Modeling of the operation modes of the electric power system to improve its sustainability of functioning

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Abstract. The factors affecting the increase in the static and dynamic stability of electric power systems are investigated. The modeling of the operating modes of the complex-closed power supply circuit was carried out using the Dlgsilent PowerFactory software and computing system. The scheme of the electric power system with the optimal configuration and technical parameters, corresponding to the standards for ensuring the quality of electricity, was developed.

1. Introduction

The stability of the electric power system (EES) is understood to mean the ability to restore its original or almost close to it state after the occurrence and elimination of disturbances entailing deviation of the values of the operating parameters of the system from the initial values. The parallel operation of several generators of different power plants included in one power system implies the presence of communication through power lines (power lines) connecting these stations. Exiting the normal mode of operation of the system, which occurs during shutdowns, short circuits (short circuits), a sudden discharge or a jump in the load, can lead to a violation of stability, which is one of the most serious accidents that lead to blackout of consumers.

The rapid growth of energy is accompanied by an equally rapid modernization and commissioning of new power supply systems. Under the current program for the prospective development of the electric power industry of St. Petersburg for 2018-2022, it is planned to build 32 substations (substations) and 309 km of transmission lines, as well as modernize 65 substations and 308 km of transmission lines. By 2018-2020 alone, Lenenergo PJSC will build 16 substations and 104 km of power lines of 35-110 kV in St. Petersburg, as well as reconstruct 28 substations and 183 km of power lines of 35-110 kV [1]. Thus, the study of the stability of EPS and its increase is very important in modern conditions of development of technology and economics.

There are two types of stability - static and dynamic. A statically stable system is able to restore the original mode of operation when small fluctuations in the operating parameters of the system occur, for example, with a small increase or load shedding. Dynamic stability is the ability of the system to withstand and restore the original mode of operation after large fluctuations, for example, in case of accidents such as short-circuit, switching off part of generators, lines or transformers, turning on and off powerful consumers. After such sudden violations of the normal operating mode, a transient process occurs in the system, at the end of which a steady state emergency mode of operation should occur. Such disruptions in the operation of energy systems lead to large economic consequences for
the population and industrial facilities [2]. Modern energy pays special attention to the fight against accidents and takes them into account even at the design stage of electric power systems of cities and enterprises.

2. **Formulation of the problem**

After carrying out theoretical calculations of the future power supply system at the design stage, in order to analyze the effective functioning, various modes of operation, accidents and load pulsations should be simulated. For these purposes, there are several specialized software systems, one of which is DIgSilent PowerFactory [3].

As the initial scheme, the scheme of the EES section is accepted, containing generation, electric network and consumer substations (figure 1). This power supply circuit consists of: a power source with a 110 kV switchgear made according to the scheme of two working partitioned bus systems with a bypass; overhead power lines made by steel-aluminum wires with a suspension on reinforced concrete supports with two single-circuit lines, since consumers belong to the 1st category of reliability; nodal step-down distribution two-transformer substation with three-winding transformers of the TDTN-40000/110/35/6 type (UP G), which acts as a power source for the internal power supply network, consisting of three consumer substations, powered at a voltage of 35 kV radial (PS D) and trunk (SS A and B) schemes; transformer substation for one of the consumers, powered by an external power supply network (PS V); complex relay protection devices and automation [4, 5].

To ensure reliable power supply at each consumer substation, 2 transformers are installed taking into account redundancy. To carry out an automatic transfer of power to consumers in the event of an emergency shutdown of one of the power transformers or power lines, the power supply circuit provides for automatic protective equipment - devices for automatic input of reserve (ATS) and automatic re-enable (AR). With such connection schemes, the basic requirements for the reliability and safety of the operation of EPS are fulfilled [6].

![Figure 1. Schematic single-line electrical power supply circuit.](image-url)
3. **Modeling system operation modes**

The first step in modeling the circuit is to build it in a specialized PVC DlgSilent Power Factory. For this, an electric circuit is assembled in a new project and the parameters of all selected equipment are set (figure 2).

From the PowerFactory PVC database, the necessary types of elements of the electric power system are selected. First, power buses are installed, and then communication lines - power lines and transformers, the load of consumers. Next, the parameters of each element are set in accordance with the type of equipment in the circuit of the investigated EPS. DlgSilent PowerFactory PVC contains its own base of standard elements of electrical equipment. In case there is no necessary element in this database, it is possible to manually set its parameters and add to the database.

As a result of modeling the initial circuit of the electric network, a single-line electric circuit was compiled (figure 3). Using the built-in database, the parameters of the main power electrical equipment and power lines are set. The steady state calculation is made and the main operating parameters are obtained. The following data is displayed in the information window on the power buses:

- actual voltage, kV;
- actual voltage, p.u.;
- power factor cosφ.

![Figure 2. The design scheme of the EPS in the software package DlgSilent PowerFactory.](image)

In the information window on the power lines, transformers and on the consumer connection buses, the following data is displayed:
As a result of the steady-state simulation, operational parameters were obtained at each of the sections of the power system. Define the voltage deviation on the low voltage side of the transformer substation A from the desired one in the maximum load mode:

- the desired voltage on the tires of consumers in maximum load mode
  \[ U_{n.z} = 1.05U_N = 1.05 \times 10 = 10.5 \text{ kV}; \]

- voltage deviation
  \[ \delta U = \left| (U_{N.fact.} - U_{n.z}) \cdot U_{n.z}^{-1} \right| \cdot 100 = \left| (10.8 - 10.5) \cdot 10.5^{-1} \right| \cdot 100 = 2.85\% \]

**Figure 3.** The design scheme of the EPS with the results of the calculation of the steady state.

The permissible voltage deviation is established with a certain degree of accuracy, based on the normalized values of the voltage loss on the tires of power consumers. For a mains voltage of 6-35 kV - from 6 to 8% in normal mode and from 10 to 12% in post-emergency mode. These values are selected in such a way that, with proper regulation of the voltage in the network, the requirements [5] with respect to voltage deviations on the tires of power receivers are observed. The results obtained confirm the correctness of the designed power supply circuit of substation A and the energy efficiency of the electric network.

The study of the stability of power systems includes an analysis of the conditions in the conditions before and after sudden changes in load or generation, during damage and planned outages. The stability of the power system is determined by its ability to maintain stable operation under normal conditions, as well as when disturbances occur. According to the three possible time ranges, transients in power systems can be classified as follows:

- short-term or electromagnetic PP;
- medium-duration or electromechanical PP;
- long-term PP.
Transients, stability issues, and mode control tasks are important in the planning, design, and operation of modern power systems. Studies that examine electromagnetic transients and various aspects of stability can be performed in PowerFactory using dynamic modeling for different time periods or using tools for analyzing static and dynamic stability [7].

In the process of studying the emergency operation of the EPS, the short circuit currents were calculated on the load connection buses. Modeling was carried out according to (figure 4). The trip time was set to 0.1 s, and the short-circuit time was 1 s. As a result, maximum short-circuit currents and capacities were obtained in each section of the design scheme (figure 4).

During the simulation, it was revealed that the PS transformers are loaded from 46 to 70%, which means that it is possible to connect new consumers to some of them - the development of the electric network. According to the results of the calculation of the internal power supply system, it was revealed that the transformers at substation B were 90% loaded, and the load voltage B was too low. In this case, it is necessary to replace the transformer TMN-6300/110/10 with a transformer of higher power TDN-10000/110/10.

![Figure 4. The design scheme of the EPS with the results of the calculation of short circuit currents.](image)

Subsequent modeling showed a 54% load on the new transformer, which meets the requirements of [5] and falls within the permissible load limits of transformers. However, in this case, the calculations showed that the voltage on the low voltage buses of the PS V is 9.1 kV. Thus, the deviation from the rated voltage of the network exceeds the permissible value, therefore, the desired voltage level on the load buses is not provided. For this, it is necessary to adjust the voltage of the power source and simulate the operation of transformers on the substation by connecting on-load tap-changers.

Based on the simulation results, it is clear that the supply generator is 82% loaded, and to maintain static stability, the load should not exceed 80%. Thus, to increase the static stability, an additional
power source should be added. Another effective way to solve the problem of ensuring the stability of EPS is the introduction of automatic regulation and control systems. The creation of effective automatic control systems gives a significant economic effect and is equivalent to the introduction of additional capacities and the use of additional material resources. Alternative options for ensuring static stability, namely: limiting the operating and post-emergency modes of the system, or the use of capital-intensive measures to increase the transmission capacity of power lines, are irrational, as they can significantly impair the efficiency of the system.

Currently, the main measure to ensure the static stability of EPS is the use of automatic excitation controllers (ARVs) at power plant generators [8]. To increase the maximum static stability of the transmitted capacities over long-distance power lines at power plant generators, automatic high-intensity excitation regulators (ARVs SD) are used, which respond not only to the deviation of the operating parameters, but also to the speed and acceleration of their change. To ensure the normal operation of the EPS, a balance of active capacities between generation and load should be maintained. The appearance of a disturbance in the form of an imbalance of active power leads to a frequency deviation, which leads to a deterioration in the technical and economic performance indicators of EPS. The following causes of the appearance and manifestation of imbalances of active power are distinguished:

- turning on or off powerful consumers, separation of EPS with a deficit or surplus;
- regular changes in load power with periods of 5-15 minutes or more;
- fluctuations in active power, the values of which do not exceed 2-5% of the total power, with periods of oscillation from tens of seconds to 5 minutes.

The imbalance of active power between generation and load leads to a change in frequency in the EES. To keep the frequency deviation within acceptable limits, primary frequency control (PR) is used. Its duration is about 30 seconds (figure 5), during which automatic turbine speed regulators (ARS) must be engaged, which change the power of the units in the EPS. The change in the active power of the PR is determined by changes in the capacities of the generators (values of the steepness coefficients of the static frequency characteristics of the turbines, which determine the participation of generators in the PR) and the load (due to the self-regulation effect).

To resume normal frequency and planned flows of active power between EPSs, secondary frequency regulation (SR) is used. Secondary regulation is carried out by changes in the generating capacities of regulatory power plants (operational or automatic using the automatic frequency control system and active power transfer (ARCM) [9]. The change in the power of an individual power plant in the automatic frequency and active power control loop is determined by its share ratio in BP. while the imbalance of active power is compensated by changes in the power of BP power plants, PR power plants return to the original load (figure 5, b). The duration of BP is from 30 seconds to 60 minutes (figure 5, a).

Tertiary frequency regulation (TR) is designed to provide specified primary and secondary reserves, update used secondary reserves of active power, as well as to promptly adjust the mode in order to optimize it.

Dynamic stability depends on the response time of the relay protection and on the response of the automatic reclosure. If the automatic reclosure is successful, normal operation will be restored. The shorter the response time of the circuit breakers, the greater the margin for dynamic stability:

\[ K_{z,ds} = \frac{S_{b,\text{max}}}{S_a} \cdot \frac{1}{t} \]

where \( S_{b,\text{max}} \) – maximum braking area;
\( S_a \) – acceleration area.
Figure 5. Interaction of types of frequency regulation: a) Timing diagram; b) Schedule of changes in active power over time depending on the type of regulation.

The shorter the response time, the smaller the acceleration area. These areas can be obtained by plotting the dependences of the angle of departure of the rotor on power (figure 6). The acceleration area is proportional to the area of the figure bounded by the straight line PT, straight line 1-2, straight line 3-4 and curve 2-3. The braking area is proportional to the second shaded area and is limited by straight lines 3-4, 5-6, PT and curves of angular characteristics I and III. The initial state of the system is characterized by point 1 in the angular characteristic I. If a fault occurs, for example, on a power line, the angular characteristic shifts to state II. There is a drop in power $\Delta P$ to point 2 due to a sharp drop in resistance and, as a result, a voltage drop in the nodes of the system. The mechanical power of the turbines becomes significantly greater than the electric and the angle of departure of the rotor $\delta$ begins to increase sharply.

Figure 6. Graphs of changes in the generator parameters over the transient decay time: a) Angular power characteristic; b) Curve of change of the angle of departure of the rotor.

Point 3 characterizes the automatic shutdown of a damaged power line on both sides of the relay protection devices. There is a movement to point 4, located on the angular characteristic III, which corresponds to the mode of operation of the network with one power line. During the change in the angle $\delta$ from $\delta_1$ to $\delta_3$, the rotors of the generators receive excess kinetic energy, which is proportional to the acceleration area. At point 4, the rotors begin to slow down, as the electrical energy exceeds the
mechanical. This inhibition will provoke an increase in the angle $\delta$ until all excess kinetic energy is converted into potential energy, which is proportional to the area of braking. The point at $\delta = 180$ is called the electric center of swing (ECC). At point 5, the automatic reclosure occurs and if it is successful, then the angular characteristic is transferred to curve I. In case of failure, to curve II. If the automatic reclosure is successful, then the increase in the angle $\delta$ will continue to point 7, where the magnitude of the acceleration area is equal to the braking area. However, the angle $\delta$ is still changing due to the superiority of the electric power of the turbines over the mechanical, but now in the direction of reduction. The process will be established at point 1 over time after several oscillations of the angle $\delta$ near the steady state values.

Consider the change in the stress angles on the PS buses as a result of modeling in PowerFactory (figure 7). As can be seen from the above dependences, one of the signs of the emergence of an emergency mode in the EPS, along with the presence of an ECC, is an abrupt change in the angle in the range from -180 to 180, which is observed on the SS V.

![Figure 7. Change of voltage angles on PS bus systems in PowerFactory.](image)

As a result of the research, a scheme of the electric power system was developed with the optimal configuration and technical parameters that meets the standards for ensuring the quality of electric power. Using the DIgSilent Power Factory PVC, an algorithm has been developed that allows with sufficient accuracy for practical purposes to simulate the processes occurring in the electric network in both transient and steady state modes. Based on the results of modeling various modes of operation of the EPS, the equipment necessary to ensure its efficient and uninterrupted operation was finally selected, and factors affecting the static and dynamic stability of the EPS were analyzed.

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