The Sensitivity of the Model of the Process Making the Optimal Decision for Electric Power Systems in Relative Units

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Abstract **— The necessity of functioning of the automatic systems of control of the condition of the electric power system (EPS) with consideration of sensitivity is presented. It is advisable to carry out optimal control of the system conditions by introducing control parameters into the optimality (insensitivity) area. The permissible range of deviation of the control parameters from their optimal values is defined by the solution of the direct and indirect sensitivity tasks. The direct and indirect sensitivity tasks can and should be solved in relative units using similarity theory methods. It is shown that in this case the limits of the permissible optimality range are determined analytically. Comparing the allowable values of the optimality of individual control parameters, it is possible to rank them and set the appropriate order and intensity of their actions. This makes it possible to compensate for disturbances in the EPS in the most rational way with the least amount of optimizing influences.**

Keywords — power system, automated control system, sensitivity, similarity theory, relative units.

I. INTRODUCTION

In the electrical power system (EPS), optimal condition control is distributed over time and space. They are characterized by long-term and short-term condition planning and operational control in the pace of the process with a general trend to them automate based on Smart Grid technologies [1–3]. A general task for them is the combination of operational and automatic control [4]. Obviously, that the technical and economic efficiency of control depends on how well this task is solved. The main problems here are the development of appropriate mathematical models that take into account the dynamics of the control object and the control system. This problem has been significantly complicated by the development of renewable energy sources (RES) in the power grids. Solar and wind power plants due to their dependence on weather conditions are unstable sources of electricity and carry out constant disturbances in the system. There is a problem of maintaining the balance of consumption and generation of electricity of power plants, which can only be solved by improving modern automated control systems (ACS). Despite the fact that many problems of automatic and operational control of dynamic systems have been solved [5, 6], their further improvement remains relevant due to the widespread introduction of modern tools of computing and information technologies, as well as structural changes of such systems like the EPS.

Optimization calculations are "means" for studying the condition of the system and are performed periodically, and their results are presented in the form of control influences on the devices of regulation. In such a control organization, the intensity of the control influences, the resource and the reliability of the switching devices must be taken into account, as well as the ranking of the control units by their regulatory effect. That is, optimal control is advisable to take into account the sensitivity of optimizing actions [7, 8].

A number of methods are developed to analyze the stability of mathematical models, which are generalized dependencies between system parameters. One such method [9] involves using the Monte Carlo method to control system conditions. However, the application of this control principle is valid only for systems with a high degree of recurrence of identical or similar conditions. [10] provides for the use of regression dependencies for both centralized and local control of the system's normal conditions. A characteristic feature of the technique here is that it uses an active experiment as opposed to a passive one to construct dependencies between condition parameters. Applying experiment planning methods, that is,

978-0-7381-4236-4/20/$31.00 ©2020 IEEE

constructing regression dependencies from the results of active experiments, increases the computational efficiency of regression control. This approach is used in the control system of the EPS, where the solution of the control problem is to simulate the reactions of the system based on experiments over its conditions [11].

The use of similarity theory and criterion methods is actual [12–14]. Under the conditions of solving the tasks of system condition control by the criterion method, in addition to determining the optimal parameters, it is possible to obtain generalized relationships (criterion models). They associate the optimization parameters of the system with the system-wide criterion of optimality, for example, total losses. They also allow you to investigate the factors that lead the system to its suboptimal condition. Such model systems provide a generalized assessment of the results of condition control that extends to a number of conditions and allow them to automate the process of control it. They also largely ensure the successful completion of the final optimization process – the practical implementation of optimal modes.

The main goal of the paper is of estimate the sensitivity of optimization models of EPS normal conditions in relative units.

II. THE TASK OF OPTIMAL CONTROL OF THE CONDITION OF THE EPS

The task of optimal control of the normal states of a system with an integral criterion can, in general, be formulated as a task of the theory of optimal control with a quadratic quality criterion:

minimize the control function

$$F(u) = \int_{t_0}^{t_k} \left[\mathbf{x}_t(t)\mathbf{H}\mathbf{x}(t) + \mathbf{u}_t(t)\mathbf{L}\mathbf{u}(t) \right] dt \tag{1}$$

in the space of conditions the system

$$\frac{dx}{dt} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t); \quad \mathbf{x}(t_0) = \mathbf{x}_0; \tag{2}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t), \tag{3}$$

where **x**(t), **u**(t), **y**(t) are respectively the vectors of condition, control, and observation; A, B, C, D, H, L – matrix of constant coefficients, generalized EPS parameters by physical content; t_0, t_k – is the beginning and the end of the time interval at which the control function to minimize (usually 15 minutes for the EPS); $\mathbf{x}_0$ is the initial value of the condition vector.

In this model:

$$\mathbf{x}(t) = \begin{bmatrix} \dot{\mathbf{J}}(t) \\ \dot{\mathbf{U}}_\Delta(t) \\ U_\delta \end{bmatrix}, \quad \mathbf{y}(t) = \begin{bmatrix} \dot{\mathbf{S}}_в(t) \\ \dot{\mathbf{I}}_в(t) \\ \dot{\mathbf{U}}(t) \end{bmatrix}, \quad \mathbf{u}(t) = \begin{bmatrix} \mathbf{k}(t) \\ \mathbf{Q}_{RPS}(t) \\ \dot{\mathbf{S}}_{RES}(t) \\ \mathbf{P}_{SE}(t) \end{bmatrix}, \tag{4}$$

where $\dot{\mathbf{J}}(t) = \hat{\mathbf{U}}_d^{-1}(t)\ \hat{\mathbf{S}}(t)$ is the vector of currents in nodes; $\dot{\mathbf{U}}_d(t)$ is the diagonal matrix of nodes voltage; $\dot{\mathbf{S}}(t) = \mathbf{P} + j\mathbf{Q}$ is the vector of powers in nodes; $\dot{\mathbf{U}}_\Delta(t)$ is the vector of the voltages of the nodes relatively basic; U_b is the voltage of the base node; $\dot{\mathbf{U}}(t)$ is the vector of nodes voltages; $\dot{\mathbf{S}}_b(t) = \mathbf{P}_b + j\mathbf{Q}_b$, $\dot{\mathbf{I}}_b(t)$ are vectors of powers and currents in the EPS branches where are tele-measurement; $\mathbf{k}(t)$, $\mathbf{Q}_{RPS}(t)$, $\dot{\mathbf{S}}_{RES}(t)$, $\mathbf{P}_{SE}(t)$ are vectors of transformation coefficients, loads of reactive power sources (RPS), power of renewable energy sources and power of storage energy systems.

In general, F is the optimality criterion consist from [17]: active power losses in the EPS; power, that is equivalent to consumer damage due to voltage deviation; power, which is equivalent to power loss due to power failure caused by fault of control devices and unstable RES power generation; a penalty function that depends on the violation of the conditions of balancing the state of the EPS.

The first equation in (2) is the equation of condition of the system, and its solution satisfying the initial requirement $x_0 = x(t_0)$ gives the vector of condition $x(t)=\psi[x(t_0), u(t)]$. The second equation in (2) determines the output parameters depending on x(t) and u(t).

The criterion of optimality of normal conditions control of the EPS can be an economic criterion – a minimum of costs or losses, provided that the specified requirements for reliability and quality are met. If the problem of optimal control of the conditions of EPS is set in such a way that at the stage of formation of the goal function, the purpose is to obtain control laws in the form convenient for their further automatic implementation, then the solution (1), taking into account (2–3), has the form [13, 15]

$$\mathbf{u}(t) = -\boldsymbol{\pi}\,\mathbf{y}(t) \tag{5}$$

for condition $\mathbf{x} \subset \mathbf{M}_x$ for anyone $\mathbf{u} \in \mathbf{M}_u$,

where $\boldsymbol{\pi}$ is the matrix of proportionality coefficients having the physical content of the similarity criteria; $\mathbf{M}_x$ is the set of values of x that can actually occur during the normal functioning of the system; $\mathbf{M}_u$ is the set of possible values of the vector of control parameters $\mathbf{u}$.

Expression (5) is the law of optimal control, the implementation of it allows us to achieve the minimum of function (1). The most famous direction of deterministic functional-adaptive control systems is the control with an etalon model [23].

Characteristic when using existing optimization methods is the mathematical formalization of processes, which are being optimized. But in mathematical modeling of systems that have a complex temporal and spatial hierarchical structure such as EPS with RES, significant complications are observed. The main ones are multicriteria control, as well as a distribution over a large area and the need to combine in time the task of short-term planning, operational (dispatching) and automatic control.

Experience in the implementation of optimization programs in the practice of operational control shows that in order to achieve significant efficiency, it is necessary to constantly adjust the system parameters. The control and correction of the conditions are based on the comparison of the current and optimal value of the optimality criterion:

$$\Delta F = F_{cur} - F_o ,$$

Where ΔF is the value characterizing the difference between the criterion of optimality between its current value F_{cur} and optimal F_o on a certain period of time control of the conditions of the EPS.

It is obvious that the complete coincidence of F_{cur} and F_o in real technical systems for various reasons is impractical and sometimes impossible, for example, due to the discreteness of the change in the control parameters. In order to achieve the equality, $F_{cur} = F_o$ for dynamic systems like is EPS, a high intensity of operation of control devices is required, which implements control actions **u**.

This leads to the fast use of their technical resource, reduced reliability of operation, and therefore, leads consequences like faults and losses, sometimes commensurate and even greater than the technical and economic effect achieved by optimization. The general approach to solving this problem is to analyze the sensitivity of the optimality criterion and to establish a reasonable zone of its insensitivity, in the middle of which all variants of the conditions of the system are equal economic.

For this, a set $\mathbf{M}_u$ is formed that precedes optimization. Its value must be such that the working condition or normal functioning of the system is satisfied. However, in many practical cases, the time and money spent on optimization results are unjustified due to the over-sensitivity of the optimized system to parameter changes, which renders the system practically ineffective. One way to overcome these difficulties is to formulate an optimization problem with sensitivity requirements [8, 9, 16].

III. Sensitivity evaluation of optimal control

Sensitive theory methods are an effective technique for the research of control systems [16]. However, known methods of sensitivity theory, based on the use of sensitivity functions or gradients of the studied properties of the system. They are not effective enough for the analysis and synthesis of systems of automatic control of EPS. The reasons for this are in the structure of the system, when the share of RES is increasing, and in the peculiarities of its formation. In this paper, we consider one of the possible ways to decide the sensitivity problem of the optimal control system of complex dynamic systems (EPS).

The proposed method is based on criterion modelling [16, 17]. The peculiarity of the criterion method is that the sensitivity is evaluated in relative units. At the same time, when it comes to optimal control, the basic parameters of the system are taken, which ensure its optimal condition in accordance with the selected criterion of optimality.

If the optimal control task is written in units by taking into account sensitivity, then his solution has the form shown in Fig. 1.

In Fig. 1 a) δF is the permissible deviation of the optimality criterion from its optimal value; u_i is the *i*-th component of the control vector; u_i^+, u_i^- – are upper and lower bounds of the area of the insensitivity of change u_i. The process of optimal control is illustrated in Fig. 1 b). The task of optimal control is to hold the parameters in the admissible area δu_i. In this case, the optimality criterion F will also be in the admissible area δF. If the parameter goes out of this area, then the corrective actions of the parameter u_i return this parameter to the optimality area (in Fig. 1 b) these are moments of time t_1, t_2, t_3.

Optimal control in such a formulation requires the determination of the boundaries of the insensitivity areas u_i^+, u_i^-, which is related to the need to solve the indirect sensitivity task [16]. For EPS this problem is especially difficult because of the lack of expression of the objective function in analytical form when the criterion of optimality or its component is the power losses and because of the need to find its extremum. We apply the criterion method to solve it.

In the criterion form, all variables are presented in relative units. Thus, the law of optimal control (5) will be rewritten accordingly:

$$\mathbf{u}_*(t) = -\boldsymbol{\pi}\, \mathbf{y}_*(t) \tag{6}$$

for condition

$$\mathbf{x} \subset \mathbf{M}_x$$

for anyone

$$\mathbf{u} \in \mathbf{M}_u ,$$

where $\boldsymbol{\pi}$ is the matrix of similarity criteria; $u_{*i} = u_i/u_{io}$ are the parameters by which the condition of the EPS is optimized in relative units (the optimal values of the parameters are taken as the basis u_{io}). All other quantities in (6) are converted into relative units by a similar approach.

An illustration of the practical implementation (6) is shown in Fig. 1. In Fig. 1 c), the function of the optimality criterion is presented in relative units – $F_* = F/F_o$. Accordingly, the zone of the insensitivity of the criterion of optimality δF_* is specified, and the control parameter du * is determined in relative units – $\delta F_* = \delta F/F_o$, $\delta u_* = \delta u/u_o$. In this case, if the origin is shifted to one, then the insensitivity zone δu_* is determined from the conditions

$$\begin{cases} F_* = f(u_*); \\ F_* = 1 + \delta F_*. \end{cases} \tag{7}$$

Unlike the previous case, the setpoint of the ACS in (6) is equal one (see Fig. 1 d), and the zone of insensitivity du * is set in relative units (in real devices more often in %). The rest of the ACS actions are similar.

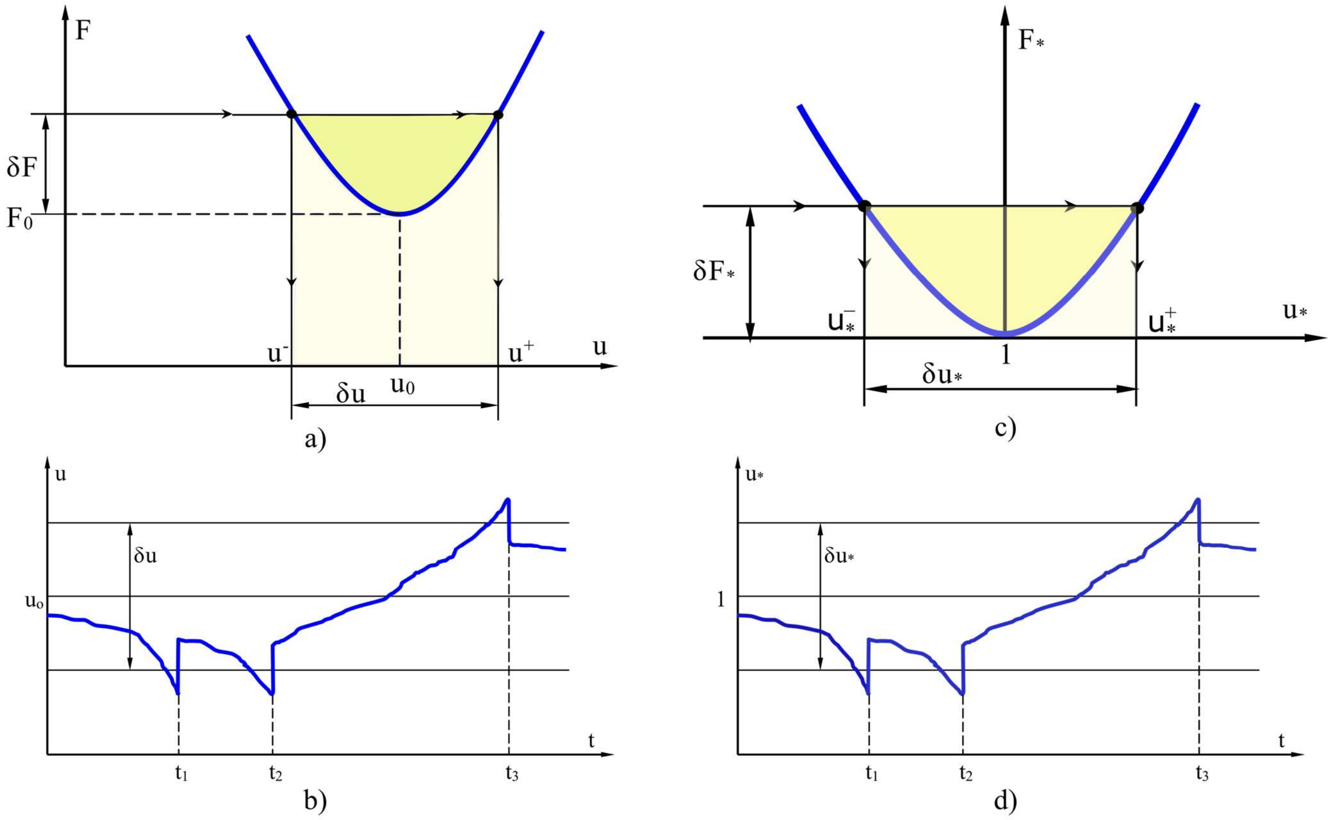

Fig. 1. Optimal control with taking into account sensitivity in units a); corrective actions of the parameter ui return this parameter to the optimality area these are moments of time t_1, t_2, t_3 b) optimal control with taking into account sensitivity in relative units c); corrective actions of the parameter u_i return this parameter to the optimality area these are moments of time t_1, t_2, t_3 in relative units d).

III. Direct and Indirect Tasks of the Sensitivity

For the task of optimal control of the condition of electrical networks with RES, two sensitivity problems are determined. Direct task, when the control parameter u_{i*} is deviated from its optimal (basic) value and is determined by how far the corresponding value of the optimality criterion deviates from its extremum (Fig. 2).

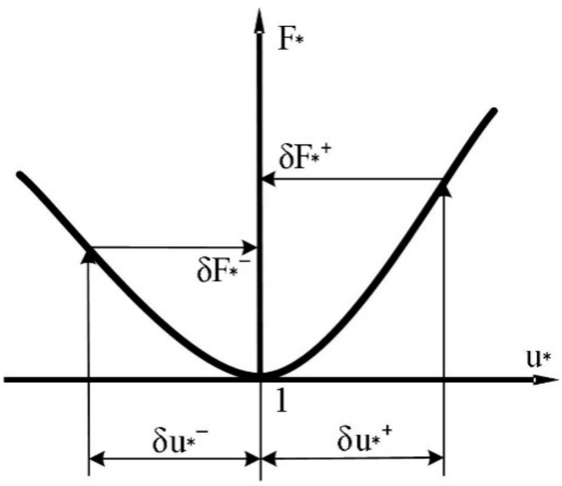

Fig. 2. Direct task of the sensitivity

Indirect task, when a possible range of deviation of control parameters from their optimal (basis) values is detected at a given tolerance criterion for optimality δF_* (Fig. 1 c)).

The detection of sensitivity around stationary points and the conditional minimum of the studied function $F_*(u_{i*})$ is of paramount importance. In this case, for example, it is possible to establish reasonable accuracy of optimization and to justify ways of realization in practice of results of calculations [11]. If changing any parameter u_{i*} does not significantly affect the value of the objective function $F_*(u_{i*})$, then there is probably no need to determine the exact optimal value of this parameter. The task of its detection lies beyond the limits of this analysis, and other conditions of the specific task may serve as a basis for its rational value. For example, when the power of the RPS or the transformer coefficient is not influencing power losses in the grid, it is advisable to use them to regulate the voltage and enter it within acceptable limits. On the contrary, if the objective function changes sufficiently abruptly when the parameter u_{i*} deviates from its optimal value, this indicates the need to determine it more carefully.

In order to gain an advantage in sensitivity analysis, the existing relationships between control process parameters and system element parameters must be presented in the form of an approximate posynomial [17]:

$$F(u_i) = a_i u_i^{\alpha_i} + b_i u_i^{\beta_i}$$

or in relative units

$$F_*(u_{i*}) = a_i u_{i*}^{\alpha_i} + b_i u_{i*}^{\beta_i}, \quad (8)$$

where a_j, b_j, α_j, β_j are constant coefficients that reflect the nature of the dependence and the degree of influence of u_{*j} on the value of F_*.

We use the criterion form (8) as the basis of the algorithm for solving the direct task of sensitivity. In the case of solving a direct task, the function δF_* is changed when the control parameter δu_* is deviated from its optimal value and when there are errors in determining the coefficients a_i and b_i of the model (8). Taking into account that in the criterion model the optimal values of the parameters and $u_{*o}=1$ are taken as the basis, according to (8), we write:

$$F_*(1+\delta u_{i*}) = (1+\delta u_{i*})^{\alpha_i} + (1+\delta u_{i*})^{\beta_i}.$$

From the last expression it follows that

$$\delta F_{i*}^{-} = a_i(1-\delta u_{i*}^{-})^{\alpha_i} + b_i(1-\delta u_{i*}^{-})^{\beta_i} - 1, \quad (9)$$

$$\delta F_{i*}^{+} = a_i(1+\delta u_{i*}^{+})^{\alpha_i} + b_i(1+\delta u_{i*}^{+})^{\beta_i} - 1$$

If we now substitute in (9) the value of the deviation of a particular *i*-th optimizing parameter that deviates from *1* ($u_{*o}=1$) toward less and more, then we obtain respectively δF_{j*}^{-} and δF_{j*}^{+}.

Thus, (9) allows one to obtain uniquely the value of δF_* at a given δu_*. In Fig. 1 a) and b) illustrates the solution of the direct sensitivity problem when deviating u_* by δu_* to one side and the other from the optimal value. Accordingly, we get additional movements δF_*.

The indirect sensitivity task belongs to the class of incorrect tasks and is solved by numerous iterative methods [16, 18, 19]. Advantages of solving indirect sensitivity problems can be obtained by approximating the investigated function for each variable in the optimum area as a two-members posynomial function, rather than linearizing it as suggested in [16, 18].

The limit values of the control parameters u_*^- and u_*^+ (see Fig. 1 a) in this case are obtained as a result of solving the equation:

$$\delta F_* = F_* - 1 = a u_*^{\alpha} + b u_*^{\beta} - 1$$

or

$$a u_*^{\alpha} + b u_*^{\beta} = 1 + \delta F_*, \quad (10)$$

Let us solve this nonlinear equation (10) by the criterion method. To do this, we write it in the criterion form:

$$\frac{a u_*^{\alpha}}{1+\delta F_*} + \frac{b u_*^{\beta}}{1+\delta F_*} = 1. \quad (11)$$

It follows from (11) that the similarity criteria will be:

$$\pi_1 = \frac{a u_*^{\alpha}}{1+\delta F_*}, \quad \pi_2 = \frac{b u_*^{\beta}}{1+\delta F_*}. \quad (12)$$

From (12) we obtain an expression for the boundary values of the control parameters, which are the roots of equation (10):

$$u_*^- = \left(\frac{1}{\pi_1}\cdot\frac{a}{1+\delta F_*}\right)^{-1/\alpha}, \quad u_*^+ = \left(\frac{1}{\pi_2}\cdot\frac{b}{1+\delta F_*}\right)^{-1/\beta}. \quad (13)$$

The values of similarity criteria can be determined from the optimality conditions of the dual geometric programming problem with respect to the direct problem (9) [17]:

$$\begin{cases} \alpha\pi_1 + \beta\pi_2 = 0; \\ \pi_1 + \pi_2 = 1. \end{cases} \quad (14)$$

From the system of equations (14) we have that

$$\pi_1 = \frac{-\beta}{\alpha-\beta}, \quad \pi_2 = \frac{\alpha}{\alpha-\beta}. \quad (15)$$

Substitute in (13) the values of the similarity criteria of (15) and finally obtain u_{*i}^-, u_{*i}^+:

$$u_*^- = \left(\frac{\alpha-\beta}{-\beta}\cdot\frac{a}{1+\delta F_*}\right)^{-1/\alpha}, \quad u_*^+ = \left(\frac{\alpha-\beta}{\alpha}\cdot\frac{b}{1+\delta F_*}\right)^{-1/\beta}. \quad (16)$$

The limit values of the insensitivity zone are determined by the known:

$$\delta u_{*i}^- = 1 - u_{*i}^-, \quad \delta u_{*i}^+ = u_{*i}^+ - 1 \text{ or } \delta u_{i*} = u_{i*}^+ - u_{i*}^- \quad (17)$$

Thus, the proposed method of approximation of the investigated function by a positive function makes it relatively easy to solve the problems of analysis of optimal solutions for sensitivity. The form of the approximating function ensures that the result is analytically obtained. The results of the researches allow us to recommend a method of approximation of the positive with respect to convex functions. With the preliminary smoothing and filtering of the data obtained through a computational experiment, the positive approximation provides high accuracy.

V. CONCLUSIONS

The proposed system of optimal control of the normal modes of the EPS, taking into account the sensitivity of the optimal modes allows to agree on dispatching and automatic control. It lets to reduce the negative impact of disturbances in the EPS caused by instability in the power generation of renewable energy sources. Such disturbances lead to deviation of the EPS from its optimal condition. It is suggested to organize the means of optimal control of the system conditions by their concerted actions. To do this, it is necessary to determine the permissible range of deviation of the optimality criterion from its theoretically determined optimum and to optimize the actions to direct the condition of the system to this optimality area and not it calculated extremum. Accordingly, the actions of the optimization tools – SRP capacity, transformation ratios of the transformers, power of RES and capacity of electricity storage system should be coordinated. For this goal, their automatic control systems, namely, settings and zones of sensitivity, should be adjusted accordingly. The latter are agreed and determined from the permissible range of deviation of the criterion of optimality from its calculated extremum.

A method for determining the boundaries of the optimality range of control parameters with a given admissible deviation of the optimality criterion from its calculated extremum is developed. Forward and backward sensitivity problems are solved in relative units using similarity methods. The advantage of this approach is that the limits of the permissible optimality range are determined analytically. This makes it possible to compare the optimality areas of the individual control parameters and to identify their real potential effects on the optimality criterion. This makes it possible to optimize the effects on the system condition without unnecessary additional actions.

When optimizing the condition of the system with the ACS, the criterion dependencies $F(u_*)$, when the sensitivity zone of the optimality criterion δF_* is specified, allow to set the sensitivity zones for the controllers of control parameters. Thus, first of all, those optimization tools that have the greatest relative influence on the optimality criterion will be employed. This reduces the number of corrective actions, does not spend unnecessarily technical resources of electrical equipment involved in the process of optimal control, and, ultimately, improves the reliability and economy of power supply.

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