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CHAPTER 1

SYSTEM OF PROACTIVE CONTROL OF REACTIVE POWER FLOWS IN DISTRIBUTED ELECTRICAL GRIDS

ABSTRACT

The paper solves the urgent problem of improving the methods and means of optimizing reactive power flows in distribution grids with significant daily volatility in the generation and consumption of electricity. The object of research is the process of automated control of a set of reactive power sources (RPS) in distribution electrical grids (DEG). Coordination of their operation will contribute to the reduction of electricity losses in the DEG and improve the voltage quality. Based on the results of the analysis of modern trends in the construction of RPS control systems, the expediency of decentralization using local automatic control systems (ACS) is substantiated.

The operational determination of the optimal powers of the RPS and the calculation of the corresponding settings of local ACS are associated with objective difficulties. The study proposes a formalization of the problem of optimizing reactive power flows in DEG and a new way to solve it. It is shown that the problem can be reduced to the determination and periodic correction of the settings of local systems of automatic control of the RPS. The latter, by adjusting the energy flows according to local parameters, taking into account the specified settings, contribute to the achievement of the overall effect of reducing losses and stabilizing the voltage in the DEG. The proposed method contributes to a reasonable simplification and increase in the reliability of the distributed control system for reactive power flows in the DEG, taking into account technical limitations.

To solve the problem, the principle of advancing control, the method of "ideal" current distribution (according to power losses) was applied. Using the model of "ideal" current distribution, the problem of nonlinear optimization of reactive power flows in the DEG was reduced to a fundamentally simpler problem of finding current distribution in a step-by-step circuit with active resistances. To determine the time intervals between the adjustment of local ACS, it is proposed to analyze the correlation between the predictive graph of the optimal power of an individual RPS and local energy consumption based on the Pearson coefficient.

A block diagram and algorithms for the operation of the control system for the set of RPSs are proposed, which provide a minimum of computational operations and data exchange operations. At the same time, a response is provided to changes in the consumption and generation of electricity in the conditions of short-term failures of information systems. This contributes to improving the quality of operation of energy distribution systems in modern conditions.

KEYWORDS

Proactive control, power distribution system, reactive power sources, optimization, "ideal" current distribution, losses, voltage quality.

The operation of modern distribution electrical grids (DEG) is characterized by a local increase in energy consumption, the appearance of two-way flows, increased requirements for ensuring reliability and controllability, as well as more stringent environmental restrictions [1]. To solve the problem of cost-effectiveness and environmental friendliness of the DEG operation, various energy-saving measures and innovative technologies are being developed and implemented.

In recent years, trends in the economical use of fossil fuels have led to the integration of renewable energy sources (RES) into distribution grids. Moreover, the share of the latter in the energy balance of some DEG already today is 30 % or more. Since DEGs were designed for centralized power supply, the development of dispersed generation gives rise to new problems and tasks [2]. From a technical point of view, the main tasks are to maintain the balance of active and reactive power.

The transmission of reactive power by grids is associated with an increase in current loads, an increase in voltage drops, an increase in electricity losses, etc. A feature of reactive power compensation in modern DEG is that optimal decisions have to be made in conditions of significant volatility of active and reactive power consumption, as well as unstable local generation. At the same time, individual RES can provide additional means to improve the efficiency of electricity distribution.

The implementation of information technologies in DEG has created the basis for the development and improvement of the operating efficiency of reactive power sources (RPS) with automatic control. However, the solution of a complex problem requires the application of efficiency criteria that link the energy efficiency of the DEG, the quality of electricity, the reliability of grids and the RPS payback. The complexity of the problem statement, the dynamism of the processes and the dispersal of reactive power sources in the DEG requires constant improvement of approaches to automated and automatic control.

Therefore, the problem of improving the methods and means of optimizing reactive power flows in distribution grids, which have significant daily volatility in the generation and consumption of electricity, turns out to be relevant.

Traditionally, to search for solutions to optimize reactive power flows in DEG, numerous methods of linear and nonlinear programming are used [3]. For the practical implementation of solutions, uncontrolled RPS or automated reactive power compensation installations are used. The latter automatically adjust the output power according to local parameters. The general disadvantage of this approach is that it gives partial solutions. To eliminate it, it is proposed to determine the optimal parameters of the RPS based on the mutual influence of all sources and consumers in the DEG. And a dispersed control system for a set of local RESs should be built on the basis of the Hamilton-Ostrogradsky principle [4] to achieve a system-wide effect.

The aim of the study is to improve the efficiency of managing a set of dispersed reactive power sources, which is manifested in reducing power losses and improving the quality of voltage in distribution grids.

To achieve the aim, the following objectives are solved:

– well-known methods for optimizing the modes of electrical grids in terms of reactive power are analyzed;

– the conditions for the optimal operation of reactive power compensation means in distribution grids are determined;

– a block diagram and algorithms for the operation of the control system for a set of RPS equipped with local automatic control systems have been developed;

– the effectiveness of the automated reactive power flow control system was tested on the example of 10 kV urban distribution grids.

The object of the study is the normal modes of distribution electrical grids with dispersed sources of electricity.

The subject of the study is methods and means of optimizing power flows by means of proactive control of reactive power compensation installations.

For the analysis and solution of the tasks set, the principle of least action in the formulation of Hamilton-Ostrogradsky, methods of linear and non-linear programming are used. The established DEG modes were modeled on the basis of the nodal voltage method. Electricity losses were determined by the method of average loads and numerical integration. Matrix algebra, graph theory and decomposition were used to develop algorithms for optimizing reactive power flows in and the formation of adjustment parameters for automatic control systems of the RES, matrix algebra, graph theory and decomposition were used. To develop an automated control system, the provisions of the theory of automatic control were used.

The conducted studies have shown the feasibility of using the Hamilton-Ostrogradsky principle to solve the problem of optimizing reactive power flows in distribution grids with a sharply changing load. In particular, using the mentioned principle, the possibility of raising the problem of nonlinear optimization of reactive power flows according to the criterion of maximum profit to the calculation of the "ideal" mode of the distribution grid is substantiated. This significantly reduced the number of calculations and increased the reliability of obtaining a solution.

The proposed approach to the calculation of the optimal reactive powers made it possible to develop an algorithm for proactive control of a set of RESs. It ensured the coordination of the RPS operation in the grids of power supply companies by preventive adjustment of the adjustment parameters of their control systems. According to the developed block diagrams and control algorithms, an automated control system for the existing RPS was created to maintain optimal reactive power flows, taking into account the rapid changes in the operating parameters of the DEG, in particular, the generation of renewable sources.

1.1 METHODS FOR OPTIMIZING REACTIVE POWER FLOWS IN MODERN DISTRIBUTION GRIDS

Optimization of reactive flows in modern DEG has certain features. In addition to traditional sources of reactive power, in particular, power plants, transmission lines and specialized devices, dispersed installations for the conversion of energy from renewable sources (RES) should be considered. Their operation is determined by the influence of the environment, so it is difficult to predict. As a result, reverse flows occur periodically, which affect the reliability and efficiency of electricity transportation. Since the pace of renewable energy development is growing every year, these problems will only get worse. This is evidenced by the experience of Western countries. In [5], using the example of Germany, it is shown that the output of RES power can cause an unacceptable increase in voltage levels.

At the same time, using inverter converters, synchronous or asynchronous RES generators can generate or consume a given reactive power without active power limitation. For example, in [6] it is shown that the controlled supply of reactive power from RES can reduce losses in the distribution grid and facilitate the flexible exchange of reactive energy with the grids of transmission system operators (TSOs).

In addition to the RES implementation, electricity consumption is increasing locally in modern distribution grids. In Italy, for example, fast charging stations for electric vehicles have significant peak powers and low power factor. The random nature of this load, which grows with the demand for electric vehicles, has a negative impact on the energy efficiency of distribution grids [7].

Thus, changes in the nature of generation and consumption in distribution grids, especially reactive power, require improvements in methods and means to improve energy efficiency.

1.1.1 METHODS FOR SOLVING PROBLEMS OF OPTIMIZING REACTIVE POWER FLOWS

To solve problems related to the optimization of reactive power flows in DEG to achieve maximum profit or profitability, methods of decomposition, linear and nonlinear programming are traditionally used [8]. However, such methods use assumptions and simplifications, so they can direct the solution process to local extrema.

In a number of works, in particular [8], the possibility of moving from a complex problem of optimizing reactive power flows to a number of separate optimization problems is shown. This allows the use of classical optimization methods [8] and traditional software. However, this approach is associated with the need for additional assumptions for the decomposition of the problem. This reduces the reliability and speed of obtaining a solution and degrades the efficiency of the operational control of the RPS [9].

The development of information technologies and computing facilities has created conditions for new approaches to solving the problem of optimizing reactive power flows. They are focused on increasing the level of automation of the DEG operation. Elements of artificial intelligence [10–12], including artificial neural grids [10], expert systems [5], genetic algorithms [11], and evolutionary programming [12], are actively used. However, the excessive time spent on finding optimal solutions in the case of using evolutionary and genetic algorithms limits their use for real-time problems [9].

For DEG, the problem of reactive power control is mainly due to its influence on the voltage deviation [13]. Therefore, the optimization of reactive power generation in DEG is often based on voltage sensitivity assessment methods. For this, in [13], a fragment of the Jacobian sensitivity matrix and voltage sensitivity index (VSI) are used. The latter is defined as the Euclidean norm of a fragment of the inverse Jacobi matrix [14].

In addition to determining the optimal powers of the RPS, an important aspect is the organization of their interaction in the DEG to ensure a systemic effect. In [15], an approach is presented to optimize the reactive power and voltage flows in the power system using game theory. It is shown that a complex interaction between the RPS is necessary to control the voltage in the DEG. For its reproduction and optimization, a non-commercial formal game was used. It is shown that the appropriate settings of the automatic control systems of individual DEGs allow their coordinated operation according to local parameters. This minimizes the total reactive power generation required to satisfy voltage limits.

Advances in information technology have made it possible to use parallel computing to optimize the DEG operation. Therefore, methods of multicriteria optimization of reactive power distribution have been developed [16]. The vast majority of them are based on well-known single-objective optimization methods, in particular, on genetic algorithms [17, 18], search engine optimization algorithms [19], and competitive algorithms [20, 21] in combination with decomposition methods [22].

In [23], a modified Pareto method was proposed to apply parallel computing to the problem of optimizing the distribution of reactive power. Three objective functions were chosen for multi-purpose operational optimization: reduction of power losses, reduction of voltage deviation and increase of voltage stability. To solve the problem, let's use the algorithm of strength Pareto multi-group search optimization (SPMGSO) [24]. The results of Pareto optimization are compared with other methods, in particular, with non-dominant sorting genetic algorithm II (NSGA II) [25], non-dominant sorting particle swarm optimization (NSPSO) [26]. The comparison confirmed the effectiveness of the method, which is manifested in a steady reduction in energy losses.

However, the practical implementation of this approach involves the prompt determination of the optimal powers of the RPS, as well as the possibility of permanent centralized control over them. The latter is mostly impossible for DEG due to the lack of a developed information infrastructure [27, 28]. Based on this, it is advisable to use distributed automated control systems based on local automatic control systems (ACS).

For such a control organization, specific approaches to solving optimization problems should be applied. In [29], it was proposed to use the iterative method of semi-definite programming (SDP) to solve the problems of optimizing the RPS power. Each iteration involves solving the optimization problem of determining the power of the RPS using SDP. Changes in the DEG parameters within the iteration are considered not critical for the adequacy of the model. After each iteration, the grid parameters are refined. The validity of this principle of distribution of the optimization process was confirmed by computational and full-scale experiments [29]. Therefore, it was used in our study to create algorithms for simulating DEG modes during the day and taking into account the influence of local systems of automatic control of the RPS.

1.1.2 OPTIMIZATION OF REACTIVE POWER FLOWS BASED ON THE "IDEAL" MODE OF THE DISTRIBUTION GRID

The objective function of the problem of optimizing the RPS powers according to the criterion of minimum power losses in the DEG is predominantly convex and has no gaps. To solve the problem, a number of methods have been developed that have confirmed their effectiveness. But the tasks of operational control of reactive power sources are more complicated. The reasons are the dynamism of the processes of the control object and severe time constraints for decision making. Based on this, the methods described above often cannot guarantee a solution to the problem. At the same time, the application of the Hamilton-Ostrogradsky principle [30] makes it possible to determine the coordinates of some "ideal" DEG mode, taking into account energy losses. After that, the search for the optimal regime is reduced to taking into account the limitations of the parameters. This approach increases the reliability and speed of the search for the optimal solution of energy problems. After all, the process of searching for a solution begins not with an arbitrary initial approximation, but with an extreme value corresponding to the "ideal" mode of the DEG (**Fig. 1.1**). In addition, the coordinates of the "ideal" mode can be determined by calculating the steady state after a certain adjustment of the calculation model [31].

The process of searching for the optimal solution is shown in the projection onto the X_1X_2 coordinate plane (**Fig. 1.1, *a***) and in the projection onto the $P(X_1, X_2)$ coordinate plane obtained by the principal component method (PCM) (**Fig. 1.1, *b***). Taking into account the peculiarities of determining the step of the gradient method, the process of finding a solution slows down significantly in the optimality region (**Fig. 1.1, *a***) [31]. Thus, the time limits of operational control may be violated.

The optimal DEG mode in terms of reactive power (**Fig. 1.1, *a***) is determined in two stages. First, the parameters of the "ideal" mode $\boldsymbol{X_i}$ [X_{1i}, X_{2i}] are calculated, which correspond to the minimum power losses at given loads and voltage levels in the DEG. The values of the optimized variables X_{1i}, X_{2i} and the objective function Z_i for such a regime are calculated by analytical expressions obtained from the Euler-Lagrange equations [31]. In practice, such a regime generally cannot be implemented. Therefore, at the second stage, restrictions are imposed on the dependent and independent parameters of the regime. This ensures the transition to the optimal DEG mode $\boldsymbol{X_o}$ [X_{1o}, X_{2o}]. Losses of electricity for the optimal DEG mode, obviously, will be greater than for the "ideal".

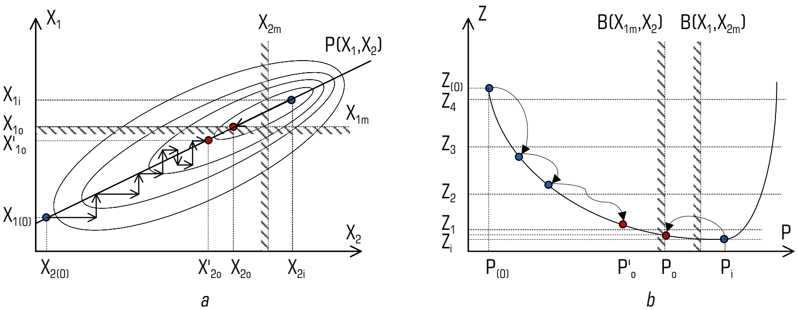

Fig. 1.1 Search for the optimal solution according to the criterion $Z(X_1, X_2)$ using the gradient method (trajectory $X(0) - X'_o$) and using the "ideal" mode (trajectory $X_i - X_o$): *a* – projection onto the coordinate plane X_1, X_2; *b* – projection onto the plane $P(X_1, X_2)$

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To form control laws and determine the debugging parameters of the ACS, one should take into account the uncertainty of individual independent parameters of the DEG. It is due to the dynamism of the regimes and the shortcomings of information support. Accounting for the mutual influence of the control actions of individual ACS and changes in the DEG parameters under the action of control is a particularly difficult task. It requires the use of simulation models and the principle of active control.

1.1.3 OPERATIONAL OPTIMIZATION OF REACTIVE POWER FLOWS USING PROACTIVE CONTROL

Decentralization of power supply in DEG and the growth of the total power of sources of dispersed generation complicate the planning of power grid modes. The existing supervisory control and automation systems were not ready to support this process. This resulted in the inability to take advantage of the potential benefits of the DESs. In particular, the use of subscriber energy sources for unloading DEG and reducing losses in them [32]. At the same time, technical problems associated with their integration emerged.

For example, power fluctuations at the inputs of powerful wind and solar power plants entail problems in energy transmission systems [33]. Traditional sources of reactive power are not able to constantly maintain the balance of reactive power in such transmissions. Therefore, it is necessary to improve the means of managing the RPS to ensure the stability of distribution grids in terms of voltage.

For the development of automation systems for RPS, it is necessary to take into account the purpose of control, as well as the requirements of industry standards. On their basis, [4, 27, 34, 35] formulated the requirements for technical means, as well as the principles of RPS automatic control:

– reduction of electricity losses in consumer power supply systems in possible daily consumption modes;

– implementation of voltage restrictions in the DEG;

– the maximum attraction of the RPS, if there are no restrictions on the exchange of reactive power between the DEG and the subscriber;

– control of actual reactive power flows at the inputs of DEG subscribers and dispersed energy sources;

– determination and implementation of the optimal settings for the power factor at the inputs of subscribers and DES. Technical support for the possibility of their remote adjustment when changing the DEG modes;

– hourly registration of reactive power flows and power factors within the balance sheet of the DEG. Remote monitoring of the state of the information-measuring subsystem;

– centralized control in automated and automatic modes using local control devices.

Distributed objects, similar to the DEG properties, are constantly exposed to a significant number of influences from sources and consumers of electricity, local controls and emergency automation, as well as the environment. These perturbations affect the dynamic processes in a distributed object and require control coordination. The general structure of proactive control of such an object is shown in **Fig. 1.2** [36]. Local automatic control systems adjust the parameters of individual elements of a distributed object to ensure its optimal operation according to a certain criterion. The local control task comes from the coordinator. It determines the control actions for individual ACS, taking into account the dynamics of the object. The predictor predicts changes in the state of a distributed object as a response to registered disturbances and controls.

However, the optimal parameters of an individual controlled element depend not only on the perturbations recorded at its level or the influence of the local ACS [37]. Adjacent controlled elements and the external environment have a significant impact. Its settings at the local level are usually not logged. To ensure proactive control, the predictor and coordinator must mimic the response of distribution grids. In addition, they must reproduce the reaction of local ACS to the recorded changes in the parameters of the DEG mode, taking into account the possible dynamics of these changes. In this case, periodic debugging of local ACS will provide stable and consistent proactive control of a distributed object [38].

The scheme for organizing the control of dynamic modes of reactive power consumption, containing links of centralized and local control, has shown its effectiveness in practice [33].

Thus, in [33], it was proposed to use a coordinated adjustment of the parameters of DC converters of wind and solar power plants and RPS. Local automatic control of the RPS provides a quick response to a decrease in reactive power flows. If the reactive power consumption exceeds the power of the RPS, then the AC filter is switched on. And the RPS is remotely reconfigured to maintain the power balance.

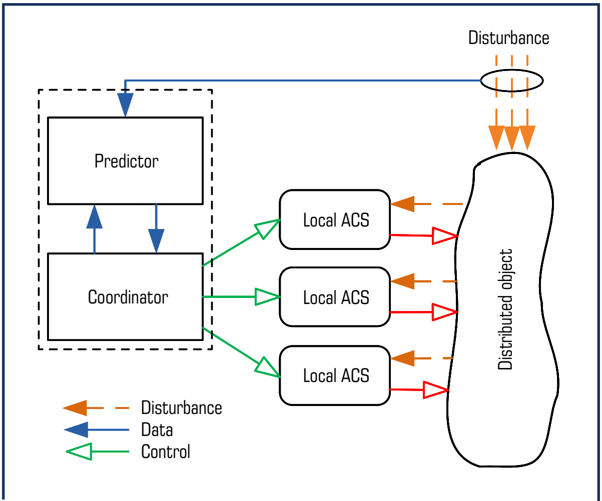


Fig. 1.2 Scheme of proactive distributed control of a distributed object

Similarly, the problems of power fluctuations for local photovoltaic stations (PVS) due to changes in insolation are solved. This leads to voltage fluctuations in the mains of the DEG and a violation of the quality of electricity. In [32], to solve this problem, PVS inverters were used as sources of reactive power. A method for local adjustment of the debugging parameters of PVSs inverters to maintain the specified voltage levels is proposed. Uncertainty of the schedule of electricity generation is taken into account.

Due to the insufficient equipment of modern DEG with data transmission tools, the use of a distributed control system was justified in [32] (**Fig. 1.2**). The system performs the main control functions autonomously according to local parameters. Communication of local systems with the distribution system operator is performed periodically to adjust their debugging parameters. To determine the necessary settings for the inverters, a short-term forecast of meteorological parameters is used. However, the described control system does not take into account the mutual influence between the local ACS of individual RPS. In addition, no attention is paid to the economic aspects of the problem of optimizing reactive power flows.

In [39], the need to take into account the mutual influence of local control systems of the RPS used to maintain the voltage profile is substantiated. The proposed approach makes it possible to solve the problem of optimizing reactive power flows in DEG by minimizing the linearized target functions of power losses for local subsystems using the Lagrange decomposition method.

It is shown that after the decomposition of the problem of finding a global optimum for RPS as a multi-agent system of large dimensions, the main attention should be paid to the coordination of the operation of local subsystems for which the information infrastructure of the DEG dispatch center used for Thus, the reduction of losses, taking into account local constraints, is provided by distribution. The effectiveness of decisions made is periodically monitored at the top hierarchical level [35, 39]. The need to coordinate the actions of local ACS is determined by the available power reserve of the RPS after maintaining the voltage profile.

So, as the practice of operating DEG [27, 35] shows, the existing information infrastructure often does not support the possibility of implementing centralized control of individual RPSs. Therefore, it is expedient to use decentralized control and local ACS that respond to local consumption of reactive power or manifestations of its change.

To coordinate the work of local ACS, it is advisable to periodically adjust their debugging parameters. Thus, the exchange of reactive power between local subsystems and DEG can be reduced to the optimal one [35]. This will increase the efficiency of sharing the RPS in distribution grids.

Determining debugging parameters for local ACS is quite a difficult task. Let's note that these parameters will remain unchanged for a certain time (from several minutes to several hours). During this time, they must ensure the effective interaction of local ACSs that support the given mode of the dynamic system. To determine the settings of the ACS, not always adequate initial data are used.

To organize distributed control of reactive power flows in DEG, ACS with voltage drop control is often used [35]. Such a system maintains a close to optimal distribution of electricity in the DEG. But the exchange of reactive power is often suboptimal due to the fact that the mutual influence of individual ACS is not taken into account.

To solve the problem of matching the ACS [35], it was proposed to use some virtual impedance in the control controller of the RPS to clarify the optimal powers in the absence of operational information from the centralized control system. Such impedances for local ACS are proposed to be determined taking into account the ratio of the squares of systematically fixed reactive power flows. The proposed RPS controller will approximately take into account the flow in the coverage area of other ACS, using only locally measured information. Its participation in the performance of system functions, in particular, the reduction of power losses and the alignment of the voltage profile in the DEG, will be determined by the change in the virtual impedance.

In this paper, it is shown that the efficiency of using the reactive power of the DEG with coordinated control can be increased by 50 % compared with local control. However, in the study [35], when determining virtual impedances, the following was not taken into account:

– influence of joint flows of reactive power along the DEG mains;

– the economic aspect of attracting subscriber RPSs to the system control of reactive power;

– that DESs have different reactive power generation capabilities.

In [40], a modified virtual impedance method was proposed. Different installed powers of the DES were taken into account. It is proposed to determine the impedances for a partially equivalent grid, in particular, to reduce the number of nodes in the design scheme. However, this did not solve the problem of coordinating the operation of local ACS and taking into account economic factors in the organization of control.

The analysis of studies has shown that in order to improve the efficiency of DEG control, it is necessary to improve information systems, introduce innovative technologies with a gradual transition to the concept of Smart Grid [41]. Currently, the use of decentralized control systems remains relevant. The main method for coordinating the operation of the RPS in electrical grids is the periodic centralized adjustment of the debugging parameters of their ACS.

From the analysis of literary sources, the following conclusions can be drawn:

1. Due to the underdeveloped information infrastructure of modern DEG, reactive power flows are controlled under conditions of incomplete and unreliable information about regime parameters and external influences. In order to increase the efficiency of using the RPS resource, it is advisable to switch to proactive control with the involvement of local ACS. The latter operate according to local parameters, but provide a systemic effect of reducing losses by adjusting the debugging parameters.

2. In order for these parameters to ensure the ACS coordination, it is necessary to perform a significant number of optimization calculations to determine them. It is expedient to determine the optimal power of the RPS for a certain point in time in the forecast interval using the "ideal" mode method. The advantage of the latter is higher reliability and performance in comparison with the methods of optimized enumeration of variants.

3. Optimization of DEG modes in terms of reactive power requires taking into account the reliability and quality of power supply to consumers. Therefore, in mathematical models on which control actions are formed and checked, this feature of the control object must be taken into account. Accounting for restrictions on dependent parameters, in particular, voltage deviations, will make it possible to reasonably make decisions about changing the operating mode of individual RPSs and their sets.

1.2 CONDITIONS FOR OPTIMAL OPERATION OF REACTIVE POWER SOURCES IN DISTRIBUTION GRIDS

Optimization of reactive power flows is a purely technical task. However, in modern conditions, RPS, which provide a systemic effect of reducing electricity losses in DEG, may be owned by another energy entity. Therefore, when solving them, it is necessary to take into account economic factors. All subjects of the electric power industry are objectively interested in reducing electricity losses and improving the quality of voltage in the DEG. Calculations show that due to the RPS inclusion in distribution grids, it is possible to reduce losses by 5–8 % [32, 35, 42]. But the effect of reducing losses is ensured not only by the introduction of RPS, but mainly by the quality of their further operation.

Automated RPS control is necessary for a number of reasons. For the consumer, it is economically justified to use automatic control systems for the RPS to reduce reactive power flows on the verge of the subscriber's balance sheet ownership. This helps to reduce the fee for the flow of reactive energy. But the main reason is the need for rapid implementation of control actions under conditions of a variable schedule of consumption and generation of reactive power in DEG. A number of studies are devoted to the development and implementation of automatic control systems for RPS, in particular [42–45]. Efficient in terms of speed and accuracy technical solutions for automating the operation of the RPS are proposed. They allow to maintain the optimal values of the reactive power factor in certain nodes of the DEG.

However, in order to optimize the reactive power flows in the DEG with the help of a set of RPSs, it is necessary to coordinate their operation. To do this, it is periodically possible to determine and change the settings for local ACS, taking into account the mutual influence of the DEG. Due to severe time constraints for such systems, it is necessary to improve the methods and algorithms for calculating the optimal powers of the RPS. They should take into account changes in the modes and configuration of the DEG during operation, as well as changes in electricity tariffs [31, 46].

1.2.1 DETERMINATION OF THE OPTIMAL RPS POWER BASED ON THE SIMULATION OF THE "IDEAL" MODE OF THE DISTRIBUTION GRID

In the simplest case, the problem of optimizing the RPS power can be represented as follows:

$$V_Q\left(Q_i\right) \to \min,\ i \in \left[1 \ldots n_q\right], \tag{1.1}$$

when balancing reactive power in the system

$$G = \sum_{i=1}^{n_q} Q_i - \sum Q_{=} - \Delta Q\left(Q_i\right) = 0,\ i \in \left[1 \ldots n_q\right], \tag{1.2}$$

and restrictions on parameters:

$$Q_i^{\max} \geq Q_i \geq Q_i^{\min},\ i \in \left[1 \ldots n_q\right]; \tag{1.3}$$

$$U_j^{\max} \geq U_j \geq U_j^{\min},\ j \in \left[1 \ldots n\right], \tag{1.4}$$

where V_Q – the power loss in the DEG; n, n_q – the number of DEG nodes for which voltage restrictions apply and the number of installed RPSs; $\sum Q_n$ – total load of consumers; $\Delta Q(Q_i)$ – losses of reactive power in DEG; $\left[Q_i^{\min}, Q_i^{\max}\right]$ – power adjustment range of the i-th RPS; U_j, $\left[U_j^{\min}, U_j^{\max}\right]$ – respectively, the calculated value of the voltage in the j-th node of the DEG and the range of permissible voltage values.

The classical solution of such a problem by the Lagrange method is the need to maintain the equality of the relative increases in power losses [14, 27]:

$$\frac{\partial V_Q / \partial Q_i}{1 - \partial \Delta Q / \partial Q_i} = idem. \tag{1.5}$$

Using equation (1.5), problem (1.1), (1.2) under certain assumptions can be reduced to solving the system of $n_q + 1$ linear equations and quickly find the optimal values of the RPS power. However, taking into account the nonlinear dependence of $V_Q(Q_i)$ and $\Delta Q(Q_i)$, such a solution will require clarification. In addition, the formulation of the problem does not take into account the economic factors of the RPS operation.

To take into account these shortcomings, it is necessary to move to the objective function through the profit from the RPS operation during a certain reporting period:

$$AP(Q_i) \to \max,\ i \in \left[1 \ldots n_q\right]. \tag{1.6}$$

After substituting mathematical expressions for the components of profit and deductions, expression (1.7) took the form:

$$AP(Q_i) = \sum_t \begin{pmatrix} \Delta P^0_{(t)} \Delta t\, C_{(t)} - \Delta P_{(t)} \Delta t (1 - \alpha_t) C_{(t)} - \\ -\left(\sum_{i=1}^{n_q} \alpha_{ei} Q_i \Delta t + \sum_{i=1}^{n_q} \alpha_{\Delta Wi} Q_i \Delta t\, C_{(t)} \right)(1 - \alpha_t) \end{pmatrix},$$

or

$$AP(Q_i) = \sum_t \begin{pmatrix} \Delta P^0_{(t)} - \\ -\left(\Delta P_{(t)} + \sum_{i=1}^{n_q} \left(\frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi} \right) Q_i \right)(1 - \alpha_t) \end{pmatrix} C_{(t)} \Delta t, \tag{1.7}$$

where ΔP^0, ΔP – the average power losses for the DEG modes during the time before and after the RPS inclusion into operation, taking into account the given schedule of their operation $Q_i(t)$; $C(t)$ – price of electricity on the intraday market during the t-th period; α_{ei} – specific costs for the production of reactive energy from the i-th RPS (for RPS on the balance sheet of DEG $\alpha_{ei} = 0$); $\alpha_{\Delta Wi}$ – specific energy losses in the i-th RPS; α_t – tax on balance sheet profit.

Based on the results of previous studies [4, 27, 31], it has been shown that it is advisable to determine the optimal power of the RPS according to the technical and economic criterion based on the "ideal" modes of the DEG. For this, spade circuits with active resistances are used (**Fig. 1.3**). The economic characteristics of the RPS operation are listed in equivalent supports, which are commonly referred to as economic. The economic pillars for individual RPSs are determined based on the fact that the cost of electricity losses should correspond to the operating costs of the RPS.

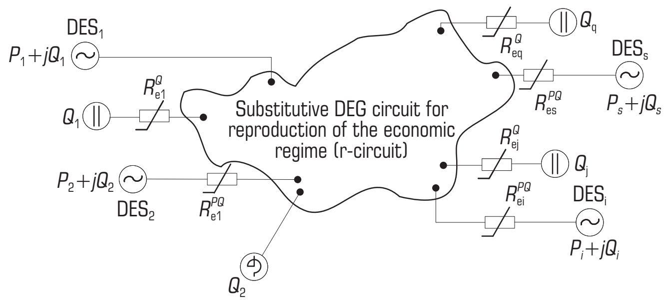


Fig. 1.3 Substitutive DEG circuit for reproduction of the "ideal" mode according to the technical and economic criterion

This approach reduces the number of calculations and makes it possible to obtain a solution close to the global maximum of the objective function. This is achieved by reducing the problem of optimizing reactive energy flows to several calculations of the "ideal" mode with the adjustment of the DEG substitutive scheme. After that, restrictions (1.2)–(1.4) are imposed and the optimal powers of the RPS are specified.

Taking into account that the power losses ΔP^0 will not change due to the involvement of the RPS, problem (1.7) can be reduced to finding the minimum operating costs in the DEG:

$$OC(Q_i) = \sum_t \left(\Delta P_{(t)} \Delta t + \sum_{i=1}^{n_q} \left(\frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi} \right) Q_i \Delta t \right) (1 - \alpha_t) C_{(t)}. \quad (1.8)$$

In (1.8), the price of electricity C(t) is a series of positive, predetermined values. Therefore, the search for the minimum of the objective function (1.8) will be equivalent to the search for the minimum of some equivalent power losses:

$$\Delta W_{eq} = \frac{OC(Q_i)}{(1-\alpha_t)C_{(t)}} = \sum_t \Delta P_{(t)}\Delta t + \sum_t \sum_{i=1}^{n_q}\left(\frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi}\right)Q_i\Delta t. \qquad (1.9)$$

Thus, the function of equivalent losses of electricity in the DEG has been obtained. They take into account losses in the RPS and the costs associated with their operation. Their reduction due to the control of the RPS will allow to evaluate the effectiveness of such control. The decrease in losses (1.9) will correspond to the increase in profit (1.7). In addition, the extreme powers of the RPS for both functions will coincide due to the equivalence of the transformations.

Calculation of the current distribution in the interceptor circuit with active resistances (**Fig. 1.3**) will allow to determine the minimum power loss $\Delta P(t)\Delta t$ and the RPS power Q_i, which are needed for this. In order to take into account economic factors in determining the "ideal" mode, it is necessary to introduce additional supports into the spacing scheme (**Fig. 1.3**). Losses in them will be equivalent to the second component of expression (1.9):

$$\Delta W_{eq} = \Delta t \sum_t \frac{Q_i^2}{U_i^2} R_{ei}^Q = \Delta t \sum_t \sum_{i=1}^{n_q}\left(\frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi}\right)Q_i,$$

where

$$R_{ei}^Q = \frac{U_i^2}{Q_i}\left(\alpha_{\Delta Wi} + \frac{\alpha_{ei}}{C_{(t)}}\right). \qquad (1.10)$$

The expression for determining the economic resistance of the i-th RPS R_{ei}^Q contains its current power Q_i and economic indicators $\alpha_{\Delta Wi}$, α_{ei}, $C(t)$, as well as dependent mode parameters U_i. Therefore, these supports need to be iteratively refined during the search for the optimal solution.

Similarly, expressions were obtained for calculating the economic resistance of the RPS for different conditions of their use to optimize the reactive power flows in the DEG (**Table 1.1**). This made it possible, within the framework of solving one problem, to ensure the optimization of the RPS powers in a multicriteria setting. That is, the powers of individual RPS are optimized according to different criteria, providing a system-wide effect of increasing profits.

The RPS powers, obtained after calculating the "ideal" DEG mode, provide the maximum profit (1.7), and usually cannot be included due to violations of the restrictions (1.3), (1.4). To move to the optimal mode, their values require adjustment.

Table 1.1 Economic resistances of the RPS for different optimality criteria

Optimality criterion for the *i*-th RPS	**Economic resistance of the *i*-th RPS**
Minimum loss of electricity in DEG	$R_{ei}^{Q}=0$
Minimum cost of RPS operation	$R_{ei}^{Q}=\dfrac{\alpha_{ei}U_i^2}{Q_i^2C_{(t)}}$
Maximum profit from the RPS operation	$R_{ei}^{Q}=\dfrac{U_i^2}{Q_i}\left(\alpha_{\Delta Wi}+\dfrac{\alpha_{ei}}{C_{(t)}Q_i}\right)$
Minimum loss for DES due to generation of excess reactive power	$R_{ei}^{Q}=\begin{cases}0,\ if\ Q_i\le Q_{i\max};\\ \dfrac{\beta_{Pi}P_{Ri}(Q_i)U_i^2}{Q_i^2C_{(t)}},\ if\ Q_i>Q_{i\max}\end{cases}$
Minimum cost of system services for voltage regulation	$R_{ei}^{PQ}=\dfrac{Q_{Ai}U_i^2}{\left(P_i^2+Q_i^2\right)}\dfrac{\beta_{Qi}}{C_{(t)}}$

Note: In expressions: $\beta_i\left(Q_i\right)$ – unit costs for the RPS operation; β_{Pi}, $P_{Ri}(Q_i)$ – the price of electricity from the *i*-th source and the reduction in power output due to forced excess generation; $Q_i>Q_{i\max}$, β_{Qi}, Q_{Ai} – specific cost and volume of additional reactive power output at the request of the DEG operator.

Taking into account the restrictions on the limiting powers of the RPS (1.3) is not accompanied by significant algorithmic difficulties. If constraint (1.3) is violated, then to fulfill it, the value of the RPS power is fixed at the upper $Q_i^{\max}$ or lower $Q_i^{\min}$ boundaries of the range of values.

If the control of the RPS power is discrete, then the calculated value of the power Q_i is rounded off to an acceptable value. There can be two such values in the vicinity of Q_i. Then, for optimal selection, the enumeration of options is used with control over the value of the objective function (1.7).

The task of taking into account voltage restrictions (1.4) cannot be solved by a simple selection of values due to the significant number of RPSs and the complex effect of their powers on the voltage level in the DEG. To correct the RPS power, taking into account such limitations, it is necessary to solve an additional optimization problem. Changing the RPS parameters to take into account restrictions is always associated with a decrease in profit from their operation. Indeed, at the same time, the RPS power deviates from "ideal". Therefore, the corrections ΔQ_i to the RPS powers must be determined so that after the restrictions on dependent variables (1.4) are met, the decrease in profit (1.7) is minimal:

$$\begin{cases} \Delta AP\left(\Delta Q_i\right) \to \min, i \in \left[1; n_q\right]; \\ \mathbf{J}_D^{-1} \Delta \mathbf{Q} = \Delta \mathbf{U}, \end{cases} \tag{1.11}$$

where $\mathbf{J}_D^{-1}$ – fragment of the inverse Jacobi matrix with the values of derivatives $J_{ij} = \partial Q_i / \partial U_j$. They relate changes in the RPS reactive power ΔQ_i to voltage deviations in the DEG nodes ΔU_j, for which the restrictions (1.4) are violated $j \in \left[1; n_?\right]$; $\Delta \mathbf{Q}$ – column vector of corrections of RPS reactive powers with dimension ; $\Delta \mathbf{U}$ – column vector of voltage deviations in the DEG nodes in excess of allowable limits. Each element of the vector is defined by an expression.

Given the relationship between objective functions (1.7) and (1.9), the formulation of problem (1.11) can be simplified. It can be reduced to the problem of minimizing the increase in equivalent losses (1.9) in the form $\Delta U_j = U_j - U_j^{\max}$:

$$\Delta V_{Q\,eq}\left(\Delta Q_i\right) = \sum_{i=1}^{n_q} \left(\frac{\partial \Delta P_{(t)}}{\partial Q_i} + \frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi} \right) \Delta Q_i \to \min . \tag{1.12}$$

Using the power loss distribution coefficients T_{Qi} [47], the objective function (1.12) was reduced to a linear one:

$$\begin{cases} \Delta V_{Q\,eq}\left(\Delta Q_i\right) = \sum_{i=1}^{n_q} \left(T_{Qi} + \frac{\alpha_{ei}}{C_{(t)}} + \alpha_{\Delta Wi} \right) \Delta Q_i \to \min; \\ \mathbf{J}_D^{-1} \Delta \mathbf{Q} = \Delta \mathbf{U}. \end{cases} \tag{1.13}$$

Such a transition greatly simplifies the solution of the problem and reduces the number of calculations. Using the simplex method, from the list of corrections to the RPS powers ΔQ_i, those ensuring the fulfillment of voltage restrictions (1.4) with a minimum deviation from the extremum of function (1.7) were determined.

The studies carried out made it possible to obtain a reliable and high-speed method for searching for the optimal RPS powers. It can be used for simulation calculations in order to determine the debugging parameters of local ACS. However, for the formation of local control laws, a different approach was used, which makes it possible to obtain the conditions for the optimality of their operation in terms of local parameters.

1.2.2 CONDITIONS FOR THE OPTIMAL RPS OPERATION FOR CONTROLLING REACTIVE POWER FLOWS

As noted earlier, in order to optimize the RPS operation in the normal modes of the DEG, the task of automatically controlling their powers in order to obtain the maximum profit from their operation is relevant. Therefore, the problem of optimizing the daily regimes of the RPS with automatic control $Q_i(t)$, $i = 1,2\ldots n$, taking into account the RPS modes with manual control, turns out to be relevant. The optimality criterion is the minimum of costs associated with compensating for electricity losses for DEG in the context of the dynamics of energy market tariffs $C(t)$ and technical restrictions on the part of consumers and RPS:

$$\int_{t_0}^{t_k} C(t)\Delta P\left(Q_i(t), i = 1..n_q\right)dt \to \min. \tag{1.14}$$

Problem (1.14) can be presented in more detail as follows [4]. A set of n_q automatically controlled RPSs and m manual RPSs is given. The total reactive power of the latter is Q_{PKj}. As controlled variables, the power of the automatic control of the RPS is taken. Losses from reactive power flows in the DEG are described as a non-linear function of the RPS powers. The composition and characteristics of the included RPS during the day are considered unchanged. Necessary on the time interval $[t_0;\ t_k]$ to find RPS modes with automatic control $Q_i(t)$ that would provide the maximum profit from reducing losses in the DEG, taking into account changes in tariffs in the energy market:

$$\int_{t_0}^{t_k} \left[C(t)\Delta\ \ \left(Q_i(t)\right) + \sum_{i=1}^{n_q}\left(\alpha_{ei} Q_i(t)\right)\right]dt \to \min, \tag{1.15}$$

subject to execution of the reactive power balance:

$$G = Q_{PKj}(t) + \sum_{j=1}^{m} Q_{PKj} + \sum_{i=1}^{n} Q_i(t) - Q_{nav}(t) = 0$$

and restrictions on parameters

$$Q_i^{\min} \le Q_i(t) \le Q_i^{\max}, i = 1..n,$$

$$U_i^{\min} \le U_i(t) \le U_i^{\max}, i = 1..n.$$

The values of the RPS powers at the beginning and end of the interval $Q_i(t_0)$ and $Q_i(t_k)$ are considered to be given.

Assuming that the dependence of losses on the RPS power, the dependences $Q_{nav}(t)$ and $C(t)$ are continuous and differentiated twice, the problem posed can be attributed to the limiting variational isoperimetric problems. In this case, the extremum (1.15) is achieved by the same functions $Q_i(t)$ as the extremum of the following expression:

$$\Phi = \int_{t_0}^{t_k} \begin{bmatrix} C(t)\Delta \ \left(Q_i(t)\right) + \sum_{i=1}^{n}\left(\alpha_{ei} Q_i(t)\right) + \\ +\lambda\varphi(t) + \sum_{i=1}^{n} P_i^Q(t) + \sum_{i=1}^{n} P_i^U(t) \end{bmatrix} dt = \int_{t_0}^{t_k} F(t)dt \Rightarrow \min, \tag{1.16}$$

where λ_i – indefinite Lagrange multipliers; $P^Q{}_i(t)$, $P^U{}_i(t)$ – penalty functions introduced into the objective function $F(t)$ to take into account constraints such as inequalities in the reactive power of the RPS and voltage in the DEG nodes.

According to Pontryagin's principle of minimum of continuous functions [14], the minimum (1.15) provides the value of $Q_i(t)$ for which the Euler equation is satisfied, as a necessary condition for the minimum (1.16):

$$F_{Q_i} - \frac{d}{dt} F_{\dot{Q}_i} = 0,\ i = 1,2,\ldots n, \tag{1.17}$$

where $F_{Q_i} = \frac{\partial F}{\partial Q_i}$; $F_{\dot{Q}_i} = \frac{\partial F}{\partial \dot{Q}_i}$; $\dot{Q}_i = \frac{dQ_i}{dt}$.

Taking into account (1.16), equation (1.17) took the form:

$$F_{Q_i} - \frac{d}{dt} F_{\dot{Q}_i} = \left(C(t) - \frac{dC(t)}{dt}\right)\left[\frac{\partial\Delta}{\partial Q_i(t)} - \frac{d}{dt}\frac{\partial\Delta}{\partial Q_i(t)}\right] + \alpha_{ei} +$$

$$+\lambda + \frac{\partial P_i^Q}{\partial Q_i} + \frac{\partial P_i^U}{\partial Q_i} = 0,\ i = 1,2\ldots n. \tag{1.18}$$

For a non-degenerate system of equations (1.18), the necessary conditions for the optimality of the RPS powers of with automatic control are as follows:

$$z^*(t) = \frac{\lambda + \alpha_{e1} + q_1^P}{\sigma_1^*(t)} = \frac{\lambda + \alpha_{e2} + q_2^P}{\sigma_2^*(t)} = \ldots = \frac{\lambda + \alpha_{en} + q_n^P}{\sigma_n^*(t)}, \tag{1.19}$$

where $z^* = z + z'$, and $\sigma_i^* = \sigma_i + \sigma_i'$ provided that

$$\begin{cases} z = -C(t);\; z' = \dfrac{dC(t)}{dt}, \quad q_i^{\text{H}} = \dfrac{\partial P_i^Q}{\partial Q_i} + \dfrac{\partial P_i^U}{\partial Q_i}; \\ \sigma_i = \dfrac{\partial \Delta}{\partial Q_i};\; \sigma_i' = -\dfrac{d}{dt}\dfrac{\partial \Delta}{\partial Q_i}. \end{cases} \tag{1.20}$$

If to neglect the changes in the operating RPS parameters during a certain time interval, for example, $\Delta t = 0.5$ h, then the condition for the optimal RPS power (1.20) will look like:

$$z_t = \frac{\lambda + \alpha_{e1} + q_1^P}{\sigma_{1t}} = \frac{\lambda + \alpha_{e2} + q_2^P}{\sigma_{2t}} = \ldots = \frac{\lambda + \alpha_{en} + q_n^P}{\sigma_{nt}}. \tag{1.21}$$

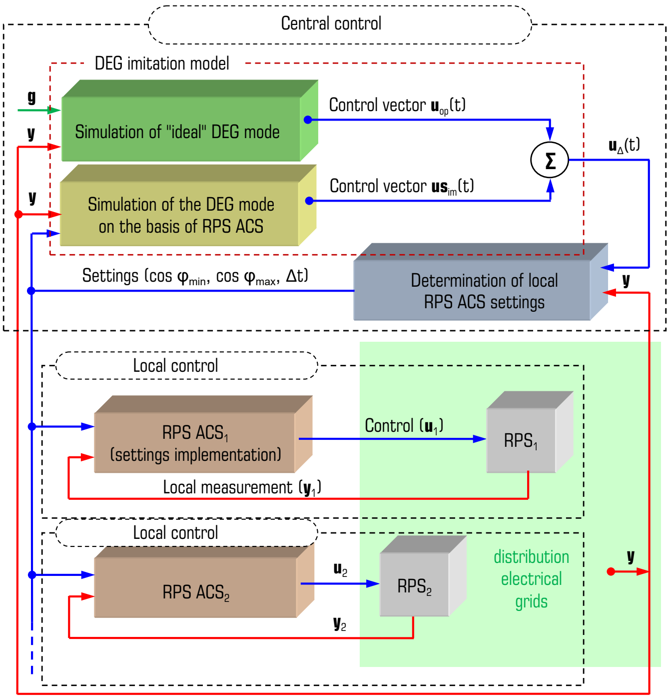
The variable λ is calculated iteratively using the boundary conditions. The main condition is to maintain the balance of reactive power in the DEG, in particular at the beginning and end of the integration time interval. In terms of physical content, λ characterizes the RPS effectiveness in the context of making a profit from reducing losses. It shows to what extent the costs of RPS operation will pay off due to a decrease in the cost of electricity losses in the DEG, if the power of the *i*-th RPS increases, for example, by 1 kvar.

$$\lambda = z_t \sigma_{it} - \alpha_{ei} = -C_t \left.\frac{\partial \Delta}{\partial Q_i}\right|_t - \alpha_{ei}. \tag{1.22}$$

The control of the set of RPSs in accordance with the optimality conditions (1.19) provides the maximum profit from reducing electricity losses in the DEG. Local automation systems will give a command to increase the RPS power only if the increase in costs is offset by a decrease in electricity losses, taking into account penalties for reducing voltage quality. Since the electricity losses in the DEG depend on voltage levels, the local control of the RPS will have a positive impact on the quality of electricity in the DEG. To ensure a system-wide effect, it is necessary to combine the set of local systems for automatic control of the RPS according to local parameters into a single system. The latter, thanks to the proactive adjustment of local ACS settings, will provide efficiency in the face of incomplete or unreliable information in data flows between the coordinator and local ACS (**Fig. 1.2**).

1.3 STRUCTURAL DIAGRAM OF PROACTIVE CONTROL OF REACTIVE POWER FLOWS IN DISTRIBUTION GRIDS

Automated systems with proactive control provide optimization of technological processes in conditions of incomplete or imperfect current information regarding the parameters of the control object and external influences. Such features are typical for a complex of spatially distributed RPSs, which together should optimize the flow of reactive power to the DEG. Therefore, an automated RPS control system was proposed, which makes it possible to combine the set of RPS with automatic control according to local parameters into a single system (**Fig. 1.4**).



⬡ **Fig. 1.4** System for proactive control of reactive power sources with a model of the "ideal" DEG mode

1.3.1 STRUCTURAL DIAGRAM OF COORDINATED CONTROL OF DISPERSED REACTIVE POWER SOURCES

Coordination of the control of local ACS is provided by the hierarchical structure of the automated control system. At the level of centralized control, tasks for local ACS are formed and their implementation is controlled. At the level of local control, automatic adjustment of the RPS power takes place according to the measured parameters (load voltages and currents). The operation of local subsystems is coordinated by periodic centralized adjustment of their debugging parameters.

Each local control loop [31] is formed by the RPS and the local automatic control system (**Fig. 1.4**). The operation of local ACS is periodically adjusted by a centralized system. The functions of coordinating centralized and local control are performed by the block for determining the ACS settings. The appropriate debug parameters are defined and passed here. They determine the frequency of control and control actions $\mathbf{u}_i$ for individual RPSs. Information support of centralized control is provided by the operational information complex. It measures the set of given DEG parameters and forms the observation vector $\mathbf{y}$.

To simulate the "ideal" DEG modes, that is, the modes that provide maximum profit from the RPS operation, a simulation model is used. According to the optimality conditions (1.19), here the control actions are determined for each RPS $\mathbf{u}_{sim}(t)$, which would ensure the transition from the current mode to the optimal one for the local control subsystem. Here, the settings of the local ACS and the dynamics of the measured parameters are taken into account.

Next, the simulation block of the "ideal" DEG mode generates control actions $\mathbf{u}_{op}(t)$, which ensure the transition to the optimal DEG mode according to the optimality criterion (1.7). Further, for each RPS controller, debugging parameters are determined that minimize the inconsistency $\mathbf{u}_{\Delta}(t)$ between the outputs $\mathbf{u}_{op}(t)$ and $\mathbf{u}_{sim}(t)$ of the simulation model [48]. The mode simulation block is also used as a source of pseudo-measurements of control parameters ui and individual local ACS. Since it is relatively simple to reproduce the processes of power transmission in DEG, the simulation model provides sufficient adequacy. This is controlled by feedback $\mathbf{y}$ [17, 48].

The decision to introduce into the centralized control circuit a block for simulating the DEG modes $\mathbf{u}_{sim}(t)$ instead of remote measurement of the grid parameters $\mathbf{u}$ is economically justified for the distribution grids of Ukraine and European countries. The latter was shown on the basis of a technical and economic analysis in [28].

At the initial stage of the implementation of the control system, it is necessary to periodically coordinate operational control with automatic control. Then the simulation model provides an estimate of the effectiveness of the manual control commands $\mathbf{g}$, including the consequences of changing the powers of the RPS. The model provides information support for manual formation and adjustment of the debugging parameters of local ACS, as well as reproduction of the predictive states of the DEG. After the accumulation of the base of typical DEG modes and the final implementation of the proposed control system, the simulation model becomes the main element of the coordination of local ACS and introspection.

The stability and efficiency of the centralized coordination of the RPS control depends on the frequency of updating the parameters of the DEG mode, as well as on the speed and intensity of changes in the observation parameters $\mathbf{y}$. To ensure the stability of local control, it is necessary to optimize the time settings Δt for individual ACS. For the efficient use of the RPS resource, in particular switching devices, it is necessary to optimize the power factors $cos\phi_{min}$, $cos\phi_{max}$. They determine the RPS response to a change in the local load, and also determine the dead zone of the ACS.

The processes of determining and adjusting the settings are carried out by the corresponding block of the control system (**Fig. 1.5**).

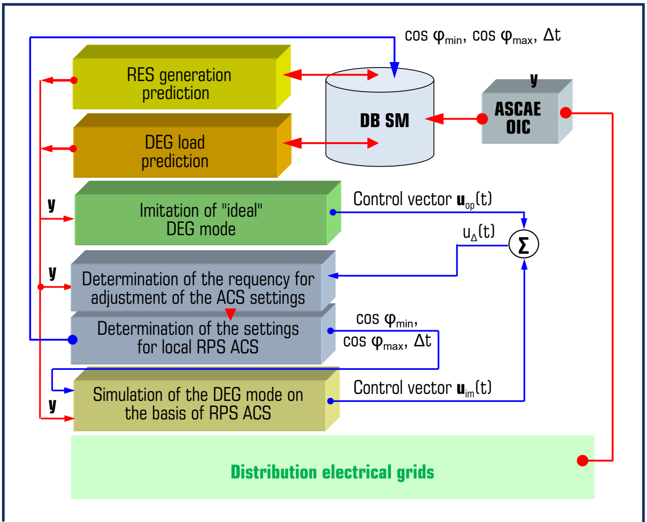


Fig. 1.5 Determination of the settings of local control systems for reactive power sources

Considering that the ACS settings can only be changed periodically, the block includes blocks for short-term prediction of DEG loads and generation of local sources. To predict loads, the method of fractal analysis of statistical data on power consumption and weather conditions was used [49]. Short-term forecasting of energy production by local sources, in particular solar stations is performed by the method of neuro-fuzzy modeling [50]. The initial data comes from the operational information complex (OIC) of the DEG, automated systems for the commercial accounting of electricity (ASCAE) of the DEG and consumers, as well as forecast weather services Gismeteo, WetherBit, Meteoblu, RP5. The data is accumulated in the database of the simulation model (DB SM) and can be used by forecasting blocks at a random time with a given retrospective depth.

Based on the results of loading forecasting and generation, signals are simulated at the output of the "ideal" mode model $\boldsymbol{u}_{op}(t)$ and the DEG mode simulation unit $\mathbf{u}_{sim}(t)$ taking into account the implementation of control actions of local ACS. Next, the intensity of the appearance of inconsistency between them $\mathbf{u}_{\Delta}(t)$ is analyzed and the necessary frequency of adjusting the debugging parameters of the local ACS is determined. This frequency will be different for individual local control systems of the RPS. Thus, information overload of communication channels does not occur.

Further, the block for determining the settings with a certain discreteness ensures the adjustment of the settings in time and $cos\phi_{min}$, $cos\phi_{max}$. The main difficulty here is the need for a significant amount of calculations to optimize the reactive power curves of the RPS. In addition, it is necessary to evaluate the correlation of these graphs and the graphs of local reactive power consumption in the coverage area of the RPS in order to optimize the periods for updating the ACS parameters. Determining the debugging parameters of the ACS requires a significant investment of time. Therefore, it is carried out preventively based on the results of forecasting and typical load schedules for DEG [38].

Thus, to ensure automatic control of the RPS, it is possible to use a dispersed proactive control system with a simulation model. Local control systems are made on the basis of the optimality conditions for the RPS operation (1.19), (1.20). For a centralized determination of the optimal DEG modes and adjustment of the debugging parameters of the local ACS, an imitation of the "ideal" DEG modes is used.

The stability and efficiency of control is achieved by dividing the functions into centralized formation of the ACS debugging parameters and their local implementation according to locally measured parameters. The proposed control system was used to optimize the reactive power flows in the Vinnytsia city power grids 10 kV. It is shown that, despite the rapid changes in the reactive load during the day, with an appropriate adjustment of the ACS settings, it is possible to achieve a significant reduction in electricity losses (**Fig. 1.6**). The experiment showed that timely adjustment of the ACS settings in terms of time and power factor brings the schedule of reactive power output by a local source closer to the optimal one. This achieves an additional reduction in electricity losses for a fragment of the distribution grid of about 8 %.

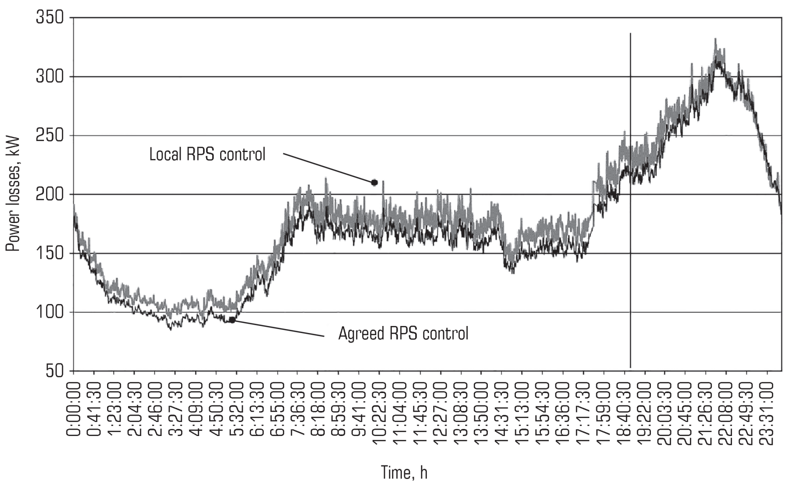


Fig. 1.6 Changes in electricity losses in the DEG based on the results of the AUKRM-160 RPS operation at TS-557

1.3.2 ALGORITHM FOR OPTIMIZING THE REACTIVE POWER OF SOURCES BASED ON THE SIMULATION OF THE "IDEAL" MODE OF THE ELECTRICAL GRID

The process of determining the debugging parameters of local ACS for their coordination involves a significant number of calculations of optimal modes. For this, a module is used to simulate the "ideal" DEG modes (**Fig. 1.7**). This module is designed to solve the following problems: calculation of the DEG mode and its entry into the allowable area; optimization of the DEG mode in terms of reactive power. These tasks are functionally linked and use a number of collaborative processes.

The initial data for determining the optimal power of the RPS are the parameters of the DEG equipment, the parameters of the current mode, as well as the design parameters of the RPS used to optimize the reactive power flows. Information about the parameters of the equipment comes from the corporate databases of the distribution system operator, the archives of the line service, substations, and the dispatch service. Regime parameters are mainly calculated on the basis of technical monitoring data and commercial electricity metering and are placed in the database of the simulation model.

The optimal powers of the RPS according to the criterion of maximum profit from their operation are determined in the following sequence:

1. From the available information support, the initial data are formed for calculating the given DEG mode. The voltages at the nodes are determined. To do this, a nonlinear system of nodal voltage equations is resolved in the form of a power balance [31]. Active and reactive powers in the nodes (except for the base one), including the RPS powers and the DEG powers, are considered unchanged. Based on the results of the calculation, the currents in the nodes are determined. This provides a transition to a linearized model of the DEG mode.

2. A calculation model of the DEG is compiled to reproduce its "ideal" mode in terms of power losses. For the replacement circuit, the DEG is supplied only by active resistances (r-circuit). Available RPS with fixed powers is supplied by direct currents. Sources, for which the optimization of parameters is carried out, taking into account the restrictions on the voltage and power of the installation, are supplied by additional economic resistances. The latter are determined from **Table 1.1** based on the affiliation of the RPS and the conditions of their operation. Such sources can mainly be owned by the DEG. However, it can be a means of compensating the reactive power of active consumers providing a voltage regulation system service. These can be conventional and renewable energy sources, which can change generation at the request of the distribution system operator. Therefore, the economic pillars for them will be different. The nodes to which the RPS is connected receive a sign of balancing reactive power. This removes their cardinalities from the list of independent variables and allows to determine their extreme values.

3. According to the linearized model of the steady state mode of the RPS, using the Gauss method, the DEG mode is calculated with minimal power losses. Since economic resistances are introduced into the interceptor circuit, the reactive currents of the RPS will correspond to their powers, which ensure maximum profit from their operation.

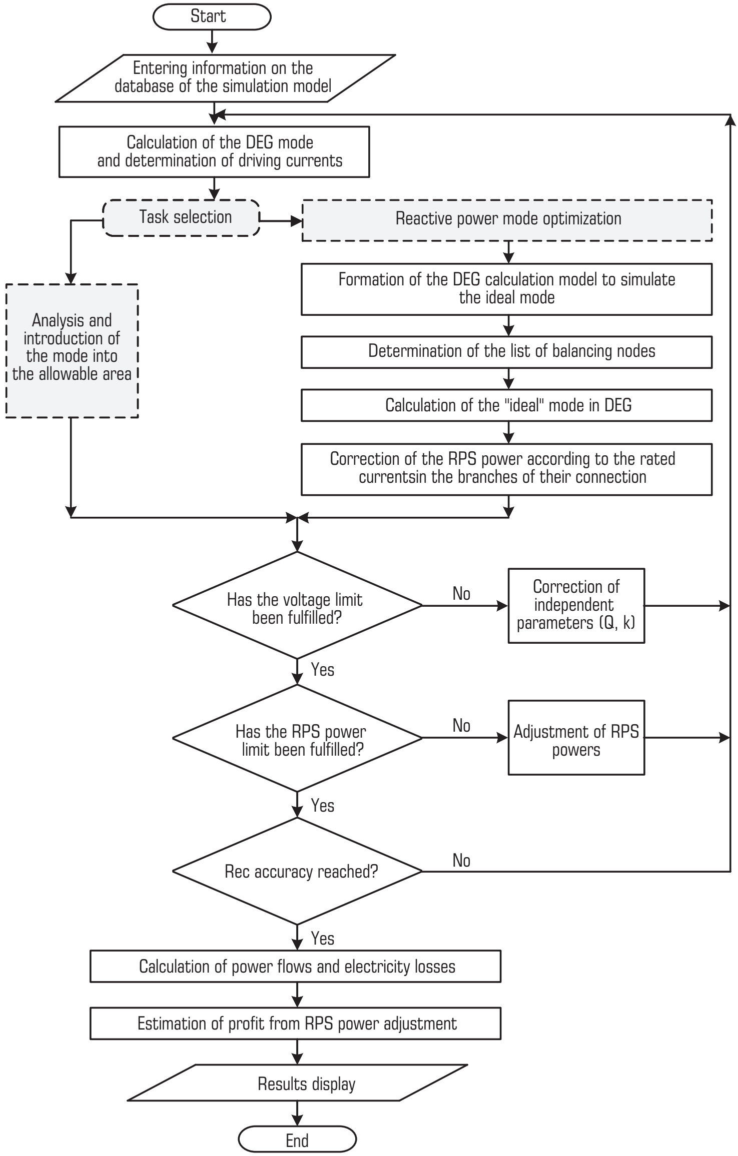


Fig. 1.7 The structure of the power optimization module of reactive power sources based on the simulation of the "ideal" mode

4. Reactive currents in branches with economic resistances of the RPS are listed in the value of the reactive powers of the RPS, providing maximum profit from their operation.

5. Voltage limits are checked at the DEG nodes. For nodes where restrictions are not met, voltage regulation is simulated by changing the transformation ratios of power transformers within their regulation range.

6. If the specified measure does not give a result, the calculated powers of the RPS are adjusted based on the results of solving the auxiliary optimization problem (1.12). After that, the powers of the corresponding RPSs are derived from the list of optimized variables. Next, the calculation model is refined and the DEG mode is recalculated.

7. The calculated power of the RPS may differ from the degrees of regulation of real devices. Therefore, these values are rounded up. If the RPS power was previously reduced to meet the voltage limits, then the direction of rounding the power to the standard value will be in the direction of reduction. Since any deviation of the RPS power from the calculated value leads to a decrease in profit, it is necessary to round off the calculated powers to the nearest standard ones in the direction of increase or decrease.

8. After the restriction on the parameters is fulfilled, the current mode is considered conditionally optimal, but requires clarification. Since the economic resistances of the RPS depend on their powers, they must be listed. If the maximum deviation between the values at adjacent iterations exceeds the specified accuracy, the "ideal" mode is recalculated starting from step 2. Otherwise, the solution is considered optimal.

9. Taking into account the optimal powers of the RPS and the transformation ratios of transformers at substations, the power overflows in the DEG are specified and the losses are determined.

10. The results of the calculation are loaded into the database of the simulation model and are used to set up the RPS, in particular, to determine the settings of local ACS by power factors.

Thus, the problem of optimizing the RPS power, regardless of the conditions of their operation, can be reduced to the problem of minimizing losses in the substituting scheme of DEG with economic supports. This problem is fundamentally simpler, since it can be solved by calculating the steady-state mode of the DEG according to its interceptor r-scheme. Fulfillment of voltage restrictions requires adjustment of the transformation ratios and clarification of the RPS power. The optimal values of the RPS power and the transformation ratios are determined from the system of nodal equations. The latter is compiled based on the results of the calculation of the "ideal" DEG mode.

1.4 ENSURING THE EFFICIENCY OF THE AUTOMATED REACTIVE POWER FLOW CONTROL SYSTEM

The adequacy of the optimality conditions (1.19), (1.20) and the efficiency of the algorithms for setting the local ACS settings (**Fig. 1.5**) was tested using the example of the 10 kV Vinnytsia city power grids. The settings for the regulated RPS installed at the transformer substation 10/0.4 kV "TS-496" were determined. The substation receives power from the power grids of the F-113 feeder of the Nova substation. At this substation, a 200 kvar AUKRM 0.4-200-10-5 RPS is installed.

The initial data for determining the optimal schedules for the RPS generation were measured by means of ASCAE. In particular, hourly consumption of active and reactive electricity was recorded on 0.4 kV buses of feeder transformer substations. For TS-496, the graphs of active and reactive consumption were measured with a discreteness of 15 s. **Fig. 1.8** shows a schedule for the release of reactive energy from the 0.4 kV buses of the transformer T-1 TS-496. It follows from the above that the reactive load changes significantly during the day. This leads to constant changes in the flow of reactive power in the feeder grid.

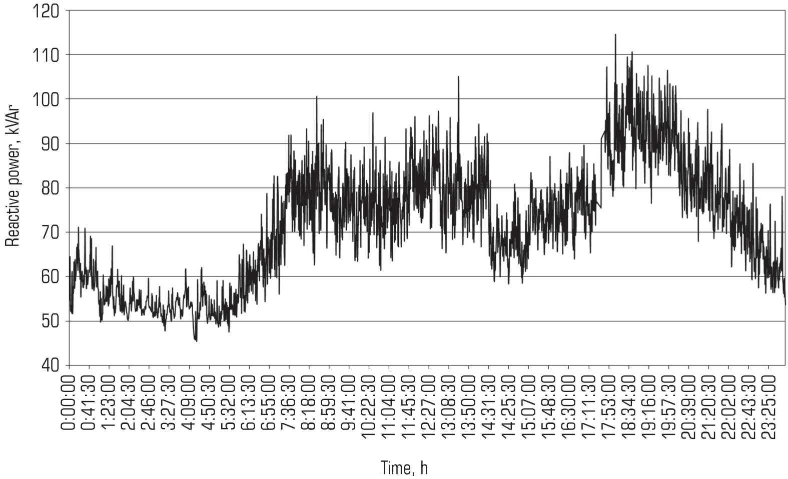


Fig. 1.8 Reactive power output from 0.4 kV buses of transformer T-1 TS-496

The power factor on the substation buses varies within 0.82–0.97 (**Fig. 1.9**). This indicates that the reactive power flows are not optimal. The graph of the optimal powers of the RPS to compensate for local consumption is shown in **Fig. 1.10**. The graph was obtained based on the results of the ACS operation with the settings: $cos\phi_{min} = 0.99$; $cos\phi_{max} = -0.99$; $\Delta t = 30$ s.

Using a simulation model, it is shown that such control contributed to a significant increase in the power factor on the TS-496 buses (**Fig. 1.11**) and a decrease in the reactive power flow by the F-113 feeder grids of the Nova substation.

Therefore, the local control system of the RPS with the selected settings ensures the generation of reactive power sufficient to compensate for local consumption. However, such a schedule for the generation of the RPS turns out to be not optimal for reducing electricity losses in the 10 kV grids of the F-113 feeder.

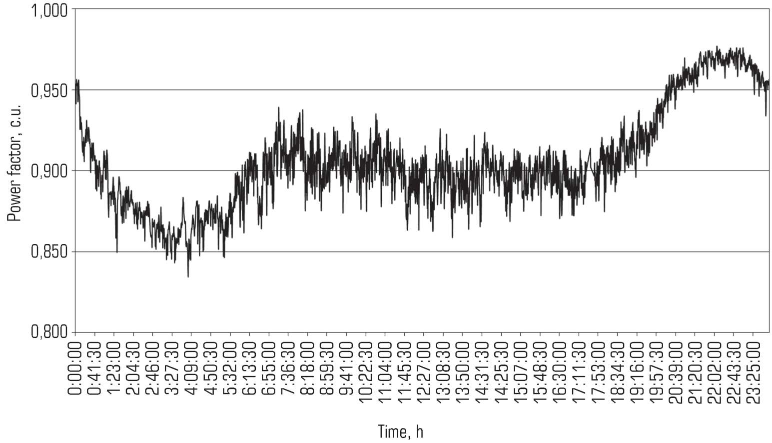


Fig. 1.9 Power factor change on 0.4 kV buses of transformer T-1 TS-496

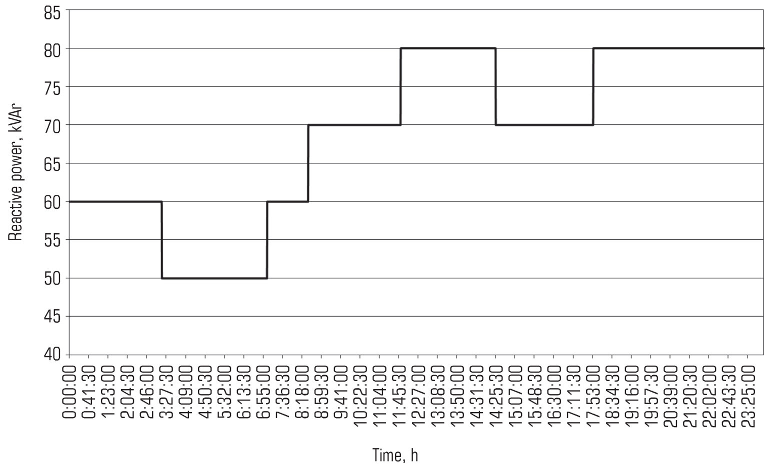


Fig. 1.10 Change in the generation of reactive power of the compensating plant installed at TS-496

Using the measurement results, the economic resistance of the RPS was determined. For each time slice, the "ideal" DEG mode was simulated and the optimal RPS power was calculated according to the criterion of maximum profit from its operation. The graph of the optimal generation power for the RPS, installed at the 0.4 kV input of the transformer T-1 TS-496, is shown in **Fig. 1.12**. The implementation of such control made it possible to reduce the loss of electricity in the experimental grid by 9 %. But reactive power control according to such a schedule is impossible. After all, RPS provides stepwise adjustment with a degree of 10 kvar. In addition, this is impractical due to the operation of the RPS resource.

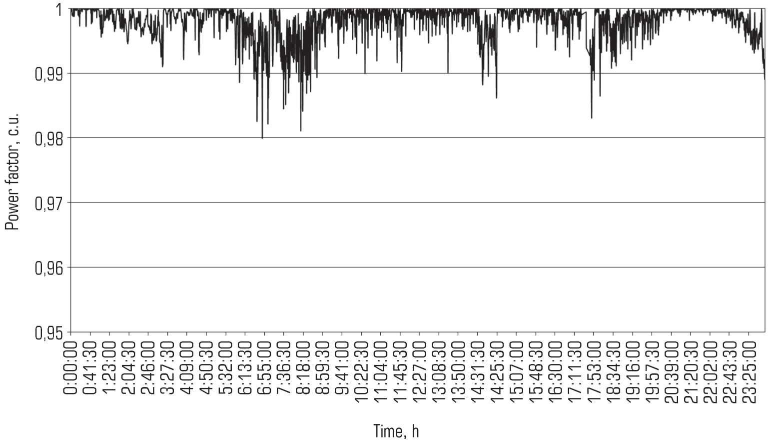


Fig. 1.11 Change in the power factor on the 0.4 kV buses of the T-1 TS-496 transformer after installing the RPS

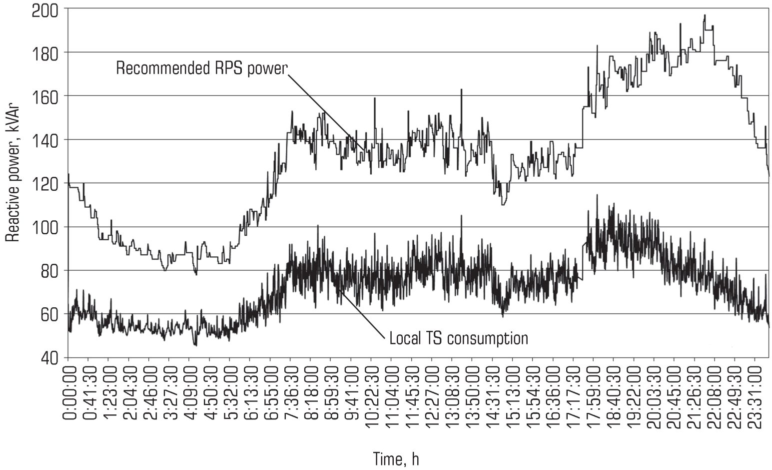


Fig. 1.12 AUKRM 0.4-200-10 optimal RPS power at TS-496, determined by the results of simulating the "ideal" DEG mode

To automatically maintain the optimal schedule for changing the reactive power of the RPS using the local control system, several groups of inserts were defined for it.

The control system settings were determined in two stages. Initially, the necessary frequency of updating the settings was determined. And then the value of insertions for each update interval is calculated. At the first stage, using the square of the Pearson exponent, the correlation between the optimal RPS power Q_{opt} and the local reactive power consumption Q_{nav} was investigated (**Fig. 1.12**). For this, changes in the Q_{opt}/Q_{nav} ratio over time were determined (**Fig. 1.13**). For this function, gradually expanding the area of comparison of the Q_{opt}/Q_{nav} and Q_{nav} graphs, time intervals were determined within which it is possible to use the same settings for the RPS ACS (**Fig. 1.14**).

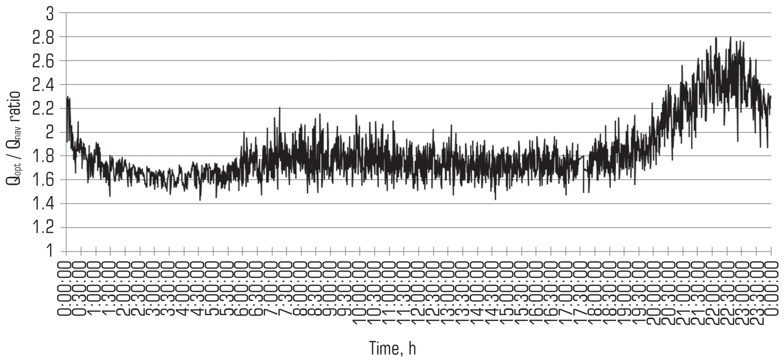


Fig. 1.13 The ratio of the optimal RPS power and the local consumption of reactive power TS-496

The boundaries of the intervals for refining the settings were determined as the moments of time corresponding to the maximum values of the squared Pearson coefficient calculated for the set of Q_{opt}/Q_{nav} (function value) and the Q_{nav} (argument value) ratios. Thus, on the daily interval, five points of time were allocated for which it is necessary to update the ACS settings.

To determine the settings for each time interval, a block for simulating the ACS operation of the automated power flow control system in the distribution zone was used (**Fig. 1.5**). For each time interval (**Fig. 1.15**), the optimal power factors $cos\phi_{min}$ and $cos\phi_{max}$ were selected according to the criterion of minimum sum of squared deviations. The deviations between the optimal RPS powers and the powers that will be issued by the RPS under the action of the local ACS were analyzed. The time settings were determined taking into account the average rate of changes in the optimal RPS power and local consumption at a given interval.

So, for TS-496, five sets of inserts were preventively formed by the automated control system for the corresponding time periods (**Fig. 1.15**) [4, 27]:

– Set 1: $cos\phi_{min} = -0.97$, $cos\phi_{max} = -0.95$, $\Delta t = 10$ min;

– Set 2: $cos\phi_{min}$ = –0.97, $cos\phi_{max}$ = –0.96, Δt = 10 min;
– Set 3: $cos\phi_{min}$ = –0.99, $cos\phi_{max}$ = –0.96, Δt = 5 min;
– Set 4: $cos\phi_{min}$ = –0.96, $cos\phi_{max}$ = –0.95, Δt = 10 min;
– Set 5: $cos\phi_{min}$ = –0.96, $cos\phi_{max}$ = –0.93, Δt = 5 min.

The results of their implementation by local ACS are shown in **Fig. 1.15**.

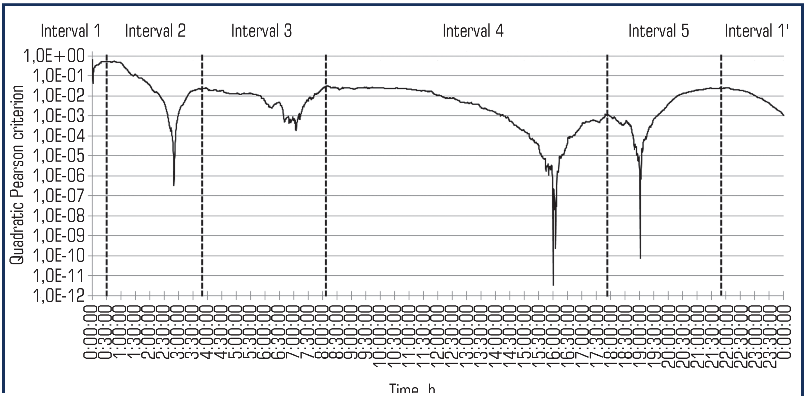


Fig. 1.14 Quadratic Pearson criterion to analyze the correlation between the sets Q_{opt}/Q_{nav} and Q_{nav} (logarithmic scale)

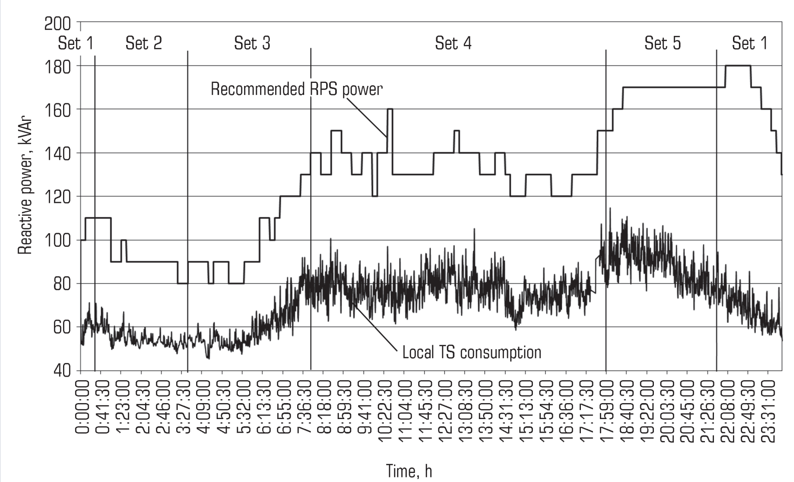
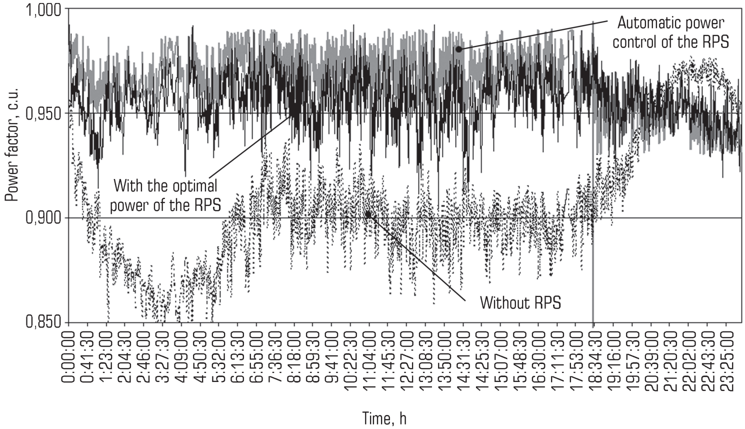
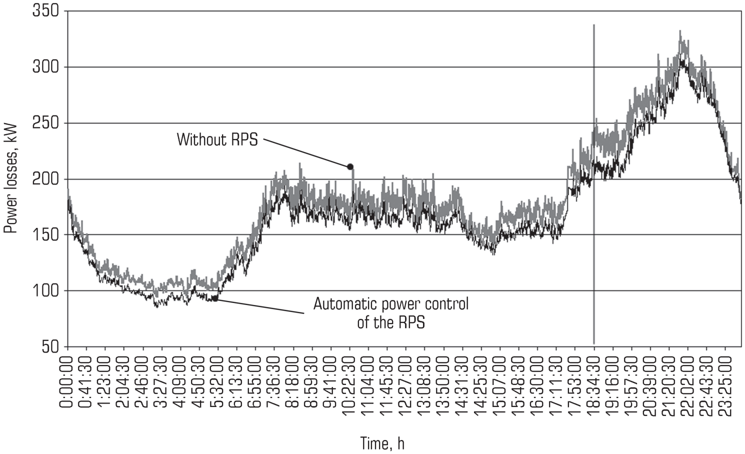


Fig. 1.15 Graph of change in AUKRM 0.4-200-10 RPS power at TP-496 under the influence of local ACS after optimization of its debugging parameters

It can be seen from the graphs that the number of RPS power configurations has been significantly reduced. At the same time, the RPS generation schedule corresponds to the optimal generation schedule. Automatic control of the RPS according to the specified settings ensures the value of the power factors for the investigated TS is not lower than 0.93 (**Fig. 1.16, *a***). In addition, the implementation of such a power distribution schedule for the RPS made it possible to reduce the loss of electricity in the investigated DEG by about 8 % (**Fig. 1.16, *b***).



a



b

Fig. 1.16 The results of the simulation of the operation of the RPS AUKRM 0.4-200-10 RPS at TS-496: *a* – graphs of changes in the power factor on the TS buses; *b* – electricity losses in DEG

To determine the settings within the period of relevance, it is advisable to use the simulation model of the RPS ACS. It is advisable to select the power factors $cos\phi_{min}$ and $cos\phi_{max}$ by the method of least square deviations between the optimal and simulated powers of the RPS. It is advisable to determine the ACS time delays by the average rate of change of the optimal RPS powers and local consumption within the period of relevance.

CONCLUSIONS

1. In the work, a new solution to the actual scientific problem of increasing the efficiency of automated control of reactive power flows in distribution grids was obtained. It consists in the development of methods and algorithms for coordinating the RPS operation with automatic control according to local parameters. Coordination is carried out by proactively determining the debugging parameters that ensure the sharing of the RPS to ensure maximum profit from the optimization of reactive power flows in grids. Their implementation makes it possible to increase the efficiency of the RPS use in the grids of distribution system operators and active consumers.

2. The expediency of using the model of the "ideal" DEG mode for optimizing the RPS power according to the technical and economic criterion is substantiated. This made it possible to reduce the specified problem of nonlinear optimization to the problem of finding an extremal current distribution in the interceptor r-circuit of the grid, which is fundamentally simpler. To take into account the economic factors of the optimization problem, the replacement r-scheme is supplemented with fictitious resistances. Their values are calculated in such a way as to ensure that the cost of operating the RPS and the cost of electricity losses in these towers. Expressions for calculating economic resistances are obtained for different types of RPS and the conditions for their operation in electrical grids.

3. A feature of the problem of optimizing the RPS power is a significant dependence of the voltage levels in the grids on these powers. To take into account the restrictions on the voltage deviation in the nodes of distribution grids, it is proposed to solve an auxiliary problem of minimizing the deviation of the optimality criterion from the extreme value. The use of power loss distribution coefficients made it possible to reduce the last problem to linear programming.

4. To improve the efficiency of operation of local reactive power optimization systems, a criterion is proposed and analytical conditions for the optimality of the RPS modes are obtained, taking into account the costs of their operation and the quality of electricity.

5. For a complex of spatially distributed RPSs that jointly perform the functions of optimizing reactive power flows in electrical grids, it is necessary to ensure coordinated control. The paper proposes a two-level block diagram of an automated proactive control system with a simulation model and local ACS. To reduce the time spent on determining the debugging parameters of local ACS, an algorithm is proposed for identifying their update periods according to typical or predicted load and generation schedules.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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