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The sensitivity of the process of optimal decisions making in electrical networks with renewable energy sources

***Abstract**. Are showed the necessity of the functioning of control automatization systems of conditions of bulk power system with renewable energy sources (RES) by taking into account the sensitivity. It is advisable to carry out optimal control of the bulk power system by introducing control parameters into the optimality (insensitivity) area. The permissible deviation range of the control parameters from their optimal values is determined by the solution of the direct and reverse sensitivity of the task. The direct and indirect tasks of the sensitivity can and should be solved in relative units using similarity theory methods. Showed that in this case the limits of the permissible optimality range are determined analytically. Comparing the allowable values of the optimality of the 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 the disturbances in the bulk power system that are carried out due to the instability of RES generation, in the most rational way.*

Streszczenie.** Wskazane jest przeprowadzenie optymalnej kontroli systemu zasilania jałowego poprzez wprowadzenie parametrów kontrolnych w obszarze optymalności (niewrażliwości). Dopuszczalny zakres odchyleń parametrów kontrolnych od ich wartości optymalnych jest określony przez rozwiązanie bezpośredniej i odwrotnej czułości zadania. Zadanie czułości bezpośredniej i odwrotnej można i powinno być rozwiązywane w jednostkach względnych przy użyciu metod teorii podobieństwa. Wykazanoź, że w tym przypadku granice dopuszczalnego zakresu optymalności są ustalane analitycznie. Porównując dopuszczalne wartości optymalności poszczególnych parametrów kontrolnych, można je uszeregować i ustawić odpowiednią kolejność i intensywność ich działań. Pozwala to w najbardziej racjonalny sposób zrekompensować zakłócenia w systemie zasilania, które są spowodowane niestabilnością wytwarzania odnawialnych źródeł energii. **Wrażliwość procesu optymalizacji decyzji w sieciach elektroenergetycznych z odnawialnymi źródłami energii.

Keywords:bulk power system, renewable energy, automated control system, sensitivity, theory of similarity, relative units.
Słowa kluczowe: system elektroenergetyczny, energia odnawialna, automatyczny system sterowania, czułość, teoria podobieństwa.

Introduction

I. Formulation of the problem

There is a whole class of dynamic systems to which bulk power systems (BPS) apply, with optimal state control 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 automate the latter based on Smart Grid technologies [1 – 4]. The common task for them is a combination of operational and automatic control [5, 6]. It is obvious 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 itself. This problem has been significantly complicated by the development of renewable energy sources (RES) in the electricity 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. As a result, there was a problem of maintaining the balance of electricity consumption and generation by 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 [7–9], their further distribution and improvement remains relevant due to the widespread introduction of modern tools of computer technology and information technologies, as well as structural changes in such systems as electric power system (EPS). Implementing them in modern ASCs involves the broad automation of the basic functions of the management process: the collection and processing of information, decision-making on condition control, their technical and economic analysis, and the automation of basic control functions. The combination of modern computers, mathematical modelling methods, and technical tools that implement control effects, allows you to move to a new level of automatic control of modes.

The experience of implementing optimization programs in the practice of operational control of the EPS shows that in order to achieve the effectiveness of optimization measures, it is necessary to constantly adjust the control parameters [10]. In this regard, it is advisable to submit the results of the optimization calculations in the form of control laws.

Optimization calculations are a "tool" for studying the condition of the system and are performed periodically, and their results are presented in the form of control effects on the means of regulation. Such a control organization must take into account the intensity of the control effects, the resource and the reliability of the switching devices, as well as rank the control devices according to their regulatory effect. That is, it is advisable to perform optimal control taking into account the sensitivity of optimizing actions [11, 12].

Given the large number of computations associated with the complexity of modern EPS, the similar task of control such a mode is difficult to solve and, often, the results of the calculations are not practical or ineffective. Therefore, a number of methods have been developed that use the analysis of stable mathematical models, which are generalized dependencies between system parameters. One such method [13] involves using the Monte Carlo method to control system conditions. The application of this control principle is valid only for systems with a high degree of recurrence of identical or similar conditions. [14] provided for the use of regression dependencies for both centralized and local control of normal conditions. A characteristic feature of the technique here is that it uses an active experiment to build dependencies between state parameters, as opposed to a passive experiment. Applying experiment planning methods, that is, 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 EPS where the solution of the control task is to simulate the reactions of the system based on experiments over its conditions [15].

It is promising to use the methods of similarity theory and the criterion method [16 – 19], based on their basis. Under the conditions of solving the tasks of control the system states by the criterion method, in addition to determining the optimal parameters, it is possible to obtain generalized ratios (criterion models). Criterion models relate the optimization parameters of the system with the system-wide criterion of optimality. For example, total power losses, and also investigate the factors that lead to the EPS suboptimal condition. Such model systems provide a generalized assessment of the results of the condition control that extends to a number of states and allow to automate the process of control them. They also largely ensure the successful completion of the final optimization process - the practical implementation of optimal modes.

Attempts to use the developed methods of calculation and study of the conditions of the system for the purpose of automation of control face some difficulties.

When solving tasks of operational and automatic control of normal conditions of EPS, there is a trend to move from tasks of analysis of their functioning to more complex tasks of process control. That includes the choice of optimal methods and controls for the purposeful correction of the processes and characteristics of controlled objects. Therefore, there is a need to improve the mathematical model of the process of operational control of the EPS normal conditions.

The goal of the paper is to improve the automated system of control of power plants with renewable energy sources by determining the acceptable range of deviation of the regulating parameters from their optimal values.

II. The task of optimal control of the EPS condition with RES

The problem of optimal control of the normal conditions of EPS with an integral criterion can, in general, be formulated as a task of the theory of the optimal control with a quadratic quality criterion [20]:

minimize the control function

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

in the space of conditions the system

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

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

where $\mathbf{x}(t)$, $\mathbf{u}(t)$, $\mathbf{y}(t)$ 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:

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

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 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, 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 [21]. 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 [20, 22]

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

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

where π 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 $\mathbf{u}$. 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.

In the formulated control problem (1) – (3) it is implicitly assumed that the area $\mathbf{M}_u$ of the possible values of the vector of control parameters $\mathbf{u}$ is known. However, in many cases this assumption is unjustified. This area must be defined. As a rule, solving the $\mathbf{M}_u$ definition problem 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 makes the system practically ineffective. One way to overcome these difficulties is to formulate an optimization task with taking into account sensitivity requirements [12, 13, 24].

III. Sensitivity evaluation of optimal control

Sensitive theory methods are an effective technique for the research of control systems [11–13, 24]. 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, 25]. 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. Figure 1a: 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. 1b. 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 ui 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 [24]. 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:

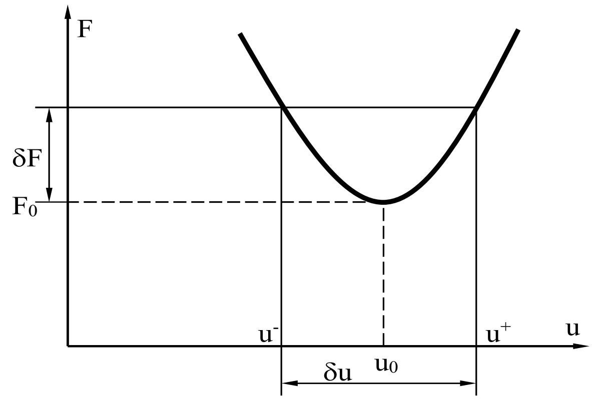
(6) $$\mathbf{u}_*(t) = -\boldsymbol{\pi}\, \mathbf{y}_*(t)$$

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

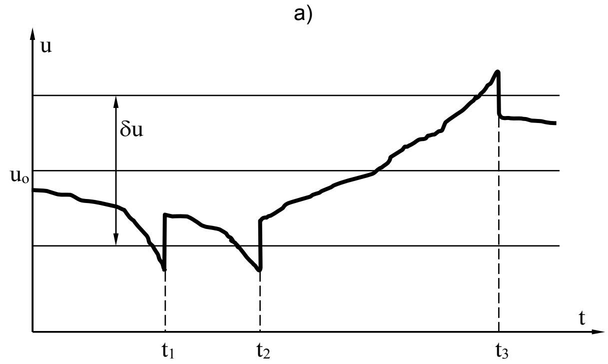
where π is the matrix of similarity criteria; $u_{*i} = u_i/u_{io}$ are the parameters by which the condition of the EPS is optimized in relative units (the optimal values of the parameters are taken as the basis u_{io}). All other quantities in (6) are converted into relative units by a similar approach.

An illustration of the practical implementation (6) is shown in Fig. 2. In Fig. 2 a), 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

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



a)



b)

Fig. 1. Optimal control with taking into account sensitivity

Unlike the previous case, the setpoint of the ACS in (6) is equal one (see Fig. 2b), 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.

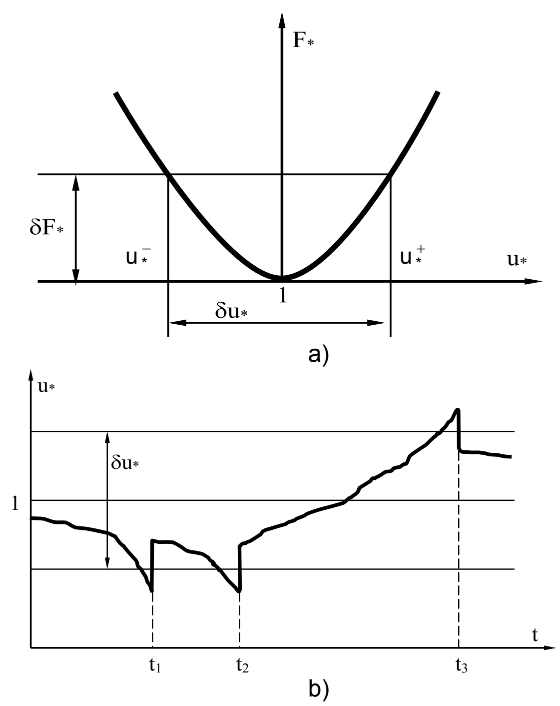


Fig. 2. Optimal control with taking into account the sensitivity control in relative units

IV Determination of individual elements influence of the control vector on the optimality criterion

Solutions of the optimal control problem are implemented here with the use of Smart Grid technologies. It is assumed that the obtained control law is implemented in criterion form (6). The efficiency of the adaptive approach can be enhanced by dividing the mode control functions into two parts. The first part is the centralized determining of control laws by complete mathematical models. The second part is the decentralized realization of these laws in control devices and the regulation by individual objects by local character using simplified models [23].

Since the influence of the individual elements of the control vector u_i on the optimality criterion F is usually different, it is obvious that the zones of insensitivity δu_i will be different for each u_i. To determine the influence of the individual component of the control vector on F, it is advisable to use the criterion method [16, 25], that is, to evaluate the influence of the parameter u_i on F in relative units.

The effectiveness of technical and economic analysis, including sensitivity, is largely determined by the chosen system of relative units [16]. The existing systems of relative units, the classification of which is given in [16], differ to a different extent from the task, that solve in this of the paper. We use the criterion system of relative units.

In general, the existing relationships between the parameters of the control process and the parameters of the elements of the system in which this process takes place can be represented in the form of an approximate posynomial:

(8) $$F(u) = \sum_{i=1}^{m_1} p_i \prod_{j=1}^{n} u_j^{\alpha_{ji}} ,$$

where F(u) some generalized technical and economic indicator; p_i, α_{ji} are constant coefficients determined by the properties of the system; m_1 is the number of members of a function; n is the number of variables

In accordance with the chosen system of relative units, we rewrite (8) in the following form:

$$\frac{F}{F_o} \cdot F_o = \sum_{i=1}^{m_1} p_i \prod_{j=1}^{n} \frac{u_j^{\alpha_{ji}}}{u_{jo}^{\alpha_{ji}}} u_{jo}^{\alpha_{ji}}$$

or

$$F_* F_o = \sum_{i=1}^{m_1} p_i \prod_{j=1}^{n} u_{j*}^{\alpha_{ji}} u_{jo}^{\alpha_{ji}} .$$

Performing the same transformations and entering a replacement:

(9) $$\pi_{io} = \frac{p_i \prod_{j=1}^{n} u_{jo}^{\alpha_{ji}}}{F_o} ,$$

We get the criterion form of the task record:

(10) $$F_* = \sum_{i=1}^{m_1} \pi_{io} \prod_{j=1}^{n} u_{j*}^{\alpha_{ji}} .$$

Note that for the optimal variant, when $F=F_o$, criterion equation (10) takes the form

(11) $$1 = \pi_1 + \pi_2 + ... + \pi_{m1}.$$

In the last equation, the similarity criteria are normalized to one. They indicate the relative part of each member of the function (each component) in the optimality criterion.

Considering criterion equation (10), it can be seen that it allows us to investigate the effect of deviation of any of the variables u_j from its optimal value on the value of the optimality criterion, namely, to investigate the sensitivity and to determine the sensitivity (optimality) zone of sensitivity δu_{i*}. Obviously, it is most convenient to do this in relative units.

For example, in Fig. 3 are presented the criterion dependences $F_* = f(Q_*)$ of the optimality criterion on the reactive power sources (RPS) δQ_i, including RES, are given. On the basis of such dependencies, zones of sensitivity of RPS are established. As can be seen, the numerical values δQ_i depend on the size of the insensitivity zone of the criterion of optimality δF_* and the view of the dependence $F_* = f(Q_*)$. The task of optimally control the power flows in the EPS is to hold the F_* value in the set δF_* sensitivity zone. For this, when F_* leaves of zone insensitivity, start to made control influences. For example, the third and fifth RPSs, since they are in the insensitivity zone, do not need to make any changes. The condition of the EPS should be corrected in the first place by the fourth and the first since they have the greatest influence on the optimality criterion.

The peculiarity and advantage of using relative units in the criterion form are that the insensitivity areas δu_{i*} are determined without the need to determine the optimal variant since in relative units the value of the optimality criterion is obviously equal to one. Thus defined areas of insensitivity for all components of the control vector and their implementation in the ACS allow you to limit and control optimizing effects on the achievement of the minimum criterion of optimality.

If, on condition that the sensitivity of the optimal solution is to be obtained in physical units, then this possibility exists. To calculate deviations or variations, all values in relative units must be multiplied by their values corresponding to the optimal (basic) variant. Obviously, it is necessary to first determine the optimal (basic) values of the studed EPS parameters. We can use any of the known optimization methods.

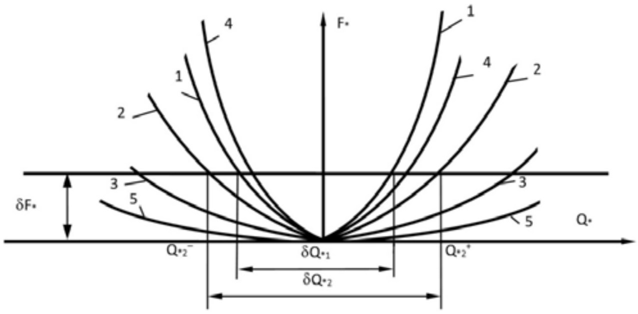


Fig. 3. Criterion dependences for determining the insensitivity zone

V 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. 4). 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. 5). Consider the features and algorithms for solving the direct and indirect sensitivity tasks based on criterion modeling.

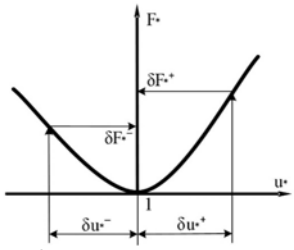


Fig. 4. Direct task of the sensitivity

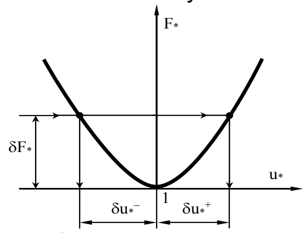


Fig. 5. Indirect task of the sensitivity

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, 24]. 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 DCP 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.

As noted earlier, the hollowness of the objective function can be estimated in two ways, namely, from the position of the direct or indirect task. Consider both approaches.

We use criterion form in the base of the algorithm of solving of the direct task of sensitivity. In the case of solving a direct task, change of function δF_* is determined for the deviation of the influential parameter on δu_* from his optimal value, and also when inaccuracies are present in determining of coefficients a_i model (8), which are included in (10) like on similarity criteria π_i.

Taking into account that in the criterion model the optimal values of the parameters and $u_{*o}=1$, according to (10), are taken as the basic values, we write:

$$F_*(1+\delta u_{j*}) = \sum_{i=1}^{m_1} \pi_i \prod_{j=1}^{n} (1+\delta u_{j*})^{\alpha_{ji}} .$$

From last expressions is the following:

(12) $$\delta F_{j*} = \sum_{i=1}^{m_1} c_i \pi_i - 1 ,$$

where $c_i = \prod_{j=1}^{n} (1+\delta u_{*j})^{\alpha_{ji}}$.

Now if we substitute in (12) the value of the deviation of a particular jth optimizing parameter that deviates from one ($u_{*o}=1$) less and more, then we obtain respectively δF_{j*}^{-} and δF_{j*}^{+}.

Thus, (12) allows one to obtain uniquely the value of δF_* at a given δu_*. In Fig. 4 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_*.

In the cause, when invariance is absent in the similarity criteria to the coefficients p_i, the unambiguous decision of the direct problem without determining π depending on p_i is excluded. Then, for the extreme values of the coefficients p_i, two dependencies of type (12) are obtained. From them the values $\delta F_{j*}^{'}$ and $\delta F_{j*}^{''}$ are obtained and the average is determined.

The indirect sensitivity task belongs to the class of incorrect tasks and is solved by numerous iterative methods [24, 26]. Advantages of solving indirect sensitivity problems can be obtained by approximating the understudied function for each variable in the optimum area as a two-members posynomial function [27, 28], rather than linearizing it as suggested in [24, 26]. The search for an approximate formula is carried out among two-members posynomial function of the form:

(13) $$F_* = a_j u_{*j}^{\alpha_j} + b_j u_{*j}^{\beta_j}$$

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_*.

To represent the function in the right form, need made computer simulate experiment, the results of which accumulate the necessary data for approximation. The values of the coefficients a_j, b_j, α_j, β_j for the j-th control parameter in (13) are obtained by solving the task written according to the method of least squares:

(14) $$\min\left\{ R(a,b,\alpha,\beta) = \sum_{i=1}^{N} \left(F_{*i} - \overline{F}_{*i} \right)^2 \right\} =$$

$$= \min\left\{ R(a,b,\alpha,\beta) = \sum_{i=1}^{N}\left(F_{*i} - au_{*i}^{\alpha} - bu_{*i}^{\beta}\right)^2 \right\},$$

where F_{*i}, $\overline{F}_{*i}$ are the experimental and calculated value of the function at the i-th point; N is the number of experimental points determined by the specified calculation accuracy.

After simple transformations of the conditions of minimization of the function $R(a, b, \alpha, \beta)$, we obtain a system of nonlinear equations that we are solving for the variables a, b, α, β.

In this case, the limit values u_*^- and u_*^+ of control parameters and (Fig. 5) are obtained as a result of solving the equation:

$$\delta F_* = F_* - 1 = au_*^{\alpha} + bu_*^{\beta} - 1$$

or

(15) $$au_*^{\alpha} + bu_*^{\beta} = 1 + \delta F_*,$$

Let us solve this nonlinear equation (15) by the criterion method. To do this, we write it in the criterion form:

(16) $$\frac{au_*^{\alpha}}{1+\delta F_*} + \frac{bu_*^{\beta}}{1+\delta F_*} = 1 .$$

It follows from (16) that the similarity criteria will be:

(17) $$\pi_1 = \frac{au_*^{\alpha}}{1+\delta F_*}, \quad \pi_2 = \frac{bu_*^{\beta}}{1+\delta F_*} .$$

From (17) we obtain the expression for the boundary values of the control parameters, which are the roots of a function (15):

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

The values of the similarity criteria can be determined from the optimality conditions of the criterion programming double task with respect to the direct task (15) [16, 17, 27]:

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

From the system of equations (19) we have that

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

Substitute in (18) the values of the similarity criteria from (20) and finally obtain:

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

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

The limit values of the insensitivity zone are determined by using known u_{*i}^-, u_{*i}^+:

(22) $$\delta u_{*i}^- = 1 - u_{*i}^-, \quad \delta u_{*i}^+ = u_{*i}^+ - 1.$$

Thus, the proposed method of approximation of the investigated function by a posynomial function makes it relatively easy to solve the problems of analysis of optimal solutions on sensitivity. The form of the approximating function ensures that the result is analytically obtaining. The results of the studies allow us to recommend a method of approximation of the posynomial 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.

VI. Conclusions

The proposed system of optimal control of the normal modes of the EPS, taking into account the sensitivity of the optimal modes allows us to coordinate dispatching and automatic control. It aims to reduce the negative impact of disturbances in the EPS caused by the instability of the generation of renewable energy sources. Such disturbances lead to deviation of the EPS from its optimal condition. It is suggested to order the means of optimal control of the EPS conditions by their concerted actions. For this firstly, it is necessary to determine the permissible area of deviation of the optimality criterion from its theoretically determined optimum. Secondly, we optimize the actions to direct the EPS condition to this optimality area, not to its calculated extremum.

Accordingly, the actions of the optimizers – the capacity of the RES, the transformation coefficients of the transformers, the power of the renewable energy sources and the energy storage units – should be coordinated. For this purpose, 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 optimality criterion of 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. Direct and indirect sensitivity tasks 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 regions 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 ASC, 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 effeciency of power supply.

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