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PREVENTIVE CONTROL OF ELECTRIC POWER SYSTEM STATE VARIABLES BY THE METHODS OF PROBABILISTIC LOAD FLOW – CONFERENCE PAPER

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Abstract: The paper considers a technique for selection of preventive control actions to provide feasibility of electric power system (EPS) state variables, taking into consideration random character of variation in loads. The authors suggest that sensor variables in EPS should be identified and potential ranges of change in their values be estimated from the analysis of their numerical and probabilistic characteristics that are obtained by analytical methods of probabilistic load flow.

Keywords: singular analysis, sensor variables, probabilistic load flow.

1. INTRODUCTION

In the course of operation electric power systems experience large and small external disturbances and respond to them by changes in state variables. The network components whose state variables change to a greater extent at random external disturbances are called sensors. A large response of a state variable to a disturbance is not dangerous in itself, if the variable remains feasible after the disturbance. The probability that the variable goes beyond the feasible limits depends on its response to the disturbance, feasible range of change and closeness of the variable's mean to the limiting value. Estimation of probability makes it possible to develop control actions to be taken to prevent emergency situations. First of all the controls should include decisions on the network reinforcement related to the installation of additional equipment to mitigate the response of sensor variables to the disturbances. Secondly, there should be decisions related to the controls developed in the course of EPS operation and aimed at maintaining variables within feasible range determined by the reliability and quality requirements.

The technology of singular analysis for the identification of sensor variables and weak places causing these sensor variables in EPS was developed in [1]. However, this technology does not allow us to simultaneously identify sensor variables, estimate possible ranges of their changes and probability of their feasibility, and choose control actions to provide the required values of the probabilities. Joint solution to all the enumerated problems can be obtained using the methods of probabilistic load flow.

A detailed analysis of the methods available for calculation of probabilistic load flow and their use in different problems of power engineering is presented in the surveys of the studies [2, 3, 4].

2. METHODS OF PROBABILISTIC LOAD FLOW

In the methods of probabilistic load flow, to be called **linear**, the means $\mu_{\Delta\delta,\Delta U}$ and covariances $\mu_{2\Delta\delta,\Delta U}$ of changes in the voltage magnitudes and phases will be determined through the means $\mu_{\Delta P,\Delta Q}$ and variances $\mu_{2\Delta P,\Delta Q}$ of loads that are found at the point of solution to the nonlinear system of equations for steady state of power system

$$\mu_{\Delta\delta,\Delta U} = J^{-1}\mu_{\Delta P,\Delta Q} \ , \quad (1)$$

$$\mu_{2\Delta\delta,\Delta U} = J^{-1}\mu_{2\Delta P,\Delta Q}\left(J^{-1}\right)^T , \quad (2)$$

where J^{-1} – an inverse Jacobian matrix.

A simpler expression for the means and covariances (1), (2) can be obtained by singular value decomposition of asymmetrical Jacobian matrix

$$J = W\Sigma V^T = \sum_{j=1}^{n} w_j \sigma_j v_j^T , \quad (3)$$

where $W = (w_1, w_2, ..., w_n)$ and $V = (v_1, v_2, ..., v_n)$ – orthogonal matrices in which columns are left and right singular vectors and Σ – diagonal matrix of singular values arranged in ascending order $\sigma_1 < \sigma_2 < \sigma_3 < ... < \sigma_n$.

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If the first singular value $\sigma_1 = \sigma_{min}$ is considerably lower than the rest of the singular values then the expression for covariances of changes in the voltage magnitudes and phases, taking into account the first generalized disturbance, can be represented by the scalar value of variance of this disturbance $\mu_{2\Delta S_1}$

$$\mu^{(1)}_{2\,\Delta\delta,\Delta U} = v_1 \left(w_1^T / \sigma_1 \right) \mu_{2\Delta P,\Delta Q} \left(w_1^T / \sigma_1 \right)^T v_1^T = v_1 \, \mu_{\,2\Delta S_1} v_1^T \,. \quad (4)$$

The components of the first right singular vector distribute scalar value $\mu_{2\Delta S_1}$ among the network nodes. The linear method of **generalized disturbance** does not require that the scenario of change in the nodal powers be specified, but it makes it possible to estimate a set of disturbance scenarios by one criterion, using the specified variance value of generalized disturbance.

The error related to linearization of load flow equations can be reduced by the methods of nonlinear probabilistic load flow.

The quadratic Taylor approximation of the steady state equations in the general form can be represented by

$$\Delta Y = J\Delta X + 0.5 H \Delta X \otimes \Delta X \,, \quad (5)$$

where a rectangular matrix H, called the Hessian matrix with k rows and k^2 columns, $\Delta Y = \begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix}$, $\Delta X = \begin{pmatrix} \Delta\delta \\ \Delta U \end{pmatrix}$.

Relation between means and variances of nodal powers, and means and covariances of state parameters on the basis of (5) can be represented as

$$\mu_{\Delta Y} = J\mu_{\Delta X} + 0.5 H \left(b_{\mu_{2\Delta X}} + \mu_{\Delta X} \otimes \mu_{\Delta X} \right), \quad (6)$$

where $b_{\mu_{2\Delta X}}$ – vector, made up of columns of matrix $\mu_{2\Delta X}$.

$$\mu_{2\Delta Y} = J\mu_{2\Delta X} J^T + 0.5 \cdot J \mu_{3\Delta X} H^T + 0.5 \cdot H \mu^T_{3\,\Delta X} J^T + \\ + 0.25 H \left(\mu_{4\,\Delta X} - b_{\mu_{\,2\Delta X}} b^T_{\mu_{2\Delta X}} \right) H^T \,, \quad (7)$$

where $\mu_{3\Delta X}$ and $\mu_{4\Delta X}$ – matrices of joint central moments of third and fourth order.

The system (6), (7) is underdefined because its two equations include four unknown matrices of moments. To get a unique solution the method **of statistical linearization** [6] (7) has only its linear part. We can also assume that the law of distribution of state variables is close to the normal law, and express the moments of the third and fourth orders through the cumulants equal to zero. Such a method is called the method of **two moments**, equation (7) for this method can be written as

$$\mu_{2\Delta Y} = J\mu_{2\Delta X} J^T + 0.25 H \left(\mu_{4\Delta X} - b_{\mu_{\,2\Delta X}} b^T_{\mu_{\,2\Delta X}} \right) H^T \,. \quad (8)$$

In order to improve the accuracy of solution to the problem of nonlinear probabilistic load flow, obtained by the method of two moments, we suggest using the **method of three moments** in which the equation for central moments of the third order should be added to the system of equations (6), (7). The system of three equations is underdefined because it contains unknown matrices of the moments. To receive unique solution the central moments of the fourth, fifth and sixth orders are represented through the cumulants equal to zero.

Additionally we analyzed the possibility of using the modification of the least labor-intensive **non-iterative** method for calculation of probabilistic nonlinear load flow [5] that does not suppose an iterative specification of solution but only makes it possible to adjust the means and moments of the second order that are obtained on the basis of linear approximation, taking into account the Hessian matrix.

The proposed improvement of the non-iterative method lies in the fact that it includes the procedure for iteratively specifying the solution. In this method, which is called **modified** expression (5) can be written as

$$\Delta X = J^{-1} \Delta Y - 0.5 J^{-1} H \left(J^{-1} \otimes J^{-1} \right) \left(\Delta Y \otimes \Delta Y \right). \quad (9)$$

The mathematical formulation of the modified method of probabilistic load flow includes the moments of first, second and third order.

The accuracy of probabilistic estimates based on the linear and nonlinear methods can be assessed when they are compared with the estimates obtained by the Monte Carlo method. The methods of nonlinear probabilistic load flow are compared on the example of nodal voltage magnitudes.

The EPS network with 14 nodes and 15 tie lines in Figure 1 was taken as a test network for comparison of the load flow methods.

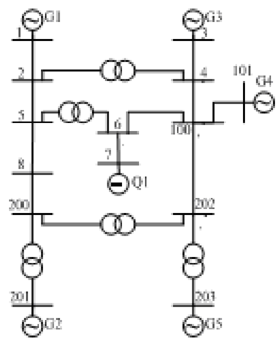

Fig. 1. 14 node test network

Figure 2 presents the standard deviations of changes in the voltage magnitudes at the test network nodes that are obtained by the corresponding covariance matrices, for two linear methods, five nonlinear methods, and the Monte Carlo method.

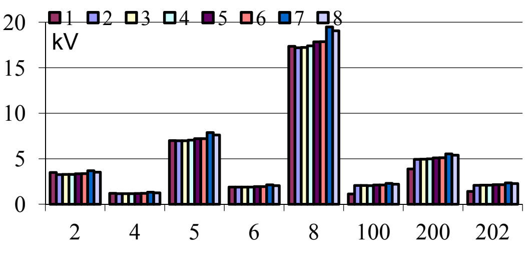

Fig. 2. Standard deviations of changes in the nodal voltage magnitudes calculated by the methods of: 1 – generalized disturbance, 2 – linear, 3 – non-iterative, 4 – two moments, 5 – statistical linearization, 6 – modified, 7 – three moments, 8 – Monte Carlo

3. PROBABILISTIC LOAD FLOW IN TERMS OF CONSTRAINTS

If the calculation of probabilistic load flow results in the fact that the probability of feasible controlled sensor variables is lower than the required one, such a probability can be increased by two ways.

The first is to search for the approaches for decreasing the standard deviation by reinforcing the weak points, which is achieved by changing their parameters.

The second is to choose the controls to minimize the distance between median m_c and mean m of the curve of random variable probability distribution in the feasible region.

The main steps of algorithm work for choosing the controls are the following.

1. Iteration index $k=0$. Calculation of the feasible steady state of EPS resulting in determination of the values of state variables that satisfy the set of constraints. Problem is solved by the reduced gradient method [4], in which the problem of quadratic programming is solved and the values of components of vectors Z^k and Y^k are determined at each linearization step, where Z^k – vector of variables, Y^k – vector of controls or independent variables that contains YN_xN_f transformation ratios, values of reactive powers of compensators, voltage magnitudes, generation capacities at PU nodes and other controlled parameters.

2. Calculation of probabilistic load flow and determination of numerical characteristics of the controlled variables, separation of the controlled sensor variables z_i, $i \in I_c$, where I_c is a set of indices for the sensor variables. Determination of the probability of feasible sensor variables. The algorithm terminates its work if the required probability for all the sensor variables is obtained. Otherwise, the N_{cv} – dimensional vector Z_v containing sensor variables z_j, $j \in I_c$ is constructed. For these variables the specified probability that the inequality constraints $(z_{vi\,min}, z_{vi\,max})$ are met is not provided. The value of $m^k_{cz_{vi}}$, to which the variable at the point of the deterministic problem solution should be equal, is determined for each sensor variable z_{vi}, $i = 1, N_{cv}$.

3. Solving of the deterministic problem of load flow calculation subject to inequality constraints to provide the required probability of feasible controlled variables. The problem determines the vector of control actions Y_{s*} minimizing the objective function

$$\min_{Y} \sum_{i=1}^{N_{cv}} \left(z_{vi}(Y_s) - m^k_{cz_{vi}} \right)^2 , \qquad (10)$$

where Y_s – components of vector Y, to whose change the controlled variables Z_v are most sensitive.

The response of variables Z_v to controls Y is determined through calculation of the sensitivity coefficients $\frac{\partial z_{vi}}{\partial Y}$.

4. Verification of the criterion of algorithm work completion. If variation of criterion (10) in two adjacent iterations does not exceed the given accuracy, the algorithm stops working. Otherwise, the index of iterations increases, $k = k + 1$, and the second step of the algorithm, where the probabilistic problem is solved, is performed.

Table 1 for the test scheme in Figure 1 presents the standard deviations of voltage magnitudes ς_U at the test network nodes that are not generation ones, the values of differences in means and rated voltages $m_U - U_{nom}$, probabilities of feasible voltage magnitudes, all being obtained by the linear method of probabilistic load flow**.** The voltage magnitudes are equal to ±30кV at 500 kV nodes and to ±25кV at 220 kV nodes.

Table 1. Probabilistic characteristics of voltage magnitudes at the test network nodes for the initial state

Nodes	ς_U (kV)	$m_U - U_{nom}$ (kV)	P
2	3.657	22.340	0.9819
4	1.326	11.497	1.0000
5	6.887	12.056	0.9954
6	1.866	5.172	1.0000
8	17.122	8.447	0.8836
100	2.033	9.241	1.0000
200	4.831	28.159	0.6484
202	2.050	13.627	1.0000

Despite the fact that the voltage magnitude of node 8 responds to external disturbances to a greater extent than that of node 200, which is seen from comparison of their standard deviations, the difference between the mean and the rated voltage for node 200 is much greater than for node 8. The latter property is determining, since the probability of feasible voltage magnitude of node 200 (equal to 0.6484) is lower than the probability (equal to 0.8836) for sensor node 8.

The identically low probabilities for node 200 are obtained by using method of generalized disturbance, the nonlinear methods and the Monte Carlo method in addition to the linear method.

In order to provide the probability of feasible voltage magnitudes at nodes 8 and 200 the weak ties were reinforced, which made it possible to decrease the standard deviations of variables and to choose the control actions allowing the shift of means of variables to the center of the feasible region.

The criterion for separation of weak ties was the maximum values of standard deviations in change in the differences of voltage magnitudes. They separated the same ties 5-8 and 8-200 of the test network that were selected as weak in [1] based on the singular analysis. The changes of the transformation ratios of transformers 200-201,200-202 202-203 were used as control actions to shift the voltage means of nodes 8 and 200.

Figure 3 shows the probability density function curves of changes in the voltage magnitude of nodes 8 and 200 for the initial state (1 and 4), for the state obtained by decreasing inductive impedances of weak ties 5-8 and 8-200 by 11% (2 and 3), and the state obtained after changing the transformation ratios of three transformers.

Reinforcement of the network results in decrease in the standard deviation of nodes 8 and 200 and increase in the difference between their means and rated voltages, decrease in the probability of feasible variables. Change in the transformation ratios leads to a slight decrease in the standard deviations of changes in the voltage magnitudes of nodes 8

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and 200 shift of their means and increase in the probability of feasible voltage magnitudes up to 0.9764 and 1.0.

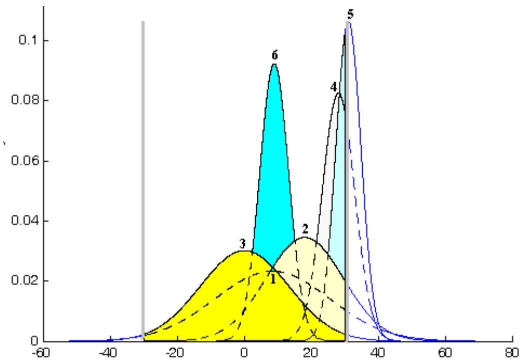

Fig. 3. Curves for the probability density functions of change in voltage magnitudes at nodes 8 and 200 for the initial state (1 and 4), the state obtained after reinforcement of weak ties (2 and 3), and the state obtained after change in the transformation ratios of three transformers

The results on increasing the probability of feasible voltage magnitudes that are obtained for the linear method are extended to all the analyzed methods of probabilistic load flow. Analysis of the results shows that the chosen controls allow the increase in probability values for all the methods.

4. CONCLUSIONS

1. The methods of probabilistic load flow reveal the same sensor variables in EPS which can be separated on the basis of singular analysis.
2. It is suggested that a combination of the analytical probabilistic method and the scalar value of the first generalized disturbance be applied to calculate the probabilistic indices of variables in the nonuniform network.
3. The authors suggest the modifications of the methods of probabilistic nonlinear load flow that include the methods of two and three moments with the use of cumulants and the modification of the non-iterative method that consists in correction of the Jacobian and Hessian matrices during iterations.
4. Experimental comparison of the analytical methods of probabilistic load flow has revealed the absolute advantage of the method of three moments with respect to accuracy of the obtained solution in comparison with the other methods.
5. The authors suggest the approach for solving the problem of choice of the control actions ensuring the required probability of feasible sensor controlled parameters.

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PREWENCYJNE STEROWANIE ZMIENNYMI STANU SYSTEMU ELEKTROENERGETYCZNEGO W OPARCIU O PROBABILISTYCZNE METODY OBLICZEŃ ROZPŁYWÓW MOCY – REFERAT KONFERENCYJNY

Słowa kluczowe: analiza singularna, probabilistyczne metody obliczeń rozpływów mocy

W referacie przedstawiono sposób wyboru sposobów sterowania pracą systemu elektroenergetycznego biorąc pod uwagę losową zmienność obciążeń. Autorzy dowodzą, że istotne dla sterowania zmienne stanu mogą być identyfikowane przez probabilistyczne metody obliczeń rozpływów mocy.