

Research of emergency cascade processes on simulation models of test and real electric power systems

Bulat Gaisin^{1,*}, Ildar Shakhmaev²

¹Ufa State Petroleum Technological University, Department of Electrical Engineering and Electrical Facilities of Enterprises, Ufa, Russia

²Ufa state aviation technical university, Department of Electromechanics, Ufa, Russia

Abstract. In this work, a heterogeneous electric power system (EPS) is investigated for the possible occurrence of cascade emergency processes. In the process of computational experiments, simulation models of test and real EPS were created in which of voltages of 6, 35, 110, 500 kV is presented. The calculation of the trajectories of the possible occurrence and development of a cascade process in the event of a disturbance (N-1) in the EPS has been performed. For the investigated EPS, a model of visual representation of the heterogeneous surface of the parameters that affect the possibility of the occurrence and development of cascade processes in the EPS has been created. The study carried out on the basis of the developed methods (search for paths of the emergence and development of cascade processes, visual representation of the heterogeneous surface of EPS parameters) allows projecting the results obtained for making effective management decisions to improve survivability when designing the development of real power systems.

1 Introduction

At the moment, the improvement of theoretical and practical tools aimed at developing the reliability and survivability of EPS does not allow ensuring the absence of emergency disturbances of various levels of complexity, including with a massive shutdown of electricity consumers, as evidenced by the data shown in Fig. 1.

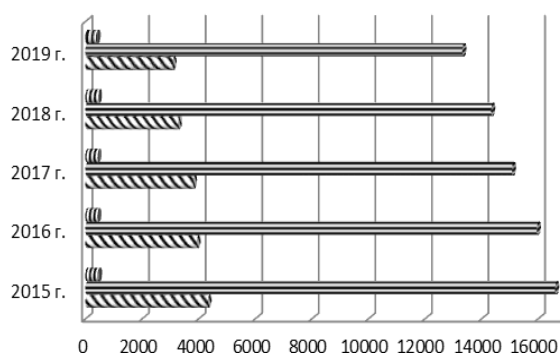


Fig. 1. Caption of the Figure 1. Below the figure.

In accordance with [1] in Fig. 1 shows statistical data indicating the regularity of accidents in the UES of Russia from 2015 to 2019. These data indicate that, for example, in 2019 there were daily: 36.5 accidents in electrical grids of 110 kV and above (horizontal shading); 8.44 accidents at power plants with an installed capacity of 25 MW and above (oblique shading); 1.1 accidents that led to disconnection of consumers in the amount of 10 MW and more (vertical shading). These

statistics, according to the Ministry of Energy of Russia, show objective data on accidents in the UES of Russia, which, in turn, may not affect the reliability of electricity supply to consumers, but in fact, on average, 2-2.5% of emergency disturbances ended in disconnection of consumers of 10 MW or more. Therefore, it is important to direct efforts to search for emergency disturbances that can weaken the survivability of the EPS and lead to a systemic accident. The emergence of other disturbances in the EPS can be admitted with the proviso that the operating personnel will do everything possible for the timely localization of the emergency disturbance and ensure that the emergency does not develop into a cascade process ending in an unacceptable mode. The proposed statistics indicate the relevance of the issue under consideration and the need to increase the requirements for ensuring the reliability and survivability of EPS.

This article proposes a tool for analyzing the possibility of the occurrence of emergency processes from the standpoint of the heterogeneity of the distribution of parameters, for specific circuit-mode conditions of the EPS. At the same time, analysis of the literature shows that in [2] the term homogeneous electrical grid means the constancy of the ratio of active resistance to inductive resistance R_{ij} / X_{ij} for any grid section $(i, j, \dots, n, i \neq j)$. But when analyzing a heterogeneous EPS, the grid parameters alone are not enough to describe the properties that affect the possibility of the occurrence and development of emergency processes.

* Corresponding author: GB9688@gmail.com

In the study [3], the heterogeneity was investigated using cluster, singular and spectral analysis. At the same time, EPS heterogeneities and their manifestations are considered when analyzing transient processes from the standpoint of various degrees of coherence of the motion of generators. Identification of groups of more or less coherent generators and cross-sections between them differing in weakness is considered as a method for studying heterogeneities. In this work [3], the calculations were carried out on the basis of the Jacobi matrix, which for steady-state modes depends mainly on the topology, parameters of the grid circuit, loads at the nodes and their static characteristics. It is important to note that calculations based on the Jacobi matrix cannot be effectively used for the real-time reliability assessment mode due to the need for significant computational costs.

2 Description of terminology

Based on the analysis of the literature [4-7], in this work, a cascade process is understood as a sequence of transitions from one quasi-stationary mode to another with step-by-step disconnection of overloaded EPS elements with termination in the range of permissible or inadmissible mode values. In case of termination in the area of unacceptable modes, the cascade process is considered part of a system (cascade) accident. The priority is to recognize and prevent the possibility of the development of a cascade process (successive shutdowns of EPS elements) into a system (cascade) accident.

According to the strict mathematical inequality proposed in [4], in the study it is assumed that a necessary condition for the existence of a cascade process is the inequality:

$$I_{ji} + \Delta I_{ji} > I_{lim,ji} \quad (1)$$

which must be performed at each subsequent step of the emergency shutdown (-s). Here ΔI_{ji} is the current surge on the overloaded element, $I_{lim,ji}$ is the permissible current value for this element. Failure to fulfill inequality (1) leads to the termination of the emergency cascade process. Moreover, its termination can be both permissible and in the unacceptable range of modes.

Based on (1) and the topological arrangement of the grid elements, when calculating the EPS modes, we obtain step-by-step options for the development of cascade processes, which, in contrast to the established point of view, allows us to consider a cascade process, up to the stage of loss of controllability, as a sequence of dependent steady-state modes, objectively flowing from each other [4].

The tasks of the study led the authors to the need to formulate the following formulations characterizing the concept of EPS heterogeneity:

- EPS heterogeneity is defined as the coordinate-wise distribution of the algebraic sum of EPS parameters affecting the implementation of the cascade process over the corresponding N-dimensional surface of the formalized system.

- The heterogeneity of the EPS depends on the circuit-mode conditions at a particular moment in time and is determined by the asymmetric and heterogeneous distribution of the set of parameters characterizing the EPS elements according to the EPS circuit.

- The heterogeneity of the EPS determines the possibility of the occurrence and development of emergency cascade processes and depends on the magnitude and topological distribution of the EPS parameters according to the system diagram.

At first glance, it may seem that the concept of heterogeneity proposed above was formulated vaguely, but in reality this formulation offers a very specific one, incl. mathematical and 3D-graphic tools for the analysis of EPS heterogeneity [8, 9].

3 Creation of simulation models of test and real EPS

Based on the proposed concepts of the cascade process and the concepts of heterogeneity, simulation models of test and real EPS were created. In this work, the test scheme of an EPS (N nodes) is understood as a scheme that, as a result of a number of mathematical studies, reveals the regularities of the influence of the arrangement of elements according to the EPS topology on the possibility of cascade processes. The mathematical apparatus used to create simulation models is described in detail in [8, 9], so the reader can refer to the above links for details.

The EPS model for studying heterogeneity, as well as the occurrence and development of cascade processes can be divided according to the voltage scale. The first model (Fig. 2) has 25 nodes and $U_{nom} = 110 \text{ kV}$, the second model (Fig. 3) characterizes approaches to backbone grids and has 36 nodes, 60 branches and $U_{nom} = 500 \text{ kV}$. The third model (Fig. 4), characterizes distribution grids with elements of distributed generation present in them, this model has 40 nodes and 67 branches $U_{nom} = 10 \text{ kV}, 35 \text{ kV}, 110 \text{ kV}$. The fourth model (Fig. 5) was created according to the developed methods [8-13] on the basis of a real EPS and describes the sequence of disconnection processes of grid elements during the development of a cascade, systemic accident that occurred on 2.07.2016 in the Republic of Bashkortostan (RB).

In the diagram shown in Fig. 2 (a) the scheme simulates a cascade process consisting of 7 steps by making changes to the distribution of parameters according to the scheme of an heterogeneous EPS. In fig. 2 (b) the value of the maximum permissible current $I_{p.c.}$ for the EPS element is represented by histograms with oblique shading. Histograms with vertical shading indicate the value of the current $I_{initial\ conditions}$ for the corresponding element before the disturbance that led to the cascade failure in the grid. The horizontal shading represents the histograms indicating the $I_{acting} + \Delta I$ values for the EPS elements. In this test model of the

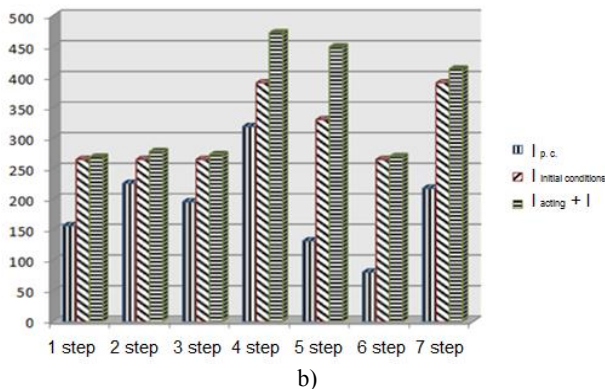
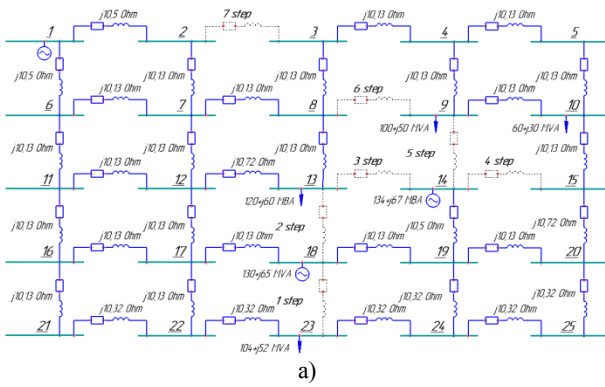


Fig. 2. Test twenty-five nodal EPS circuit ($U_{nom} = 110kV$), for studies of the influence of EPS heterogeneity on the possibility the occurrence and development of emergency cascade processes. Figure: 4 - Test 40-nodal EPS scheme with RG elements.

EPS, at time t_1 , a trigger disturbance occurred due to an increase in power consumption in node 23 from $52 + j26 MVA$ to $72 + j36 MVA$, which led to current overload of branch 18-23. In this case, the parameters of the branch 18-23 are represented by the brand of the AC-70/11 wire with the parameters: $R = 10.7 Ohm$, $X = 10.13 Ohm$, $B = -255 \cdot 10^{-6} S$. In the branch 18-23, the ratio of the flowing current to the maximum allowable current is 1.02, which indicates that the maximum allowable value has been exceeded and the overloaded element is disconnected in accordance with condition (1). This study is presented in more detail in [8].

In fig. 3 shows a test 36-nodal diagram of an integrated EPS (IES) in which the conditions for the flow of active power of 2868 MW between EPS 1 (left 3 columns of the grid diagram nodes) and EPS 2 (right 3 columns of the grid circuit nodes) are modeled. On this simulation model, studies were carried out to increase survivability by changing the power flows between power plants with cheap and expensive electricity generation costs, due to which the current unloading of branches close to the limiting values was carried out.

When calculating the cost of raising expensive generation, we use the following data [14]:

- electricity is considered cheap if it is produced at the rate of 310 grams of standard fuel per $1 kWh$, we take its cost of 3.9 rubles for $1 kW \cdot h$;
- electricity is considered expensive if it is produced at the rate of 650 grams of standard fuel per $1 kW \cdot h$, we take its cost as 5 rubles per $1 kW \cdot h$.

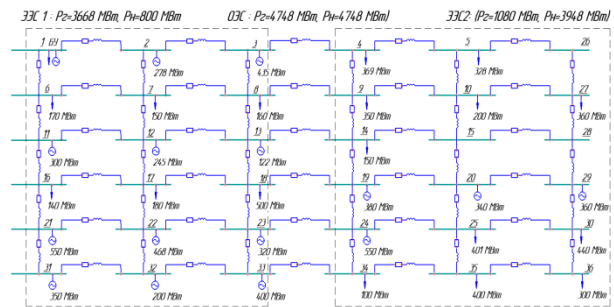


Fig. 3. Test thirty-six nodal diagram of the backbone grid on the united EPS ($U_{nom} = 500 kV$).

Also, using the example of this (Fig. 3) simulation model, a study was carried out to improve the survivability of the UPS by using devices related to flexible AC power transmission (FACTS), taking into account a 2-fold decrease in the reactance of one intersystem branch and a corresponding increase in the power flow between EPS 1 and EPS 2. Further calculations of a feasibility study were performed in accordance with [15], as a result of which a comparative justification of the cost indicators of FACTS devices, a standard solution for the construction of a new 500 kV line, and the possibility of changing flows by redistributing the load of generators at power plants with expensive and cheap generation electricity.

At the next stage of research, a 40 nodal EPS scheme was created with $U_{nom} = 10 kV, 35 kV, 110 kV$ (Fig. 4), which includes distribution grids (DGr), as well as elements of distributed generation (DGen), as a factor of a possible increase vitality.

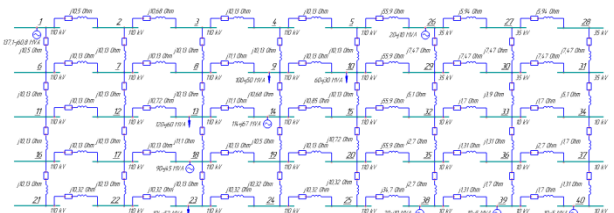


Fig. 4. Test forty nodal scheme of EPS with DG elements ($U_{nom} = 10 kV, 35 kV, 110 kV$).

In this model (Fig. 4), on the basis of studies (Fig. 2), a similar cascade process is modeled, consisting of emergency shutdowns of 7 elements of the EPS in accordance with condition (1). On the basis of this model, the cascade process was prevented by connecting power plants based on RG elements (Node (N) 38 - 20 MW, N 39 - 10 MW, N 40 - 10 MW, N 26 - 20 MW). This study shows the applicability of the proposed tools to DGr with elements of the DGen.

The task of the next simulation model (Fig. 5) was to demonstrate the application of the above proposed mathematical models and test circuits based on a real EPS, in which a cascade system accident occurred on July 2, 2020. In fig. 5 shows a 3D-graphic model of the surface of the heterogeneous distribution of the current parameter (I, A) in the elements of the EPS RB during the step-by-step development of a cascade accident, after disconnecting the 500 kV Buisakaya - Ufimskaya overhead line for 110 kV, 220 kV, 500 kV grid elements.

10. B. Gaisin, A method of making effective decisions to increase survivability in the design and development of power systems // Vestnik USATU, Electrical Engineering, **21**, No. 3 (77), 47-53 (2017).
11. I. Shahmaev, B. Gaisin, O. Shiryaev. A new method of taking management decisions at designing and developing electric power systems // 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 1-7, (2016).
12. F. Ismagilov, I. Shahmaev, B. Gaisin, The technique to improve the effectiveness of control systems in inhomogeneous electric power grids // International Siberian Conference on Control and Communications (SIBCON), 1-7 (2017).
13. I. Shakhmaev, B. Gaisin, Methods for identifying (recognizing) emergency cascade processes in electric power systems // Vestnik USATU, Electrical Engineering, **22**, No. 2 (80), 97-104, (2018).
14. Cost indicators of electricity generation // Open Joint Stock Company "Administrator of the Trading System of the Wholesale Electricity Market" [Electronic resource]. URL: <http://www.atsenergo.ru> (date of access: 09.10.2020).
15. Methodology for assessing the technical and economic efficiency of using FACTS devices in the UNEG of Russia. Moscow, 35 (2009).
16. Act No. 01 of investigation of the causes of the accident that occurred on 02.07.2016, Ufa, 88 (2016).