Non-stationary modes of electric networks

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Abstract. Ensuring energy efficiency and solving problems of energy saving of power supply systems is impossible without forecasting the state of energy sources and elements of the electric network. Distribution networks consist of a set of elements whose parameters follow stochastic regularities and collectively organize a nonlinear dynamic system with parameters that depend on and do not depend on the mode. Description of networks requires the involvement of higher mathematics in conjunction with modern hardware and software of computer technology. The article is devoted to modeling of non-stationary modes of operation of multi-node electric networks with a large number of degrees of freedom and a high order of differential equations describing the processes under study in the model under consideration. The influence of such factors on transients as abrupt changes in the load of consumers, disconnection-connection of one of the voltage sources, short circuits on the consumer side, stability of the oscillatory process is considered. On the example of a 6-node circuit with 3 alternating voltage sources and 6 consumers, the nature of changes in the generated electrical power of the sources is analyzed. The system of differential equations corresponding to the scheme under study is solved by numerical methods. The proposed approach allows us to evaluate the efficiency of the power supply network while maintaining the mode parameters and predict the possibility of undesirable overloads during short circuits and conditions for exceeding variables that determine the practical stability of the system.

1. Introduction
The modern energy market covers power supply systems that ensure the production, transmission and consumption of electric power and requires flexible integrated solutions to a number of complex problems. Constant growth of electricity consumption in conditions of limited global fuel resources requires optimization of processes at all levels of the energy market [1].

The nearest future of the energy complex is the development and implementation of new technologies based on digitalization [2], which cannot be implemented without an objective assessment of the state of power systems and a clear definition of operating parameters.

One of the key problems of power supply at the present time is dispatching the flows of transmitted power [3].

In branched power supply schemes that have a complex topology, an unfavorable combination of the required modes on the part of consumers can lead not only to overloads, but also to instability of the entire network [4].

Multi-purpose optimization of power losses in power supply systems is possible if a mathematical apparatus is developed that combines adaptive control algorithms [5] and methods of evolutionary calculations [6], which can be implemented in voltage and reactive power management [7].
Hardware for reactive power compensation is possible using thyristor compensators [8], SAPF compensators [9], and GRID systems [10].

Modeling of power supply systems is becoming increasingly important. There are three major problems that determine the quality of solving the problem of preliminary calculations of technical objects:

- description of objects: the number and location of elements of the power supply system, their characteristics, topology and connection parameters [11];
- operating conditions of the power system, the nature and intensity of the load, the presence of random factors [12, 13];
- mathematical methods [14], hardware and software, and computer system resources.

A promising direction is the use of Micro-Grid systems that solve the problems of mode management based on monitoring the parameters of the state of the electric network using renewable energy sources [15], modeling is carried out on the basis of MATLAB SIMULINK [16].

2. Materials and Methods
A 6-node circuit with 3 AC voltage sources and 6 electric power consumers is studied (Figure 1).

![Figure 1. Diagram of the simulated power supply network.](image)

The following assumptions were made when drawing up the calculation model:

- AC voltage sources generate a common-mode sinusoidal voltage.
- Network branches connecting nodes, sources, and consumers are represented as active-inductive load R-L.
- The branch of the electric power consumer is represented as a step-down transformer with a transformation coefficient K, feeding the active-inductive load R-L and the capacitive load C (Figure 2).
- Magnetic hysteresis, mutual influence of windings, and transformer current leakage are not taken into account.

The presented electrical network diagram is considered as a linear dynamic model consisting of 21 1-order differential equations in concentrated parameters.

The research method is numerical integration of a system of differential equations taking into account time – varying parameters of the simulated system.
The system of equations is reduced to a typical Cauchy form with the derivations of the unknowns highlighted on the left side. The system of equations is represented in matrix form for using subroutines of the mathematical package. Standard functions of the mathematical package implement numerical algorithms for solving differential equations (4-order Runge-Kutta method with automatic selection of the integration step).

The following possible changes in the state of the network under study are simulated:

- disconnection-connection of one of the AC voltage sources,
- an abrupt change in the load of the consumer,
- short circuits on the consumer side,
- stability of the oscillatory process depending on the combination of network parameters.

The analysis is based on the resulting calculations of oscillograms of changes in the strength of currents, voltages, and electrical capacities.

3. Results

Simulation of disconnection-connection to the network of one of the AC voltage sources showed a significant impact on the nature of the transition process of its phase matching.

As an example, the transition process was calculated when the 3rd source was disconnected from the network at a time of 0.0505 s (corresponds to the mark 252 of the abscissa axis of the waveform in Figure 3) and connected to the network at a time of 0.1075 s (mark 537 of the waveform in Figure 3).

Disconnection-connection of the 3rd source caused a corresponding change in the load on the remaining sources, and the connection was accompanied by a power jump caused by a phase mismatch between the connected source and the network. By adjusting the oscillation phase of the 3rd source, you can eliminate an undesirable jump in the power generated by it.

Modeling of the effect of changes in a load of consumers was carried out with a jump change in the load resistance (coefficient of change of 0.02) for a certain period of time, after which the load value was abruptly restored.

So, when the load of the consumer R12 changes, the power waveforms from the network sources (Figure 4) showed that the main load falls on the 3 voltage source closest to the consumer.
The current waveforms (figure 5) in the branches connecting the consumer to the network confirm the above – the current jump takes place in the RL11 branch. Differences in current values are caused by the influence of the transformer.

The study of the effect of short circuits on the network was carried out on the example of a consumer circuit closure.

Short circuits were modeled by an abrupt change in the resistance of the selected consumer (coefficient of change of 0.0002) at a given time. After a certain period of time, the consumer's resistance was restored.

As an example, the reaction of power supply sources to a short circuit of the consumer R12 is shown in figure 6. The main load falls on 3 voltage sources, as the closest to the place of the short circuit.
A comparison of the current waveforms (figure 7) in the RL11 and RL12 branches shows the softening effect of the transformer located between the power lines and the RL12 consumer.

![Figure 7. Waveforms of the current strength in the RL11 and RL12 branches when R12 is short-circuited.](image)

Issues of ensuring the stability of the power supply network appeared when trying to model when the voltage level increases. Thus, an increase in the voltage from 6 kV to 10 kV showed an increase in current fluctuations in the connecting branches between the nodes (figure 8).

![Figure 8. Waveforms of the current in the RL11 branch at a voltage of 10 kV and 6 kV.](image)

4. Discussion
Modeling of power supply networks from the perspective of calculating transients makes it possible to predict the dynamics of the system behavior under random influences, which can include the current load change, short circuits, and disconnection-connection of sources. Of particular interest is to obtain load characteristics of sources that can be used to predict the consumption of fuel resources required for generating electricity. Issues of dispatching electricity flows, as well as related economic calculations, can be partially solved at the level of designing power supply systems.

Taking into account the possibility of short circuits in the power supply system provides a justification for choosing protective equipment that ensures reliable operation of the entire system as a whole.

Changing the load in electric networks can lead to undesirable power overflows, which increases the financial costs of consumers. By the nature of the power transmitted in electric networks, it is possible to judge the operating mode of electrical equipment, and in case of its overload, to initiate measures to improve its reliability and durability.

Simulation of transients by numerical methods requires appropriate hardware and software and qualification of calculators. Consideration of multi-node power supply schemes with a number of nodes in several tens leads to the consideration of high-order calculation matrices that can be formed only by formal methods. As presented in the article example, the formation of the design matrix was conducted manually, without formal methods (matrix, topological relations, etc.). The number of nodes and links of the considered example (sparse matrix) allows using the interface of the mathematical package that allows you to directly control the process of generating payroll results (Figure 9).
Ensuring the stability of a dynamic system requires separate consideration involving methods of automatic control theory and automatic control theory. A simple calculation of the transition process gives a direct answer to the question – whether the system is stable under these parameters or not.

![Figure 9. Example of the calculation matrix of the considered electrical network scheme.](image)

It is of interest to consider the influence of nonlinearities introduced by transformers on the mode of electric networks, as well as unbalanced load modes in the case of three-phase electric circuits. Issues related to the input-output interface of mathematical packages, which determine the complexity of solving the problem at the preparation stage, are of particular importance.

5. Conclusion
Modeling of non-stationary modes of multi-node electric networks based on solving systems of differential equations makes it possible to take into account the entire set of specific features of the functioning of electric networks. The proposed approach makes it possible to predict the state of the electric network with a changing number of sources and a variable load of consumers, which makes it possible to avoid possible overloads of electric energy sources.
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