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OPTIMAL SOLUTIONS SENSITIVITY ANALYSIS IN COMPLEX SYSTEMS IN RELATIVE UNITS

The capabilities of modern computer and microprocessor technology allow us to set new challenges in order to improve the control of technological processes. It becomes realistic to automate the optimal control of conditions of complex dynamic systems that have a complex Spatio-temporal control structure, that is characterized by frequent and rapid changes in states. Such, for example, as power systems (PS). They are characterized by long-term and short-term condition planning and operational control in the process with a general tendency to automate the latter based on Smart Grid technologies[1]. The common task for them is a combination of operational and automatic control[2]. Obviously, the technical and economic efficiency of control depends on how well this problem 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. Mathematical modeling in the problems of optimizing the conditions of such systems has specific features. When developing a mathematical model, it is necessary to take into account the fact that the final technical and economic effect of the control of conditions of dynamic systems is determined by the results of the practical implementation of the optimal conditions that are planned. Once the optimal solution is obtained, it is necessary to interpret it in terms of a real system in accordance with the chosen criterion of optimality and implement it in practice. That is, the optimization of system states does not end with the solution of the problem. The most important part of optimization research consists of substantiation of the correctness of the decision and the analysis

1 Buchholz, B. M., Stychinski, E. A. (2017). Smart Grids – Fundamentals and Technologies of the Energy Systems of the Future. M.: IDMEI; European Smart Grids Technology Platform. European Commission (2006). Directorate-General for Research Sustainable Energy System. Retrieved from https://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf; Lezhniuk, P., Kravchuk, S., Buslavets, O. (2019) Selfoptimization Modes of Electric Grids with Renewable Energy Sources Using the Principle of Least Action. 2019 IEEE 6-th International Conference on Energy Smart Systems. Retrieved from https://doi.org/10.1109/ESS.2019.8764181; Mahmud, K., Sahoo, A. K., Fernandez, E., Sanjeevikumarand P., Holm-Nielsen, J. B.(2020) Computational Tools for Modeling and Analysis of Power Generation and Transmission Systems of the Smar Grid, IEEE Systems Journal, 14(3), 1-12. Retrieved from https://ieeexplore.ieee.org/document/8970595

2 Korotkov, V.F. (2013). Automatic regulation in power systems. M.: ID MEI.

of its sensitivity [3]. From the point of view of efficiency of the process of transition of the system from its current condition to optimum, the data on a condition of the system near the area of optimal decision is more important. This allows you to better understand its basic properties and use them to build an adaptive automatic control system (ACS).

The sensitivity of a solution to the changing in system parameter values indicates which parameter estimating needs to be improved in order to find the optimal solution with a given accuracy. As a result of sensitivity analysis, the following is determined [4]. First, we look for the parameters that have the greatest impact on the optimal solution. If such parameters exist, it may be appropriate to investigate the correction of the relevant properties of the system. Secondly, the influence on the optimal conditions of the system of variations of inaccurately set parameters is determined. Sensitivity analysis allows you to really formulate the requirements for information support of the optimization problem, as well as to identify those parameters, the error of which does not have much impact on the results of optimization, and therefore do not need to specify their value. Third, possible reactions of the system to uncontrolled external influences are found out. It may turn out that the original mathematical model needs significant correction because the practical implementation of optimal solutions does not give the expected result.

Nowadays, a large number of mathematical models of real systems are used. These models were created during the emergence of appropriate practical problems in relation to certain real objects. All of them can be used to some extent to analyze the optimal solutions. The most effective here are the methods of sensitivity theory, which are based on the use of sensitivity functions or gradients of the properties of the system[5] under study. However, the latter are not effective enough in analyzing the optimal states of systems such as EPS (electric power system). The reasons here are in the structure of the systems themselves, and in particular the formation of their states In relation to such systems, one of the methods of mathematical modeling of complex dynamical systems has been developed, which is based on the theory of similarity, namely, criterion modeling[6]. The peculiarity of the use of criterion modeling is that the optimization study, including sensitivity, is carried out in relative units. In this case, if we are talking about optimal control, then the basic parameters of the system are taken to ensure its optimal state in accordance with the selected criterion of optimality[7].

3 Kochenderfer, Mykel J., Wheeler, Tim A. (2019). Algorithms for Optimization. The MIT Press Cambridge, Massachusetts London: England; Rosenwasser, E., & Yusupov, R. (1999). Sensitivity of Automatic Control Systems (1st ed.). CRC Press. https://doi.org/10.1201/9781420049749.

4 Kochenderfer, Mykel J., Wheeler, Tim A. (2019). Algorithms for Optimization. The MIT Press Cambridge, Massachusetts London: England; Rosenwasser, E., & Yusupov, R. (1999). Sensitivity of Automatic Control Systems (1st ed.). CRC Press. https://doi.org/10.1201/9781420049749; Lezhniuk, P., Komar, V., Rubanenko, O., Ostra,N. (2019). The sensitivity of the process of optimal decisions making in electrical networks with renewable energy sources. Przeglad Elektrotechniczny, 10, 32–38. DOI: 10.15199/48.2020.10.05.

5 Rosenwasser, E., & Yusupov, R. (1999). Sensitivity of Automatic Control Systems (1st ed.). CRC Press. https://doi.org/10.1201/9781420049749

6 Venikov, V.A. (1976). The theory of similarity and modeling (in relation to the problems of the electric power industry). 2nd ed., Rev. and add. M.: Higher school.

7 Astakhov, Yu.N., Lezhnyuk, P.D. (1990). Application of the theory of similarity in problems of control of normal modes of electric power systems. Izv. Academy of Sciences of the USSR. Energy and transport. 5. 3–11.

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[8]:

minimize the control function

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

in the space of conditions

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

where x(t), u(t), y(t) are respectively the vectors of condition, control, and observation;відповідно вектори стану, керування та спостереження; A, B, C, D, Q, R – matrix of constant coefficients; t_0, t_k is the beginning and the end of the time interval; x_0 is the initial value of the condition vector.

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 $x(t)=y[x(t_0), u(t)]$. The second equation in (2) determines the output parameters depending on x(t) and u(t).

If the problem of optimal control of the conditions of sysrem 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 realisation, then the solution (1), taking into account (2), has the form:

$$u(t) = -w\,y(t), \qquad (3)$$

where w is the feedback matrix.

Expression (3) is the law of optimal control, the implementation of it allows us to achieve the minimum of function (1). In the formulated control problem (1)–(2) it is implicitly assumed that the region M_u of possible values of the vector of control parameters u is known. However, in many cases such an assumption is unfounded. This area must be defined. As a rule, the solution of the problem of determining M_u precedes the optimization. Its value must be such that the condition of serviceability or normal functioning of the system is satisfied[9]

$$\mathbf{x}\subset\mathbf{M}_x \text{ for any } \mathbf{u}\in\mathbf{M}_u, \qquad (4)$$

where M_x is values x, that can actually take place during the normal operation of the system.

In relative units or criterion state the law of optimal control (3)–(4) will be rewritten accordingly[10]:

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

8 Horn, R., Johnson, C. (1989). Matrix analysis. Moscow: Mir.

9 Rosenwasser, E., & Yusupov, R. (1999). Sensitivity of Automatic Control Systems (1st ed.). CRC Press. https://doi.org/10.1201/9781420049749

10 Lezhnyuk, P.D., Kulik, V.V., Obolonsky, D.I. (2007).Modeling and influence compensation of inhomogeneity electric networks on economy of their modes. Electricity, 11, 2–8.

$$\mathbf{x}_* \subset \mathbf{M}_{x_*} \text{ for any } \mathbf{u}_* \in \mathbf{M}_{u_*}, \quad (6)$$

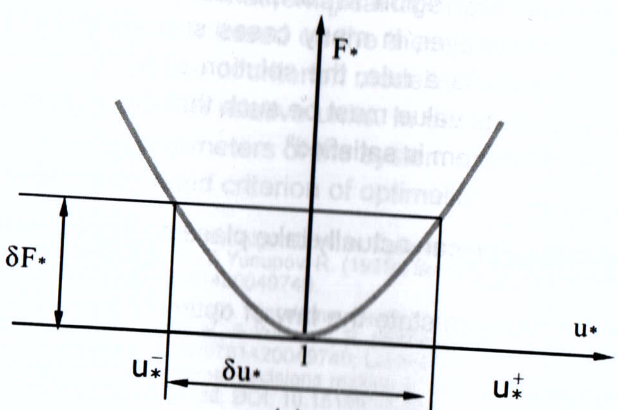
where p is the matrix of similarity criteria[11]; $u_{*i} = u_i/u_{io}$ are the parameters by which the condition of the system is optimized in relative units (the optimal values of the parameters are taken as the basis u_{io}). All other quantities in (5–6) are converted into relative units by a similar approach.

An illustration of the practical implementation (5)–(6) is shown in Fig. 1. In Fig. 1. (a), the function of the optimality criterion is presented in relative units $F_* = F/F_o$. F_o is the optimal value of the optimality criterion. Accordingly, the zone of the insensitivity of the criterion of optimality dF_* is specified, and the control parameter du_* is determined in relative units – $dF_* = dF/F_o$, $du_* = du/u_o$, where u_o is the optimal value of the control parameter. In this case, if the origin is shifted to one, then the insensitivity zone du_* is determined from the conditions

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

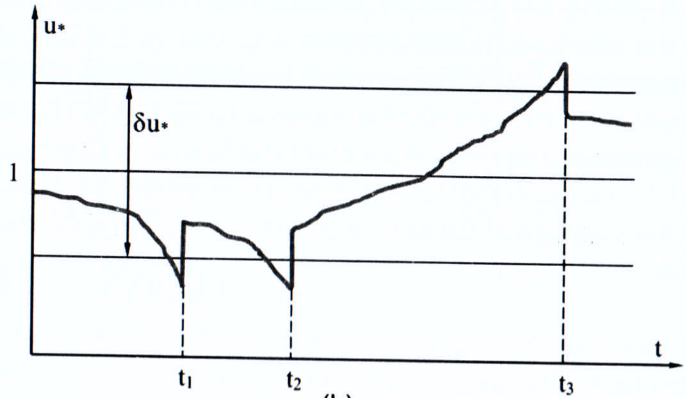
In contrast to the case when the problem is solved in named units, the setting of the automatic control system (ACS) in (5)–(6) is equal to one (see Fig. 1, b), and the insensitivity zone δu_* is set in relative units (in real devices more often in %).

The special advantages of solving the problem of sensitivity analysis in relative units are felt when the problem of optimal control is multiparametric. In Fig. 2, as an example, shows the criterion dependences of the optimality criterion on the control parameters $F_*=f(u_*)$ of the power system, which can be the transformation coefficients of communication transformers of electric networks of different voltage or power of reactive power sources. On the basis of such dependences, the zones of the insensitivity of the transformation coefficients δu_i are established. It is obvious that the numerical values depend on the size of the insensitivity zone of the optimality criterion δF_* and the nature of the dependence $F_*=f(u_*)$.



(a)

11 Astakhov, Yu.N., Lezhnyuk, P.D. (1990). Application of the theory of similarity in problems of control of normal modes of electric power systems. Izv. Academy of Sciences of the USSR. Energy and transport. 5. 3–11; Lezhnyuk, P.D., Kulik, V.V., Obolonsky, D.I. (2007).Modeling and influence compensation of inhomogeneity electric networks on economy of their modes. Electricity, 11, 2–8;



(b)

Figure 1. Optimal control with taking into account the sensitivity control in relative units

When it comes to reducing power losses in the EPS by coordinating the coefficients of transformers k, it is carried out by the criterion dependences F*=f(k*). They reflect the technical capabilities of transformers in the management of power losses in the power system and are used to determine their impact on power flows. In order to divide the transformers into functional groups and determine the role of each of them in the ACS by power currents, the inverse sensitivity problem is solved. As a result of its solution, for a given zone of insensitivity of the optimality criterion δF *, the zones of insensitivity δk_i of the transformation coefficients are determined. As can be seen from Fig. 2, the sizes of these zones correspond to real possibilities of transformers to influence losses F. According to their regulating effect various intensity of switchings for EPS transformers is established. With such an organization of the control system, the introduction of the EPS mode in the area of optimality is realized using the minimum possible number of control effects, which in turn ensures the reliability and rational use of the resource of control devices. For example, (see Fig. 2) the second transformer to introduce F in the optimality region should perform three switches.

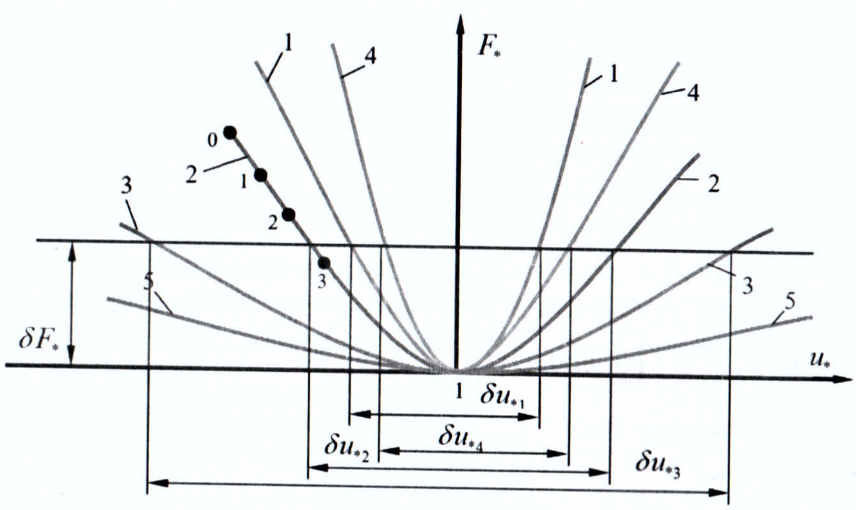


Figure 2. Criteria dependencies of the optimality criterion on parameters of influence (control)

The task of adjusting the control parameters in the system in order to minimize F requires solving the inverse sensitivity problem.

In contrast to the direct ones, which are mainly related to the analysis of the additional motion of the optimality criterion, in the inverse problems for the given sensitivity functions ∂F/∂u, and the additional deviation of the function δF, the parametric effects ∂u are estimated. In the general case, the relationship between a given deviation of the function δF and the variation of the control parameter vector δu is described using the operator equation:

$$\partial F = G \partial u \,, \qquad (8)$$

where G is an operator whose elements are functions of sensitivity and are determined by the type of function under study.

Formally, inverse problems can be solved using a relation

$$\partial u = G^{-1} \partial F \,, \qquad (9)$$

where G^{-1} is an operator inverse to the operator G.

However, the last expression can be used only if the problem is correct. To do this, the following conditions must be met[12]:

- for any value of ∂F there is a solution ∂u Mu;
- the solution is defined unambiguously;
- the task is stable.

It is difficult, and sometimes even impossible, to use expression (9) for practical calculations due to the incorrectness of inverse problems, such as those that do not satisfy the conditions of unambiguous solutions[13]. In particular, the reason for the incorrectness of the considered problem is the nonlinearity of problem (1)–2) and, consequently, the nonlinearity of equation (9) with respect to the variation of the parameters u. The solution to the inverse sensitivity problem in this case may be ambiguous. However, even if the solution exists and is unique, it may not have stability properties. This is expressed by the fact that small errors in the original data (in the value of ∂F) cause significant errors in the solution of ∂u. Thus, one of the conditions of correctness is violated[14].

Incorrect inverse problems do not have a general solution sensitivity. They are solved by numerical methods. The most widely used in engineering practice for solving inverse problems is the method of selection[15]. With respect to the problem (1)–(2), the essence of this method is as follows. It is assumed that for an arbitrary ∂u from the region M_u a direct sensitivity problem is solved and among the possible solutions is the value of $\partial \tilde{u}$. Whereas the approximate solution of the inverse problem is taken to be the value of $\partial \tilde{u} \in M_u$ at which the minimum distance between f(∂u) and ∂F is reached,

$$J = \rho\left[\delta F, f(\delta \tilde{u})\right] = \min_{\delta u \in M_u} \rho\left[\delta F, f(\delta u)\right], \qquad (10)$$

12 Tikhonov, A.N, Goncharsky AV, Stepanov VV, Yagola AG Numerical methods for solving incorrect problems / - M .: Наука, 1990. - 237 с.

13 ib.

14 ib.

15 Rosenwasser, E., & Yusupov, R. (1999). Sensitivity of Automatic Control Systems (1st ed.). CRC Press. https://doi.org/10.1201/9781420049749

where ρ is the distance in the space M_u between the point ∂F and the calculated $f(\partial u)$, which is determined by solving a direct problem.

Numerical methods are used to minimize the expression (10). However, it is usually necessary to solve the complicated task of finding the function extremum of many variables. The expression can be simplified if the value is approximated by sensitivity functions, for example, around the point u_o.

By linear approximation, when

$$\tilde{F}(u_0 + \delta u) = \tilde{F}(u_0) + h\delta u \, , \tag{11}$$

where h is the sensitivity function, the solution can be obtained by iterative method. At the same time, a direct problem is solved at each step.

If the functional J is selected as

$$J = \int_{t_0}^{T} (F - \tilde{F})_t V (F - \tilde{F}) dt \, , \tag{12}$$

where V is the weight (usually diagonal) matrix, then after substitution (11) in (12) we obtain:

$$J = \int_{t_0}^{T} (\delta F - h\delta u)_t V (\delta F - h\delta u) dt \, . \tag{13}$$

The vector ∂u can be found using the necessary extremum condition (13). To do this, we need to differentiate (13) by ∂u

$$\frac{\partial J}{\partial \delta u} = 2\int_{t_0}^{T} (h_t V h \delta u - h_t V \delta F) dt$$

and equate to zero. As a result, is obtained the following extremum condition:

$$H\delta u = P \, , \tag{14}$$

where $H = \int_{t_0}^{T} h_t V h dt, P = \int_{t_0}^{T} h_t V \delta F dt$ The columns of the matrix h are the sensitivity vectors: $h = \dfrac{\partial \tilde{F}}{\partial u_i}$.

The required vector ∂u is the result of solving a system of linear equations (14). Thus, mathematical models have been developed that allow to more effectively solve the problems of sensitivity analysis of optimal solutions for state control of dynamic systems such as electric power. They are based on criterion modeling, which involves the transformation of the initial mathematical model into a dimensionless form. This approach to the sensitivity analysis of optimal solutions in complex systems allows you to coordinate the action of ACS and enter the system in the field of optimality most rationally, the most effective optimizing actions and the least number of them.

In the power system for the adjustment of the ACS must be preceded by a parametric sensitivity analysis, the results of which identify places to changes in the parameters in which the criterion of optimality – the loss of active power is the most sensitive. It is best to do this in relative units because it allows the coordination of transformers and reactive power sources. This ensures that these control devices are ranked in accordance with the greatest impact on power flows in the electrical networks of the power system and reduce electricity losses in them. For this purpose it is enough that ACS transformers and reactive power sources were adjusted with the corresponding zones of insensitivity ∂u_i.

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DISINFECTION OF THE ENVIRONMENT ON THE BASIS OF ULTRAVIOLET LEDS IN THE CONVENTION OF THE COVID-19 PANDEMIC

Formulation of the problem. One of the most pressing problems of today, which affects every inhabitant of the planet and on which the future of mankind depends, is the provision of requirements for the quality of the environment. The presence of various types of pollution in it can lead to a man-made disaster, which is today the Covid-19 pandemic. Therefore, hygienic regulations of developed countries regulate extremely high requirements for the quality of the environment, including microbiological indicators. However, the existing methods of cleaning the environment, as well as traditional schemes of its disinfection are not always able to meet such requirements and are guaranteed to protect the population from infectious diseases and do not fully meet the requirements of today.

Existing UV sources in bactericidal plants are based on the use of gas-discharge mercury-argon or mercury-quartz lamps, in which UV radiation of the bactericidal range is generated in the process of electric discharge. They are installed in a quartz cover in the

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