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Minimization of Losses in Electric Networks by Optimization of Transformer Ratios

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Abstract

Minimization of losses in electric networks due to the regulation of their modes provides for determining the optimal values of reactive powers of regulated sources, voltage of reference nodes and transformation ratios of regulated transformers in circuits. At present, there are many methods and algorithms for optimizing reactive powers and node voltages that are reflected in the works of many authors. At the same time, despite the existence of a number of works, the development of more advanced algorithms for optimizing the transformation ratios of loop transformers, which ensure minimal losses due to the forced distribution of power flows in closed networks, remains an urgent task.
In this paper, we propose an effective algorithm for minimizing losses in closed electrical networks by optimizing the transformation ratios of adjustable loop transformers taking into account all types of restrictions. The results of a study of the effectiveness of the proposed algorithm on a typical example are presented.
Keywords: *electric network, loss minimization, optimization, transformer, transformation ratio, power flow.*

1. Introduction

Optimization of operating modes of electric power system (EPS) provides for determining the optimal values of all adjustable parameters, i.e. active and reactive powers of stations, reactive powers of compensators (synchronous compensators, variable capacitor banks, static sources of reactive power, etc.), voltages of reference nodes (in which the voltage level is kept constant) and transformation ratios of regulated transformers, which ensure reliable supply consumers with high-quality electricity with minimal costs associated with the production, transmission and distribution of electricity. It, in the general case, is a complex multipurpose nonlinear optimization problem with many constraints of a different nature and large volumes of required initial information and defined variables of different scales. Often, the probabilistic and partially indefinite nature of some required initial information is also added to these features of the problem.

Accordingly, the solution of such complex problem without any simplifications, which in turn lead to corresponding errors, is impossible. Therefore, the procedure for solving it by decomposition into two separate tasks, which are called optimization of power system modes and optimization of electric network modes, has been adopted [1, 2]. In the first task, optimization is carried out on active power of power stations, and in the second - on remaining adjustable parameters listed above. When solving one problem, the parameters of another problem are taken from the results of its separate solution or from the results of the EPS mode implementation in characteristic hourly intervals of the previous days. In principle, a sequential iterative solution of these two problems allows us to get the optimal solution of initial problem of complex optimization. However, studies have revealed that a single solution of these two problems allows us to get the optimal solution of initial problem with sufficient accuracy for practical purposes [2]. In this paper, we consider the problems of solving the second problem.

In optimization of electric networks mode, the optimal values of reactive power of regulated sources, the voltages of reference nodes and the transformation ratios of regulated transformers, which ensure reliable power supply to consumers with high-quality electricity at minimal costs are found. Since the station which power varies depending on the optimized parameters is the balancing station, the minimum cost is ensured with the minimum power of this station. And in turn, the power of this station will be minimal at minimal losses of active power in electric network. In addition, the multipurpose optimization problem under consideration is traditionally solved by bringing it to the single-criterion optimization problem by replacing the criteria for the reliability of power supply and the quality of electricity with the corresponding constrains imposed on the parameters that determine these indicators. Thus, the objective function in the considered problem is the total loss of active power in electric networks.

Over the past several decades, many publications have appeared aimed at developing the theory and methods of minimization of losses in electric networks by optimization the listed controlled parameters. Most of them are devoted to the optimization of reactive power and node voltages [3-5, 10]. At the same time, a number of papers can be noted on optimization the transformation ratios of loop transformers, which have made an appropriate contribution to the development of scientific and technical work in this direction. These include, in particular, [6–8].

In [6] an algorithm for choosing the optimal transformer ratio of the transformer, which reduces to optimization of voltage of a virtual node on the secondary side was proposed. In our opinion, the use of this interesting algorithm in the presence of some functional limitations in the form of inequalities, such as constraints on maximum power flow or current, is associated with special difficulties. The authors of [7] proposed an algorithm for selecting the optimal control branches of the transformer by the particle swarm optimization method. However, from the descriptions it is not clear how it takes into account various constraints in the form of inequalities. In [8], various methods for minimization of losses in electric networks by opening a loop of a closed network and reactive power compensation are given. In [9], an algorithm for calculating the optimal transformation ratios of transformers in terms of providing acceptable voltage levels for consumers is presented. However, these algorithms cannot be used to calculate the optimal transformation ratios of loop transformers, ensuring minimal losses. Thus, the issues of improving the methods and algorithms for minimization of losses in closed electrical networks by optimization of transformation ratios of adjustable loop transformers, taking into account all types of constraints, remains an important problem.

Adjustable transformers in closed electrical networks can be used to control voltage and power flows in circuits. Accordingly, it should be find such transformation ratio, when at acceptable voltage levels, a power flow distribution corresponding to the minimum losses in the networks is ensured. In this paper, we propose an effective algorithm for minimization of losses in closed electrical networks by optimization of transformation ratios of loop transformers.

2. Optimization Method

Regulation of power flows and thereby losses in closed networks can be done by simply opening the circuit or by creating additional loop EMF. Opening the circuit in order to ensure minimal loss of active power involves a preliminary calculation of the optimal distribution of power flow in it. According to the results of this calculation, a place with a switch in the circuit, where the power flow is the smallest is determined, and then the circuit is opened at this point. We note that this method of minimization of losses is approximate. Because at the point where the power flow before the circuit was opened was the smallest, after opening it becomes equal to zero and, accordingly, in all branches the power fluxes differ by some amount from their optimal values. Despite it, this method of ensuring minimal losses in closed electrical networks is the simplest and can easily be applied with minimal costs.

The creation of additional loop EMF for regulating power flows can be achieved by compensating the reactance of networks or by changing the transformation ratio of a loop transformer [10, 11]. The more effective of these is the second method.

Thus, all methods of minimization of losses in closed electrical networks, regardless of the method used, provide for determining at first the optimal power flows in them. The simplest method for determining of optimal power flows is based on the fact that in closed homogeneous electric networks, the natural distribution of power flows corresponds and satisfies the condition of minimum losses in them [11]. The determination of the optimal transformation ratios by this algorithm provides for a double calculation of the steady state of electric network. As a result of the first calculation according to the initial scheme, taking into account only the real resistances of the elements, the optimal power flows are determined. The second calculation is carried out according to the open-loop circuit at the transformer site, taking into account the impedances of the network elements. At the same time, in the nodes that appear after opening the loop, the optimal power flows obtained as a result of the first calculation are deposited. The optimal transformation ratio is defined as the ratio of voltages in these nodes obtained as a result of the second calculation. Despite the prostate, the use of this algorithm for complex electric networks with many adjustable loop transformers causes particular difficult.

The essence of the proposed algorithm is described below. Objective function i.e. the function of total losses of active power in electrical networks is the algebraic sum of the active powers of all nodes, including the slack bus. In turn, the power of each *i*th node is represented as the algebraic sum of the power flows in the branches departing from it:

$$\pi = \sum_{i=0}^{n} P_i = \sum_{i=0}^{n} \sum_{j \in J_i} P_{ij} \,. \qquad (1)$$

Constraints are

equations representing the balance conditions of active and reactive powers in nodes

$$W_i' = P_i - \overline{P}_i = 0, \qquad i \in G + N; \qquad (2)$$

$$W_i' = Q_i - \overline{Q}_i = 0, \qquad i \in G + N - G_u; \qquad (2a)$$

inequalities on the limiting values of active power of balancing station

$$P_0^{min} \le P_0 \le P_0^{max}; \qquad (3)$$

on limiting values of reactive power of nodes with fixed voltage modules

$$Q_i^{min} \le Q_i \le Q_i^{max}, \qquad i \in G_u; \qquad (4)$$

on limiting values of the node voltage

$$V_i^{min} \le V_i \le V_i^{max}, \qquad i \in G + N; \qquad (5)$$

on limiting values of real and imaginary components of complex transformation ratios of loop transformers

$$\left.\begin{aligned} K_l^{'min} \le K_l^{'} \le K_l^{'max} \\ K_l^{''min} \le K_l^{''} \le K_l^{''max} \end{aligned}\right\}, \qquad l \in T_k: \qquad (6)$$

on limiting values of active power and current flows in controlled power transmission lines (PTL), determined from the conditions for ensuring the static stability of the electric system

$$P_l^{min} \le P_l \le P_l^{max}, \qquad l \in L_P; \qquad (7)$$

$$I_l^{min} \le I_l \le I_l^{max}, \qquad l \in L_I. \qquad (8)$$

In these expressions $P_i, \overline{P_i}, Q_i, \overline{Q_i}$ are calculated and set values of the active and reactive powers of the *i*th node; K'_l, K''_l are the real and imaginary components of the complex transformation ratio of transformer with longitudinal-transverse regulation; P_l, I_l are active power flow and current of the *l*th PTL; *n* is the number of nodes in the electric network (except for the balancing one); J_i is the set of nodes having direct connections with node *i*; *N* is the of load nodes; *G* is the set of generating nodes; G_u is the set of reactive power generating (reference) nodes; T_k is the set of branches containing transformers with adjustable transformation ratios; L_P, L_I are the set branches in which active power flows and currents are controlled.
Expressions for active and reactive powers are presented in the following form:

$$P_i = \sum_{j \in J_i} P_{ij} = g_{ii} V_i^2 - V_i \sum_{j \in J_i} V_j \left(g_{ij} \cos \delta_{ij} - b_{ij} \sin \delta_{ij} \right), \qquad (9)$$

$$Q_i = \sum_{j \in J_i} P_{ij} = -b_{ii} V_i^2 - V_i \sum_{j \in J_i} V_j \left(g_{ij} \sin \delta_{ij} + b_{ij} \cos \delta_{ij} \right), \qquad (10)$$

where $\delta_{ij} = \delta_i - \delta_j$; $g_{ii}, b_{ii}, g_{ij}, b_{ij}$ are intrinsic and mutual active and reactive conductivities of nodes *i* and *j*; $U_i, U_j, \delta_i, \delta_j$ are modules and phase angles of the voltage vectors of nodes *i* and *j*.

A branch with an adjustable transformer is presented in the form shown in Figure 1.

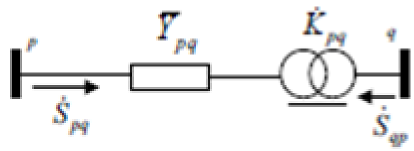

FIGURE 1: Representation of the transformer branch while optimization of its ratio.

Power flows along the transformer branch $\dot{S}_{pq}$, $\dot{S}_{qp}$ and their components P_{pq}, P_{qp} (active power flows) are expressed in terms of branch conductivity $\overline{Y}_{pq} = g_{pq} + jb_{pq}$, *p* and *q* node voltages and transformation ratio. At each optimization step, the transformation ratio of the transformer changes to $\Delta K_{pq} = \Delta K'_{pq} + j\Delta K''_{pq}$, as a result of which the power flows P_{pq}, Q_{pq}, P_{qp}, Q_{qp} change by values ΔP_{pq}, ΔQ_{pq}, ΔP_{qp}, ΔQ_{qp} that are expressed both through $\Delta K'_{pq}, \Delta K''_{pq}$ and voltage component of nodes *p* and *q*.
The losses of active power in electrical networks when the transformation ratio of the transformer is changed to ΔK_{pq} is expressed as follows:

$$\pi = \sum_{i=0}^{n} P_i + \Delta P_{pq} + \Delta P_{qp} . \qquad (11)$$

The problem of conditional minimization of function (11), taking into account constraints (2) - (8), reduces to the problem of minimization the generalized function

$$F = \pi + PF + \sum_{i \in G+N} \mu'_i W'_i + \sum_{i \in G+N-G_u} \mu''_i W''_i , \qquad (12)$$

where $PF = PF_0 + \sum_{i \in G_u} PF_{Q_i} + \sum_{i \in G+N} PF_{Ui} + \sum_{l \in Lp} PF_{P_l} + \sum_{l \in L_I} PF_{I_l}$ are total penalty function which takes into account constraints (3), (4). (5). (7) and (8), respectively; μ'_i, μ''_i are indefinite Lagrange multipliers.

At the point where the function *F* has a minimum value, the condition that the partial derivatives are equal to zero with respect to all unknowns is satisfied. In principle, a joint solution of the resulting system of nonlinear equations allows us to simultaneously determine the optimal transformation ratios of all transformers and the corresponding uncertain Lagrange multipliers and voltages of all nodes. However, solving such system is generally a difficult task. In addition, the convergence of the iterative process in this calculation is unreliable. Therefore, according to the proposed algorithm, the transformation ratio and other parameters are calculated in separate iterative cycles. For each new value of the transformation ratio, the steady state mode of the electric network is calculated, i.e. the system of equations (2) - (2a) is solved. The minimization of function (11) in each iteration is carried out by the gradient method, and the steady state mode of the electric network is calculated by the Newton-Raphson method.

To ensure reliable convergence of the iterative process, the components of the complex transformation ratio in the new *k*th step are found by the formulas

$$K_{pq}^{'(k)} = K_{pq}^{'(k-1)} + h_{pq}^{'(k)} \Delta K_{pq}^{'(k)}, \tag{13}$$

$$K_{pq}^{''(k)} = K_{pq}^{''(k-1)} + h_{pq}^{''(k)} \Delta K_{pq}^{''(k)}, \tag{14}$$

where $h_{pq}^{'(k)}$, $h_{pq}^{''(k)}$ are steps the initial values of which are selected on the basis of experience in solving similar problems. In subsequent iterations, they are adjusted from the condition of acceleration of convergence of the iterative process.

3. Results and discussions

The effectiveness of the described algorithm by the example of minimization of active power losses in electric networks, the circuit of which is shown in Figure 2, by optimizing the transformation ratio of the transformer in branch 8-6 K_{86} is studied. The complex impedances of the PTL and transformers Z (in Ω), the conductivity of TPL (in Siemens), as well as the complex powers in nodes (in MVA) are shown in Figure 2. The range of transformer control branches is ± 6x2%. In series with the transformer in branch 8-6, an adjustment transformer which rotates the voltage phase is connected. Taking into account these permissible values of real K'_{86} and K''_{86} components of sequential transformer are

1.91≤K’86 ≤2.43 and -0.5≤K’86 ≤.0.5.

Permissible voltage ranges

for nodes 1, 3, 4, 5, 6 and 7:	198 kV-248 kV,
for node 8:	475 kV -525 kV,
for nodes 6 and 10:	15 kV - 17 kV.

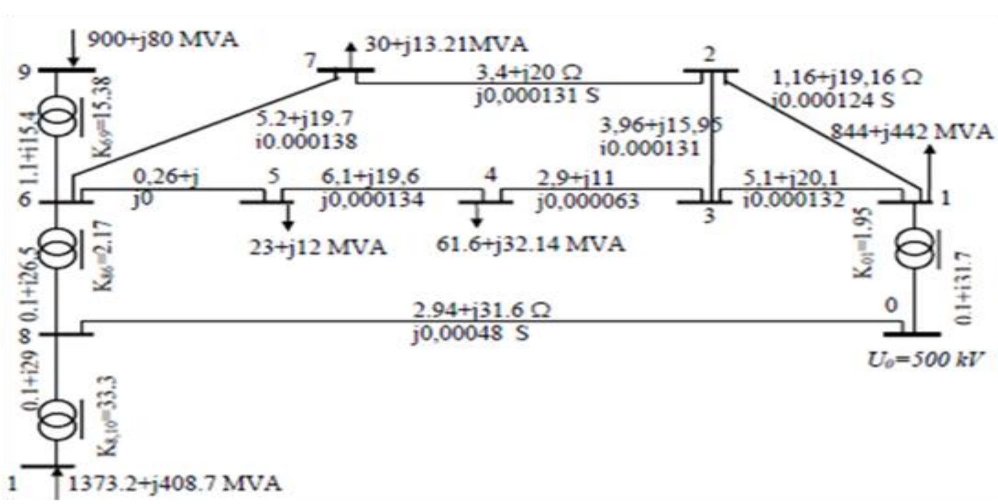

FIGURE 2: Scheme of the electrical network

For compare the optimization results, the initial steady-state mode of the electric network was calculated at K_{86} = 2.17 (K'_{86} = 2.17 and K''_{86} = 0). The calculation results are shown in table 1. The total loss of active power in this case is π = 83.53 MW.

TABLE 1: Parameters of the initial mode of the electric network.

Node number, *i*	V_i, kV	δ_i, rad.	P_i, MW	Q_i, MVAR
1	232.06	-0.0527	844.00	442.00
2	227.51	0.0376	0.00	0.00
3	227.53	0.0432	0.00	0.00
4	225.74	0.1016	61.60	32.14
5	230.09	0.2265	23.00	12.00
6	230.40	0.2331	0.00	0.00
7	226.29	0.1305	30.00	13.21
8	506.62	0.2049	0.00	0.00
9	15.10	0.4935	-900.00	-80.00
10	15.71	0.3553	-1373.20	-408.70

Table 2 shows the results of minimization of losses in electrical networks by optimization the complex transformation ratio of transformers in branch 8-6. At the same time, the optimal complex transformation ratio turned out to be $K_{86.opt.}$ = 1.91+ j0.5 (K'_{86} = 1.91 and K''_{86} = 0.5). The total losses of power in electric networks decreased to π = 66.69 MW, i.e. 16.84 MW, which is 20.2% of the total losses in the initial mode.

TABLE 2: Parameters of the optimal mode of the electric network with minimal losses

Node number, *i*	V_i, kV	δ_i, rad.	P_i, MW	Q_i, MVAR
1	239.14	-0.0823	844.00	442.00
2	240.79	-0.0425	0.00	0.00
3	240.79	-0.0414	0.00	0.00
4	241.49	-0.0179	61.60	32.14
5	247.44	0.0406	23.00	12.00
6	247.78	0.0438	0.00	0.00
7	243.09	-0.0030	30.00	13.21
8	499.15	0.2425	0.00	0.00
9	16.29	0.2676	-900.00	-80.00
10	15.49	0.3974	-1373.20	-408.70

A similar minimization of losses in electric networks by proposed algorithm was carried out under the condition that there is no control transformer, where optimization was carried out only on $K_{86} = K'_{86}$ at $K''_{86} = 0$. The result is $K_{86.opt.} = K'_{86.opt.} = 1.91$, the total losses in electric networks decreased to π = 80.06 MW, i.e. by 3.47 MW, which is 4.2%. Thus, in the absence of a phase rotation of the voltage on the transformer, the loss reduction is much less than in the presence of it. This is due to the fact that the phase rotation of the voltage strongly affects to distribution of power flow in closed loop and, accordingly, to losses in networks. To illustrate this factor, Table 3 shows the integrated power flows along branche 8-6 and the corresponding total power losses in the initial, optimal in the absence and presence of the control transformer which rotates the voltage phase.

TABLE 3: Integrated power flows at various modes of the electric network.

Modes	Optimized parameter	Power flow $S_{86}=P_{86}+jQ_{86}$, MVA	Total losses *π*, MW
Initial	-	-269.59+j132.25	83.53
Optimal on K'_{86}	K'_{86}	-205.14+j240,31	80.06

Optimal on K'_{86} and K''_{86}	K'_{86} and K''_{86}	-527.81+j204,44	66.69

Negative signs in front of active power flows along branches 8-6 in Table 3 mean that such active powers do not flow in the direction from node 8 to node 6, but in the opposite direction.

4. Conclusion

The algorithm for minimization of power losses in closed electrical networks by optimization the transformation ratios of adjustable loop transformers based on the gradient method is proposed. It allows us to reliably find the optimal complex and real transformation ratios with effective consideration of all types of constraints.
Minimization of losses in closed electrical networks in optimization the transformation ratios of loop transformers occurs due to the corresponding regulation of power flows. The presence of an control transformer that performs the phase rotation of the voltages makes it possible to significantly control the power flows and corresponding reduction power losses in them.

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