23.03 t.f.e./h. or by 2.6%. At the same time, the total losses of active power in electrical networks decrease from 89.71 MW to 80.62 MW, i.e. by 9.09 MW or 10.1%.
As a result of optimization the EPS mode only on active power of TPP, the hourly total consumption of equivalent fuel is reduced to 869.22 t.f.e./h., i.e. at 21.02 t.f.e./h. or 2.3%. The total active power losses in electrical networks are reduced to 83.83 MW, i.e. by 5.88 MW or 6.5%.
When optimizing the modes of electrical networks, the total losses of active power are reduced to 86.77 MW, i.e. by 2.94 MW or 3.3%.
Comparison of the results of complex optimization and optimization on individual parameters shows that complex optimization gives the greatest effect. For example, if, as a result of complex optimization, the total consumption of equivalent fuel decreases by 23.03 t.f.e./h., when in the optimization only on active power this value is 21.02%. Similarly, if the total losses of active power in electrical networks in complex optimization are reduced by 10.1%, then as a result of optimization of electrical network mode on reactive power and transformation ratio of regulated transformer - by 3.3%.
Thus, complex optimization of EPS mode on all the adjustable parameters, in general case, provides a significant economic effect at the specified constraints are met.
The results of the calculation experiments confirm the high efficiency of the proposed model and complex optimization algorithm.

IV. CONCLUSION

1. A mathematical model of the problem of complex optimization of EPS modes, characterized by the use of a generalized objective function consisting of the sum of original objective function, functions that take into account constraints in the form of equalities with indefinite Lagrange multipliers and penalty functions that take into account functional constraints in the form of inequalities is presented.
2. An algorithm for complex optimization of EPS modes, in which the values of the optimal powers of station and node voltages at each iteration are found based on the use of partial derivatives of the generalized objective function for them, and the optimal transformation coefficients of adjustable transformers - based on the calculation of their optimal increments by solving a system of linear algebraic equations is proposed.
3. Taking into account functional restrictions in the form of inequalities in the proposed algorithm with penalty functions allows us to obtain a solution with the least possible violations of some constraints in conditions of their inconsistency.
4. Using a specific example, it was revealed that complex optimization of EPS mode provides a significant additional economic effect compared to solving the problem based on its decomposition.

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