Development of Mechanisms for Active-Adaptive Control of Reactive Power Based on Intelligent Electrical Networks

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Abstract. Improving the energy efficiency of the power grid complex is an urgent problem. The need to solve this problem is due to various technical and economic reasons. First of all, this is due to high power losses in distribution electrical networks, caused by a significant load of its elements by reactive power flows. In this regard, the development of mechanisms for active-adaptive control of reactive power is becoming increasingly important. Currently, the Smart Grid concept has become widespread in the global electric power industry. The use of these technologies allows not only to optimize power losses in distribution networks, but also to improve the efficiency of the electric grid complex. The article proposes an algorithm for optimizing the placement of compensating devices in the distribution network on the example of one of the territorial network organizations of the Kuzbass. This algorithm is based on the theory of multilevel systems using the method of indefinite Lagrange multipliers. The results of applying this algorithm based on the developed simulation model are presented.

1 Introduction

Currently, there are over 3,000 power grid companies operating in the power grid complex of the Russia. At the same time, a significant part of these companies is characterized by relatively low energy efficiency indicators. This is due to significant power losses in distribution networks, as well as high depreciation of power grid equipment.

In the general case, technological power losses s consist of: technical losses due to physical processes occurring during transmission of power through the network elements, power consumption for the auxiliary needs of substations, as well as losses due to permissible errors of the power metering system.

Analysis of the structure of technological power losses shows that they are largely determined by the excess reactive power transmitted through the network [1]. It follows from the diagram (Fig. 1) that the share of losses due to the transfer of reactive power accounts for 47%. These include no-load losses of transformers and load losses from the flow of reactive power through the network elements. Technological power losses due to active power transmission account for 31% and include other conditionally constant losses, as well as load losses from active power flow. Another 22% falls on the share of losses caused by permissible errors of the accounting system.

The presence of excessive reactive loads in networks leads not only to an increase in losses, but also causes a decrease in the throughput of distribution networks, and also negatively affects the voltage mode.
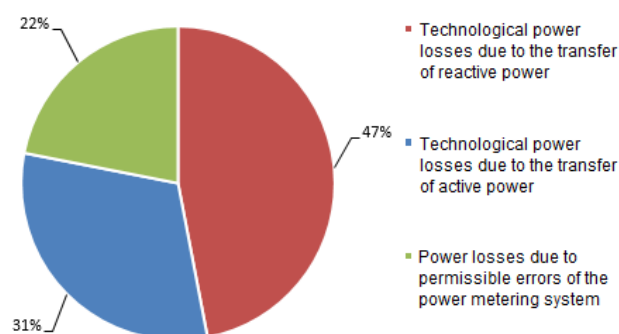

Fig. 1. Generalized structure of technological power losses in distribution networks of power grid companies

In Fig. 2 shows the dynamics of power losses changes in the distribution networks of power grid companies [2]. It shows that for the period 2015–2019, losses increased from 104.9 to 107 billion kWh. At the same time, there is a tendency for a further increase in power losses.

The depreciation of power grid equipment also has a significant impact on the energy efficiency of distribution networks. To date, the share of distribution networks that have reached their standard term is 50%. At the same time, 8% of power grids have worked out two standard terms. The total wear of distribution networks is 70% [3]. In addition, there is an irrational configuration of distribution networks.

Thus, an urgent problem is to reduce the reactive power transmitted through the distribution networks of power grid companies. The need to solve this problem is due to various technical and economic reasons.

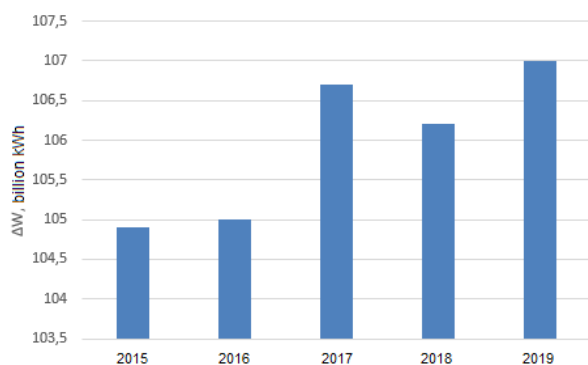* Corresponding author: brv.egpp@kuzstu.ru

Fig. 2. Dynamics of power losses changes in the distribution networks of power grid companies

2 Study Objects and Methods

There are different approaches to improving the power efficiency of distribution networks. The most algorithmically developed and software-tested approach is the reduced gradient apparatus [4, 5] with stochastic consideration of the variety of modes [6].

At the present stage of development, an important role is assigned to the active-adaptive control of the of technological processes parameters.

The development of mechanisms for active-adaptive control of reactive power is becoming increasingly important. These mechanisms should be based on the regulation of reactive power when changing voltage, load, structure and other parameters of the network.

This is also in line with the general policy of the Russian Federation's transition to the digital economy. The essence of digital energy as a part of the digital economy, in addition to technological equipment, is the formation of new mechanisms of economic interaction. This gives its subjects an increased potential for efficiency gains. The greatest effect of digitalization can be achieved when the scale and nature of such interaction changes qualitatively.

An active-adaptive network assumes the development of elements aimed at improving the efficiency of control over the generation, transmission and distribution of electricity and interaction with consumers.

At present, the concept (technology) of intelligent electrical networks (Smart Grid) has become widespread in the world power industry [7]. In the Energy Strategy of the Russian Federation for the period up to 2035, intelligent electrical networks are defined as "key areas and technologies that should ensure the effective economic and social development of Russia" [8].

Despite the fact that research in the field of smart electrical grids has been conducted since the 1970s, in world practice, a unified approach to their definition and principles of construction has not yet been formulated. The most complete definition of this approach is formulated by the IEEE as the concept of a "fully integrated, self-regulating and self-healing electric power system, having a network topology and including all generating sources, transmission and distribution networks and all types of power consumers controlled by a single network of information control devices and systems in real time " [9].

An active-adaptive network is built using advanced intelligent systems for monitoring and controlling the main parameters in real time, as well as using the multi-agent principle of organizing the control system. These solutions are based on next-generation ICT and power electronics.

The Russian power grid complex is characterized by high moral and physical depreciation of equipment. Therefore, the introduction of smart power grid technologies, obviously, should be carried out in parallel with the comprehensive technical re-equipment of the power grid complex.

At the same time, today there are the following scientific and technical prerequisites for the development and implementation of this concept in Russia: the use of emergency control systems; the presence of automated control of the operation modes of the united power systems; the use of intelligent technologies elements in power grids (devices for regulating reactive power, voltage), etc. [9].

The following main factors stimulating the introduction of smart grid technologies can be identified:
− demand response and reduction of power losses;
− monitoring and regulation of power consumption and power distribution modes;
− increasing the capacity of power grid facilities;
− adaptive control of the power system and its elements;
− reduction of the land allocated for power grid facilities [10].

Distribution networks built using Smart Grid technologies are a multi-level system. It includes measuring systems, automation equipment, and voltage and load control devices. Based on the measurement results, both short-term and long-term power consumption forecasts can be built. Also, active-adaptive control of modes can be realized by regulating the voltage and load in the network nodes, carrying out switching operations, introducing additional sources of reactive power, etc.

Each distribution network is characterized by its own optimization efficiency in accordance with predetermined criteria, which is the difference between their values at the optimal reactive power compensation mode and the initial state of the network. Therefore, the choice of compensating devices for controlling reactive power is an optimization problem. Its purpose is to determine the best location, capacity and load of compensating devices and the organization of such control of their mode of operation, which provides the maximum economic effect, subject to all technical conditions for the normal operation of power grids [11].

The choice of levels (models) with which the system is described depends on the objectives of the study. The hierarchical approach consists in a certain set of subtasks that should be solved iteratively. The solution to each of them determines some parameters in the subsequent problem, making it more definite. The concept of

organizational hierarchy implies that the system consists of a set of strictly defined interacting subsystems, which are decision-making elements. In this case, the subsystems are arranged hierarchically, that is, some of them are under the control of other subsystems.

The existing methods for optimizing the placement of compensating devices differ in the initial formulation of the problem and its subsequent implementation, but they are united by the fact that they refer to direct methods of solution based on iterative processes of calculating and comparing the values of the optimized functions. In this case, the original problem is, as a rule, an unconstrained optimization problem.

At the same time, this optimization problem should be considered as a conditional optimization problem, formed in the form of a classical mathematical programming problem [5, 12, 13]. They define the relative extremum of the objective function, that is, the extremum of the objective function in the presence of connecting constraints on its variables, which allows obtaining solutions that best meet the conditions of the real problem.

It is obvious that solving problems of conditional optimization is much more difficult than solving problems of unconstrained optimization. Therefore, it is natural to strive to reduce the problem of conditional optimization (search for a relative extremum) to a simpler problem of unconditional optimization (search for an absolute extremum) [14]. One of the most general approaches in which this procedure is implemented is the method of indefinite Lagrange multipliers. This method belongs to indirect methods of solution and is widely used to solve nonlinear optimization problems [15]. The method of indefinite Lagrange multipliers is used to solve problems of the same complexity class as when using direct methods of solving, but with restrictions on independent variables. In addition to the requirement of the possibility of obtaining analytical expressions for derivatives of the optimization criterion, a similar requirement is added regarding the analytical form of the equations of constraints [16].

The analysis shows [1] that among the considered optimization methods, the method of indefinite Lagrange multipliers most closely meets the requirements of accuracy, completeness and ease of implementation for solving the problem. A certain complication in this case arises only from the introduction of additional variables, as a result of which the order of the system of equations solved to find the extrema of the optimization criterion increases by the number of restrictions. Otherwise, the procedure for finding solutions and testing them for optimality fully corresponds to the procedure for solving problems without restrictions.

In this case, a multilevel hierarchical decision-making system will include:

− determination of Lagrange multipliers according to the main optimization criteria and search for an optimal solution;

− taking into account factors that are difficult to formalize (determining the optimal dimension of the system);

− taking into account the uncertainty of the initial data (interval estimates);

− multivariate development of distribution networks (planning methods).

3 Results and Discussion

As a result of the research, an algorithm was developed to optimize the placement of compensating devices in the distribution network on the example of one of the territorial grid organizations of Kuzbass, based on the theory of multilevel systems using the method of indefinite Lagrange multipliers [1].

In this algorithm, the process of reactive power flow control is implemented on the basis of a set of complex and mutually influencing subsystems. The presented algorithm allows to achieve the optimal value of reactive power in distribution networks and provides a significant reduction in power losses. In addition, using this algorithm, it is possible to implement reactive power control based on compensating devices, taking into account the load of installed transformers. This allows to optimize the operating mode of distribution networks of power grid companies.

The algorithm assumes an input assessment of the actual reactive power factor $\text{tg}\varphi$ in the distribution network in relation to the economically justified normalized value equal to 0.4.

If $\text{tg}\varphi \leq 0.4$, then the distribution of reactive power in the electrical network is optimal, or close to optimal. If $\text{tg}\varphi > 0.4$, then this indicates an increased consumption of reactive power. And, hence, about increased losses of electricity. Then it is necessary to take measures to reduce the reactive power in the electrical network.

First of all, it is necessary to assess the load factor of power transformers β installed in the distribution network of the territorial grid organization, and determine the feasibility of replacing them. If $\beta \leq 0.2$, then low-loaded power transformers should be replaced and other organizational measures to compensate for reactive power with the obligatory determination of the economic effect from their implementation. After carrying out these measures, a re-assessment of the load factor of transformers in the electrical network should be performed.

If, after normalization of β, the reactive power factor $\text{tg}\varphi$ exceeds the normalized value, then it is necessary to proceed to technical measures to compensate for reactive power with the optimization of the placement of compensating devices in the distribution network based on the method of indefinite Lagrange multipliers. The characteristic modes of operation of the electrical network should be selected, the objective function should be formulated, the optimization criteria and the corresponding restrictions should be determined. For these conditions, the Lagrange function must be compiled, and then its partial derivatives are determined and equated to zero. The solution of the obtained system of equations gives the optimal solution for the placement of compensating devices in the distribution network based on the criterion of minimum active power losses:

$$\Delta P = \sum_{i=1}^{n} \left(Q_i - Q_{Ki}\right)^2 R_i \Big/ U^2 \to \min, \qquad (1)$$

where Q_i – reactive load of the *i*-consumer, kvar; n – the number of consumers; Q_{ki} - power of the *i*-compensating device, kvar; R_i – active resistance of the *i*-element of the network, Ohm; U – mains voltage, kV.

If the obtained value deviates from the optimal one, the objective function and task constraints must be refined, then the optimization process is repeated until condition (1) is satisfied.

When this condition is met, a control comparison of the actual tgφ value with the normalized value must be made. If tgφ ≤ 0.4, then the reactive powers are optimally distributed, and the results of optimizing the placement of compensating devices and controlling reactive power in the distribution network are achieved. If tgφ exceeds the normalized value, the algorithm must be repeated until the reactive power factor is within the range of tgφ ≤ 0.4.

The constant development of electrical networks makes the decision-making process for the selection and placement of compensating devices multi-stage, continuous in conditions of constant updating of information, which is characteristic of open systems. At each stage one should not limit oneself to a single inflexible solution, but one should focus on a certain set of solutions that are close to optimal according to the adopted criteria. It should be such a decision-making system that would adapt the selection and placement of compensating devices in relation to the changing conditions of the development of the electrical network with minimal costs..

In this respect, adaptive reactive power control is important. It is a process of changing the value of reactive power flowing through the network, with a change in its load, composition and configuration.

The solution of the considered optimization problem should begin at the design stage of electrical networks. It is a solution to the dynamic problem of short-term and medium-term development planning, when calculations of flow distribution in perspective development schemes are made. In this case, the choice of places and capacity of compensating devices is performed without restrictions on their total capacity. At this stage, the problem of optimization criteria for each specific network should be resolved. It depends primarily on the voltage levels in the network nodes in normal operating modes. The next stage of the problem of optimal compensation of reactive loads is the operational stage as a solution to the static problem of optimal network functioning.

The choice of capacity and location of compensating devices is made taking into account the restrictions, based on the given total reactive power available from these networks. The solution of both problems can be carried out in parallel and does not exclude one another. This assumes the application of the principles of the adaptive approach (sliding planning) [17] and the direct implementation of adaptive control mechanisms [18]. Thus, the definition of the rules for regulating reactive power is assumed taking into account the entire set of modes [5, 6] according to the adopted optimization criteria in accordance with the needs of the power grid complex.

According to the principles of adaptive reactive power control in distribution networks of power grid companies, smart grid technologies are of considerable interest. In this case, the proposed algorithm can be represented as a hardware and software complex, which includes several basic subsystems, such as: intelligent information and measuring systems (Smart Metering), Dynamic Grid Management and Load Regulation (Demand Response). Intelligent information and measurement systems allow technical metering of power consumption in real time and with high accuracy. Based on information about the actual operating mode of the network, it is possible to predict the active and reactive load, as well as to carry out operational control of the electrical network modes by automatic load regulation, control of compensating devices, etc. To reduce power losses, an increase in operating voltages, optimization of the distribution of power flows, and the use of transformers with low ohmic losses are used.

Thus, the use of the developed algorithm makes it possible to optimize the placement of compensating devices in distribution networks, helping to reduce power losses and increase their energy efficiency.

In order to evaluate the efficiency of the proposed algorithm, a simulation model of a real grid of a territorial network organization was developed using the MATLAB Simulink package [1].

For this model, based on the method of indefinite Lagrange multipliers, the power of compensating devices was optimized according to the criterion of minimum active power losses (1), taking into account the corresponding restrictions. The normalized value of the reactive power factor in the distribution network was taken equal to tgφ = 0.4.

For this purpose, a model was built from MATLAB Simulink blocks to optimize the objective function. Next, using Simulink Design Optimization, variables were defined that will change during the optimization process. The initial average load factor of transformers in the distribution network was β = 0.15.

As a result of the iterative optimization process, the optimal values of the capacities of the compensating devices installed in the network nodes were determined.

Further, the load factors of transformers in the distribution network of the territorial grid organization were changed. As a result, their average load factor increased to β = 0.502. At the same time, the optimal values of the powers of the compensating devices were recalculated using the developed model.

As a result of optimization, the reactive power factor decreased to tgφ = 0.4 and began to be within the economically justified standardized value. At the same time, losses in the distribution network with an average load factor of transformers β = 0.15 and optimal placement of compensating devices decreased by 15.7%, with β = 0.502 - by 3.3% (Table 1).

Table 1. Parameters of distribution network 6 kV before and after optimization of the placement of compensating devices

Parameter	Network without compensating devices		Network with compensating devices
	β = 0,15	β = 0,502	
Reactive power factor tgφ	0,697	0,479	0,4
Active power losses ΔP, kW	386,8	336,9	325,7
Power losses ΔW, thousand kWh	1547,2	1347,5	1302,8

Due to the fact that it is recommended to install compensating devices in a low voltage network, the placement of compensating devices in a 0.38 kV distribution network was similarly optimized using the resulting model, all other initial conditions being equal.

As a result of optimization, the reactive power factor decreased to tgφ = 0.4 and is within the economically justified standardized value. At the same time, зщцук losses in the distribution network with an average load factor of transformers β = 0.15 and optimal placement of compensating devices decreased by 16.7%, with β = 0.502 - by 4.3% (Table 2).

Table 2. Parameters of distribution network 0.38 kV before and after optimization of the placement of compensating devices

Parameter	Network without compensating devices		Network with compensating devices
	β = 0,15	β = 0,502	
Reactive power factor tgφ	0,697	0,479	0,4
Active power losses ΔP, kW	386,8	336,9	322,3
Active power losses ΔP, kW	1547,2	1347,5	1289,2

The economic effect from the implementation of these measures amounted to about 2 million rubles with a payback period of less than 1.5 years.

Thus, the developed simulation model of the distribution network showed a sufficiently high efficiency of optimization of the placement of compensating devices, ensuring the optimal distribution of reactive power and a significant reduction in electricity losses in the electrical network. In addition, with the help of this model, it is possible to control reactive power in the network depending on the load factors of power transformers, which allows you to obtain the most optimal operating mode of the network.

4 Conclusion

The widest and most promising group of methods and tools for improving energy efficiency is currently the use of Smart Grid technologies. The relevance of the innovative development of the Russian power grid complex based on this concept is due to the low potential for increasing the efficiency of the use of power grid assets (the possibilities for increasing the productivity of equipment are practically exhausted) and the limited investment resources.

The need to implement solutions based on Smart Grids is due to the following factors:

− changes in the conditions for the functioning of the electricity and capacity markets;

− decrease in the reliability of power supply;

− the emergence of new technologies that have not found their application in the power grid complex;

− a pronounced trend of constant growth of tariffs for power;

− the presence of an objective need to increase both the energy and environmental efficiency of the power grid complex;

− implementation of a systematic approach in terms of building a digital economy.

In this regard, the use of intelligent electrical networks technologies pursues the main goal of ensuring the reliability and improving the energy efficiency of the power grid complex.

The implementation of the proposed algorithm for optimizing the placement of compensating devices based on the method of indefinite Lagrange multipliers using the developed simulation model of the distribution network has shown its efficiency. As a result of optimization, power losses have significantly decreased, and the technical and economic indicators of the network have increased.

Thus, the use of Smart Grid technologies allows not only to reduce power losses in distribution networks. Using active-adaptive elements, the main directions of modernization of power grid assets can be determined, studies of the efficiency of implemented innovations can be carried out to make decisions about the possibility of their further distribution, etc., which ultimately should ensure an increase in the efficiency of the power grid complex as a whole.

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