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PROBABILISTIC EVALUATIO N OF VOLTAGE STABILITY LIMIT OF POWER SYSTEM UNDER THE CONDITIONS OF ACCIDENTAL EMERGENCY OUTAGES OF LINES AND GENERATORS

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Abstract- Maintenance of the power system safety is the most important problem for system stability preservation in case of emergency failures of its main elements – generators and power lines. To evaluate the degree of impact of emergency failures of individual elements on the power system, the analysis of the maximum network load and the critical voltage values is carried out. In the conditions of stochastic variability of powers in the load nodes, as well as in the presence of intermittent-random power generation in the generation nodes, the evaluation of critical voltages and maximum transmitted power values over the power lines of the system network requires a probabilistic evaluation of these critical parameters for failure case of failure. The method and algorithm for the operational evaluation of the distribution of probability of critical voltage and maximum power transfer for various emergency situations – failure options of lines and generators according to the *N*-1 scheme. The random variability of generation is represented by the Wind Power Plant power generation model, which takes into account the variability of its share in the total load coverage. The stochastic of the load model is specified using the Monte-Carlo method. The results of test studies on IEEE schemes and circuits of real power systems are presented. A comparative assessment of the risks of emergency failures when taking into account random processes in the load and generation shows the high efficiency of the proposed approach.

Keywords: Power System, Operational Control, Emergency Failures, Elements of Power Grids, Distribution of Probabilities, Critical Voltage, Maximal Power Transfer, Line Load.

1. INTRODUCTION

A distinctive aspect of modern power systems is the accelerated growth of consumption, for the coverage of which not only traditional, but also various types of renewable sources are widely used. The transfer of large powers to consumers has led to additional overloads for a number of supply lines within the transmission network of the power system. The transmitted power values in some periods of the day may be higher than the maximum permissible values in case of emergency failures of lines or generators, as a result, even at small disturbances, there may be a risk of loss of the systems stability [1, 2].

The probability of instability becomes even greater in a power system with a significant proportion of integrated wind farms, whose power generation is intermittent and random [3]. In addition, the stochastic load variability may be found dangerous for power lines (PTL) operating in modes close to the maximum power transmission [4]. There is a need to develop methods of probabilistic modeling of the system mode to assess the range of variability of the ultimate loading of supply lines and determine the corresponding variability of critical voltage. The voltage stability of the power system shows its ability to maintain the permissible voltage levels in all controlled nodes of the network in normal modes established after the disturbance [2, 5].

The main reason for the voltage instability is the lack of reactive power, the insufficiency of its value to cover the increased demand at failures of consumer's mains and generators. A continuous sequence of voltage stability disturbances, at the end, turns into a complete blackout of the system. Similar consequences of voltage instability occurred in power systems of a number of countries.

The probability of voltage collapse is high in power systems in the presence of a Fully loaded PTL, supplying network, and limited opportunities to produce additional power by sources and fulfillment of a schedule of power flow at unforeseen under voltage. At stochastic load variability and random value of power generation by sources (wind and solar PV stations), at certain states of the scheme (disconnected power lines, generators), the value reduction, as well as the change of limit value can occur so quickly that existing controls will not be able to provide corrective actions to save system from blackout.

Currently, methods based on the representation of the disturbed state of the system by deterministic models are mostly developed for the analysis of the power system static stability.

In recent years, in connection with the increased requirements for the increase of the efficiency of the operational control of the power system, new approaches have been proposed for the evaluation of the system state stability, taking into account the stochastic changes in the power values of sources and loads, occurring in the real operation, as well as random failures of the system elements [9-12]. Among the problems associated with the power system stability, the voltage stability is the most important.

The algorithm of probabilistic evaluation of voltage stability in the system subject to the stochastic of load power and emergency failures of the systems elements is proposed in the paper.

The results of test studies of the probability distribution characteristics of the voltage stability limits when changing the systems loading conditions and emergency failures of different elements are presented.

2. MODEL AND ALGORITHM OF PROBABILISTIC EVALUATION OF VOLTAGE STABILITY LIMIT BASED ON RANDOM LOAD VARIABILITY BY EXAGGERATION METHOD

Probabilistic evaluation of the voltage stability of the power system is to determine the probability of instability of the steady mode of the system caused by small perturbations by means of stochastic changes in the input variables of powers of sources and loads for each case of variability of the network structure.

If the probability density distribution for each variable is specified (is calculated on the basis of real measurements of stochastic processes for all variables or data of modeling of these processes by Monte-Carlo method), then on the basis of repeated calculations according to the steady state model the probability density functions for output variables (voltages in nodes U_i and power flows in the network P_{ij}, Q_{ij}) can be constructed .

For the probabilistic evaluation of the system parameters at the point of disturbance of state stability U_{cr}, $P_{\max.ij}$, the method of continuous calculation of steady-state modes is used [7]. As a result of this calculation, the $P_{\max.ij} - U_{cr,i}$ relationship for all N nodes of the system is determined. Each point on the curve corresponds to a single sample from a set of samples of stochastic load power changes at nodes generated by the Monte-Carlo model. The maximum rpermissible loading of supply network of the system, starting from the predetermined steady state to the critical state, determines the voltage stability limit. The stability limit state in the coordinates of the bifurcation point through $P_{\max.ij} - U_{cr,i}$ can be described in a generalized form in the way of the following equations [10]:

$$f(x,\lambda) = 0 \tag{1}$$

$$f_x(x,\lambda)\cdot v = 0 \tag{2}$$

$$I^T \cdot v - 1 = 0 \tag{3}$$

where, $f(x,\lambda)$ is power flow equations; λ is scalar bifurcation parameter (determines the degree of network loading by active power); $x = [\theta, U]$ is the vector of state variables that determine the angle and magnitude of the voltage vector U at the PQ nodes of characteristic Equation (2) in the bifurcation node assumes that the Jacobian matrix $f_x(x,\lambda)$ of power flow equations is singular; v is a normalized eigenvector (3) and is the normalized function entered into the (1)-(3) system for the v restriction from equality to zero.

The power flow equation in the detailed form is described as follows:

$$\Delta P_i = P_{G,i}(\lambda) + P_{R,i} - P_{L,i}(\lambda) - \\ -U_i \sum_{j=1}^{N} U_j \left[G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij} \right] = 0 \tag{4}$$

$i \in N_{PU}$, N_{PQ}

$$\Delta Q_i = Q_{G,i} + Q_{R,i} - Q_{L,i}(\lambda) - \\ -U_i \sum_{j=1}^{N} U_j \left[G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij} \right] = 0 \tag{5}$$

$i \in N_{PQ}$

where, $P_{G,i}(\lambda)$ is the active generation power of power plant with traditional sources connected to the i node of the system; $P_{R,i}, Q_{R,i}$ are the active power generation and reactive consumption power of wind farm connected to the i node; $Q_{cr,i}$ is power of reactive power compensation device in node i ; U_i is voltage in node i ; θ_{ij} is the phase angle of shear between voltages in i and j nodes; G_{ij} and B_{ij} are mutual active and reactive conductivity of transmission between nodes i and j ; N is number of nodes; N_{PU} and N_{PQ} are number of PU and PQ nodes respectively.

$P_{G,i}(\lambda)$, $P_{L,i}(\lambda)$, $Q_{L,i}(\lambda)$ are functions of the mode exaggeration parameter by which the load power increase is specified in all N nodes. x, v, λ values, corresponding to the ultimate loading of the elements of supply network, are determined from the solution of the linearized equations obtained from the nonlinear Equations (1)-(3).

The voltage stability limit is calculated as follows:

$$U_{cr} = f\left[\sum_{i=1}^{N} P_{L,i}(\lambda) - \sum_{i=1}^{N} P_{L,i,0} \right] \tag{6}$$

where, $P_{L,i,0}$ is the active load power in the i node in the initial steady mode.

3. ALGORITHM OF PROBABILISTIC EVALUATION OF VOLTAGE STABILITY LIMIT AND THE RISK OF INSTABILITY AT FAILURES OF SYSTEM ELEMENTS

The computational procedure for probabilistic evaluation of the voltage stability limit is based on the continuity of repeated calculations of steady-state modes in accordance with the generalized description (1)-(3). The initial data from measurements of stochastic processes of load and generation using Monte-Carlo simulation are created in the form of M samples for each input variable in the nodes PU and PQ of the system.

Similarly, the calculations are carried out for different levels of load increase up to the maximum $P_{\max.ij}$ of power transfer over the controlled power lines and, accordingly, the voltage stability limit $U_{cr.i}$.

The density histogram and the corresponding probability distribution function are constructed according to the estimated aggregate of sets $P_{\max.ij}$ and $U_{cr.i}$. The block diagram of the $P_{\max.ij}$ and $U_{cr.i}$ probability distribution estimation algorithm is shown in Figure 1.

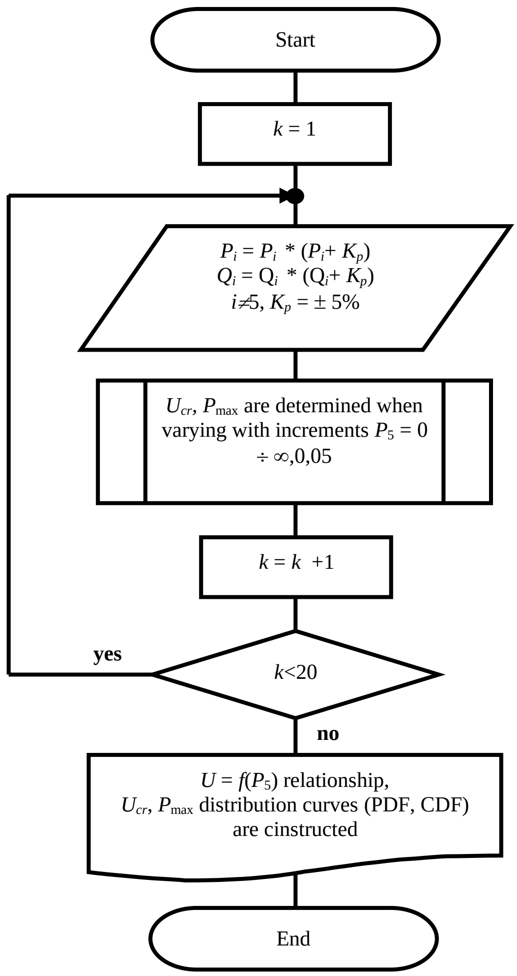

Figure 1. Block diagram of algorithm of estimation of distribution of probability $P_{\max.ij}$ and $U_{cr.i}$

Each of the probabilistic estimates $U_{cr.i}$ is associated with a certain risk of instability. Such risk indicators should be defined in order to be able to assess the consequences of emergency failures in the power system.

For the given schemes and mode of the power system, the expected values of the voltage stability limit are set, showing the possibilities of maximum power generation and transmission of this power over the network. From this point of view, the case when the value $U_{cr.i}$ is less than the predetermined value $U_{cr.s,i}$ is considered as a risk. Thus, the risk is equal to the probability that the voltage stability limit is less than or equal to $U_{cr.s,i}$.

$$Risk\left(U_{cr,s,i.}\right)=\frac{N\left(U_{cr,i}\le U_{cr,s,i}\right)}{N_S}\cdot 100\% \qquad (7)$$

where, $N\left(U_{cr}\le U_{cr,s}\right)$ is the number of Monte-Carlo simulation samplings in which the resulting estimates $U_{cr.i}$ are equal to or less than $U_{cr.s}$.

4. EXAMPLE OF STUDIES

In order to assess the impact of emergency failures on the voltage stability limits in the power system, the studies were conducted on the IEEE test schemes and the real scheme of the power system in Azerbaijan. The results of probabilistic modeling of stability limit modes for the standard 14-nodal IEEE scheme (these schemes and modes are taken from [2, 3]) are given below.

Density histograms and probability distribution functions of the critical voltage in the node 4 at levels of 5% and 25% of the increase of load power consumption at normal diagram of the system are given in the Figures 2 and 3. As can be seen from the figures, the maximum probability of the voltage instability for the load stochastic interval in the range of 5% is within the interval $(0.68\text{-}0.7)\cdot U_{cr}$, at the same time for the load variability of 25% the same range is $(0.66\text{-}0.73)\cdot U_{cr}$.

A comparative analysis for the probabilistic characteristics of the voltage stability limits in the same node in case of emergency failure of the supply line 1-4 are given in the Figures 4 and 5. It is obvious from the comparison of density histograms and probability distribution functions, that in case of line failure, there is a probability of voltage instability at small values of network overload.

Curves of the risk of possible instability of the power system at parallel states of the scheme and at failures of the supply lines in it are shown in the Figure 6. As can be seen, in the case of the failure of even one PTL the risk of voltage instability increases significantly. And during stochastic processes, there is no load at all in the mode of increase of the total power by 25%.

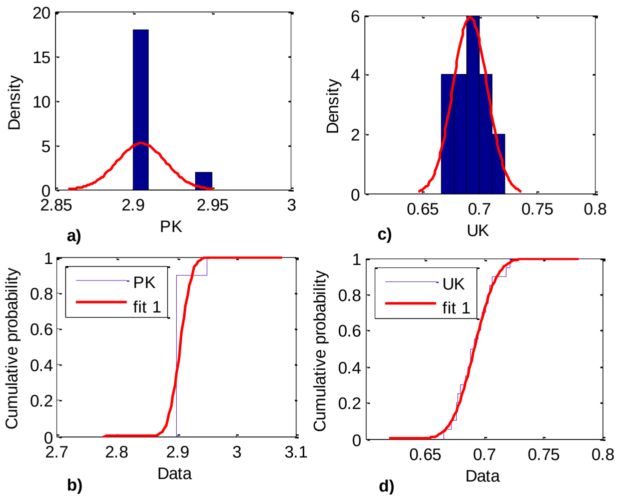

Figure 2. Density histogram and probability distribution function of the ultimate transmitting power of the system (a,b) and critical voltages (c,d) at node 14 (14-nodal IEEE diagram) in the load stochastic range of the system of 0.05 (the normal complete diagram of the system)

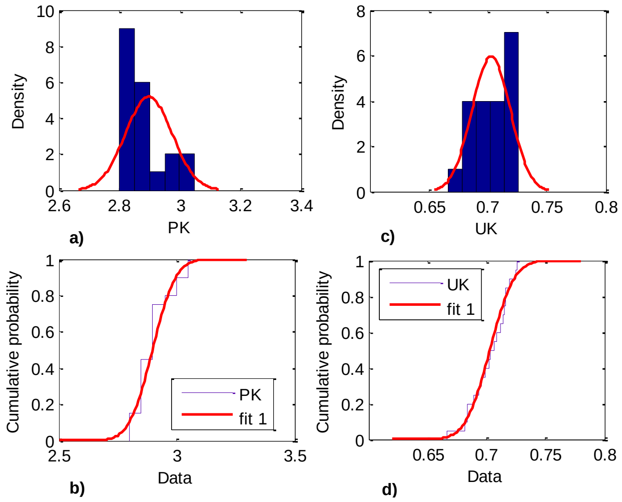

Figure 3. Density histogram and probability distribution function of the ultimate transmitting power of the system (a,b) and critical voltages (c,d) at node 14 (14-nodal IEEE diagram) in the load stochastic range of the system of 0.25 (the normal complete diagram of the system)

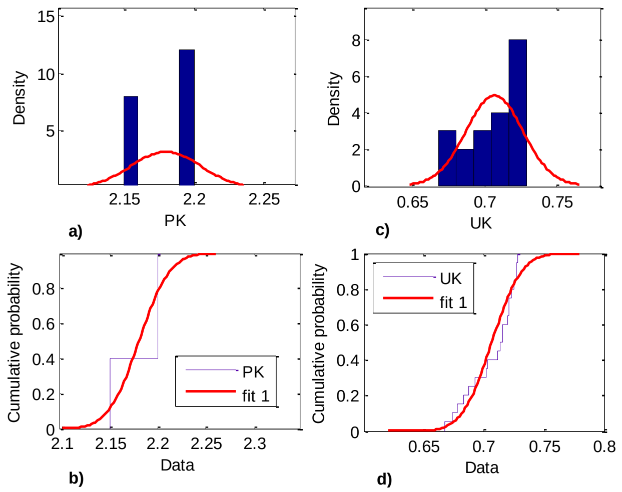

Figure 4. Density histogram and probability distribution function of the ultimate transmitting power of the system (a,b) and critical voltages (c,d) at node 14 (14-nodal IEEE diagram) in the load stochastic range of the system of 0.05 (the diagram at emergency failure of one PTL 2-4)

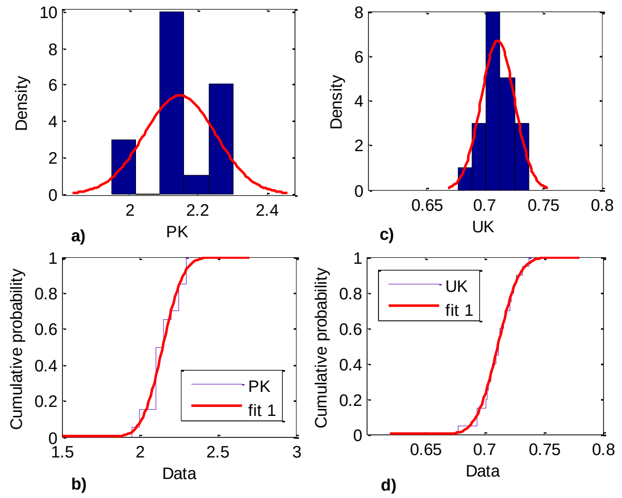

Figure 5. Density histogram and probability distribution function of the ultimate transmitting power of the system (a,b) and critical voltages (c,d) at node 14 (14-nodal IEEE diagram) in the load stochastic range of the system of 0.25 (the diagram at emergency failure of one PTL 2-4)

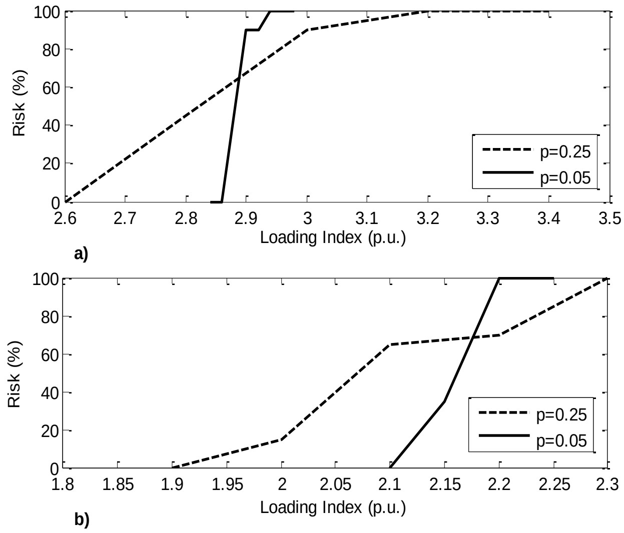

Figure 6. Curves of the risk of system instability for complete scheme (a) and failure (b) of PTL 2-4

5. CONCLUSION

Method and algorithm for the probabilistic evaluation of voltage stability in case of emergency failures of system elements (power lines and generators) taking into account the stochastic of power generation processes at stations and its consumption at load nodes are proposed in this paper. Based on the analysis of the probability distribution functions of the critical parameter values that determine the limiting state of stability (maximum load of the transmission network, critical voltages), the indicators of the risk of instability at different types of failure and load stochastic levels are determined.

In the future, the continuation of this work will be the inclusion of wind farm models in the study, as well as the consideration of cases of failure of the *N*-2 element in the identification of weak areas of the power system that are most sensitive to failures

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BIOGRAPHIES

Arif Mamed Hashimov was born in Shahbuz, Nakhchivan, Azerbaijan on September 28, 1949. He is a Professor of Power Engineering (1993); Chief Editor of Scientific Journal of "Power Engineering Problems" from 2000; Director of Institute of Physics of Azerbaijan National Academy of Sciences (Baku, Azerbaijan) from 2002 up to 2009; and Academician and the First Vice-President of Azerbaijan National Academy of Sciences from 2007 up to 2013. He is laureate of Azerbaijan State Prize (1978); Honored Scientist of Azerbaijan (2005); Cochairman of International Conferences on "Technical and Physical Problems of Power Engineering" (ICTPE) and Editor in Chief of International Journal on "Technical and Physical Problems of Engineering" (IJTPE). Now he is a High Consultant in "Azerenerji" JSC, Baku, Azerbaijan. His research areas are theory of non-linear electrical Networks with distributed parameters, neutral earthing and ferroresonant processes, alternative energy sources, high voltage physics and techniques, electrical physics. His publications are 350 articles and patents and 5 monographs.

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