RELIABILITY ASSESSMENT MODEL OF ELECTRIC POWER SYSTEMS IN LONG-TERM OPERATION PLANNING

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ABSTRACT

The paper presents a conceptual statement of the problem of determining the reliability indices of electric power systems of random configuration, mathematical formulation of the problem, and problem-solving methods. The authors provide the reference data on the computer program developed for solving the given problem and recommend possible application areas for the program.

References: 9 sources.
Keywords: reliability, electric power industry, individual reliability characteristics, indices, models, probability, factors.

1. INTRODUCTION

One of the indices of effective development and operation control for the electric power system is the reliability. Specialists from different countries continue the development of methods and tools for analysis and support of reliability at all levels of territorial and temporal control.

In the process of its operation the electric power system, as any other technical system, experiences various disturbances: internal disturbances conditioned by failures of components, mistakes made by the operating personnel, etc.; and external ones caused by changes in the level of demand, conditions of resource supply to the system, influence of the environment [0]. The consequences of the indicated disturbances can be represented by the interruptions to power supply to consumers.

These consequences are partially or fully compensated for by enhancing the equipment reliability; creating the redundant production capacities, transfer capability margins of transmission lines and resource reserves; as well as improving the control systems; and organizing the operation process more effectively, etc.

Modern electric power system reliability theory based on the postulates of the general reliability theory has some specific differences determined by the characteristics of expansion and operation control of the electric power system that are not inherent in other technical systems. First of all, electric power industry has to deal with large systems spread over vast territories; therefore, one of the important technological constituents is the electricity transport. Secondly, the physical nature of electric power system components is quite specific and diverse (a variety of power equipment, types of power plants, transmission lines, etc.). Thirdly, the structure of energy production, conversion, transportation, distribution and consumption is such that the reliability assessment requires the special operability criteria and particular reliability and efficiency indices to be introduced. This, in turn, needs the development of special mathematical models and methods of study.

The electric power system reliability is characterized by a number of so called "individual" properties: failure-free operation, longevity, maintainability (restorability), stabilability, survivability, controllability, and storability [2]. The assessment of these properties within one model is still impossible, that is why when constructing the computational electric power system models intended for the determination of indices describing certain individual reliability characteristics, the developers confine themselves to one or several most compatible individual characteristics.

Below we present our calculation model that assesses the reliability in terms of failure-free operation and restorability of large complex electric power systems represented by any (radial, ring) multi-node calculation scheme with constrained transfer capabilities of ties among the nodes. Each node of the scheme is a concentrated subsystem, which, in the general case, is represented by the generation unit commitment and the total load and electricity consumption. The problem is solved for national, integrated regional and local electric power systems. The reliability indices determined using this model consider the rest of the individual properties to the extent to which they are reflected in the indices of failure-free operation and maintainability of the system equipment (components) that represent the input data in this model. In fact, this model is a model for assessing the reliability of power supply to consumers as a set of electric power system reliability properties that determine the output performance of the system.

In the market environment with a large number of energy market participants modern electric power systems are characterized by an increase in generating capacities, improvement in their structure, and development of backbone and interstate electric ties due to the construction of super high-voltage transmission lines. This makes it possible not only to satisfy the needs of local consumers, but also to enter the wholesale electricity and capacity markets. Therefore, when solving the problem of electric power system reliability assessment, we should take into account the market conditions and introduce technical and economic indices to the problem statement. It is known that the electricity and capacity markets require extra investment in reserves due to greater uncertainty of development as compared to the planned economy. Additional redundancy is also necessary for the competitiveness among energy companies and for extra profit. Elevated redundancy can be connected to legislative and contractual obligations of energy companies to provide reliable power supply to consumers. The reliability model should consider different types of mutual aid of power companies, depending on their contractual relations.

The current stage of development of electric power systems is also characterized by a more intensive integration of large systems for their simultaneous operation within the Unified Power System of Russia and creation of interstate and even intercontinental interconnections. The integration of electric power systems requires a feasibility study, which should take into consideration the system effects closely connected to reliability.

The reliability models should take into account the extent to which the electric power system is provided with resources of different kinds: financial, human, physical. It is especially important to provide power plants with primary energy resources (fuel at thermal power plants and water at hydro power plants). In the planned economy fuel was first of all supplied to power plants, whereas under the market conditions the fuel transportation costs can be overestimated, fuel supplies can fail due to crisis phenomena in the society and the economy, etc. Moreover, it is very difficult to select a strategy and tactics of energy resource consumption, which should be reflected in the algorithm of the model. This is conditioned by the fact that there are no clear principles (except certain cases), and there is a wide variety of strategies and tactics in practice. Here we have to take into account a substantial number of different characteristics of the electric power system operation. This variety is explained not only by objective reasons (for instance, actual share of hydro power plants in the system, great uncertainty of forecasting the subsequent operating conditions of the electric power system), but by subjective factors as well (values pursued by the management of energy companies and rules of regional energy commissions, instant benefits and ways to limit the consumers: frequency and voltage decrease, "special" constraints, rolling (rotating) blackouts, etc.).

It is known that under the conditions of market and competition any economic activity is associated with risks due to impossibility of accurately predicting and considering the conditions under which the planned activity is going to be carried out. In the electric power industry, with the transition to the market economy the economic (commercial) risk has started to dominate the technological risk of failure to perform the main functions related to the equipment failures.

Therefore, it is crucial to find the means and ways to neutralize or reduce the negative consequences of the commercial risk. To prevent such consequences it is suggested to create an extra reserve in the electric power system (in addition to the technological one) conventionally called “commercial reserve” [3].

Let us present the problem statement and a method of solving the problem of reliability assessment of the central electric power system segment, i.e. the main structure, which, along with the distribution segment and schemes of power supply to certain plants of consumers, significantly determines the power supply reliability.

By the main structure we mean the unit commitment and parameters of generating equipment and the backbone network equipment of the electric power system. Thus, assessing the reliability of the main structure we do not take into consideration the reliability of the electric power system distribution network and the reliability of schemes for power supply to consumers (their reliability should be assessed by other software packages, but in terms of reliability of the main electric power system structure).

There are a lot of methods for assessing the reliability of the main electric power system structure (analytical, statistical, etc.) [4, 5]. The models are commonly constructed using different combinations of methods, each of which is applied to solving the subproblems. Combined models are the most suitable in terms of accuracy and calculation speed.

Let us present the statement of the electric power system reliability assessment problem. Its mathematical form is based on a variety of methods. We will consider the properties and specific features of the developed software package and the areas of its application.

2. CONCEPTUAL STATEMENT, INITIAL PROPOSITIONS, MAIN ASSUMPTIONS, SIMPLIFICATIONS, AND CALCULATION CONDITIONS

Solution to the problem is of an assessment character. It is necessary to determine the selected reliability indices for the specified variant of the main electric power system structure operation. The corresponding calculation scheme is considered as a set of load and generation nodes and ties among them. The components of the system are represented by the main electric power system equipment (generating units and transmission lines). Each node in such a scheme is “concentrated”, i.e. a network of transmission lines provides the power flows at the node under all possible operating conditions. The ties among the nodes of the calculation scheme represent a set of all transmission lines among the corresponding subsystems represented by the given nodes.

The problem of determining the reliability indices is formulated in the following way:

For the specified levels and structure of power consumption at the concentrated nodes (subsystems), configuration of backbone ties, unit commitment and parameters of electric power system equipment (generating units and backbone transmission lines), and the availability of different resources, determine the reliability indices of individual nodes and the entire system for the considered period and for the specified intervals of the period.

The developed model considers the most significant factors of the electric power system operation that influence its reliability. These are first of all failures, emergency and scheduled maintenance of the system equipment. The model also takes into account seasonal unevenness of random processes in the electric power system (for instance, equipment failure flows) and the changes in the unit commitment and parameters of equipment during the year; power consumption in the form of characteristic daily load curves in terms of time zone shifts for different areas of the electric power system; and random deviations of load and supply of primary energy resources. In the case of calculated failures the calculated states are optimized with respect to the strategy assumed for the limitation of consumers in individual subsystems and possible mutual assistance among the subsystems.

The reliability of complex electric power systems in terms of physical and technical characteristics is assessed in accordance with the following initial considerations. The adequacy of the electric power system viewed here as a degree to which consumers are supplied with electricity [2] is characterized by frequency, duration, and amount of possible power deficit in the system. In the determination of power supply reliability with respect to the buses of nodal substations feeding the load, the operating conditions of consumers are taken as an external factor specified by the corresponding equivalent load curves. In this case the states of the electric power system can be quite fully determined using the curves of electricity consumption, energy parameters of the main equipment, and its reliability indices. In the latter case it is necessary to take into account any downtimes of the main equipment (complete and partial), including the downtimes caused by unreliable operation of auxiliary equipment of the electric power system (auxiliary needs of the plants and substations; switching equipment; protection, automation, and control devices), as well as the downtimes caused by water deficit at hydro power plants or fuel deficit at thermal power plants.

According to the initial propositions, the general state of loads and the main equipment determines a set of the main possible states of the electric power system in space and time.

The electric power system operation model based on the indicated initial propositions is typified by the following specific features, assumptions, and simplifications.

1. By the system downtime we mean a transition of the electric power system [2] to any operating conditions characterized by power deficit. It is assumed that the automation and personnel made the deficit conditions feasible by rationally using all the possibilities of reducing the deficit and limiting the consumers by the minimum possible value.

Here we do not consider the operation failures of consumers in emergency transient processes, which can be severer than under the steady-state postemergency conditions, yet their duration is by several orders less than the duration of the postemergency conditions. Therefore, some underestimation of the power undersupply value can be considered as negligibly small compared to the power undersupply in the whole period of the system operation under postemergency (deficit) conditions.

With this assumption we take into consideration the system operating conditions sufficient for practical calculations, when some of the components are in a non-operating state. In this case it becomes much easier to make an analysis, since there is no need to assess many sudden emergencies and prepared disconnections, transient processes that correspond to them and conditions that ensure their optimality, duration, and scale of short-term emergency power dips, which depend on various factors.

2. Scheduled maintenance of generating equipment is modeled according to the standards provided it is definitely performed. Instead of the standards it is possible to specify a schedule of current and overhaul maintenance of the equipment. It is suggested that the scheduled maintenance of transmission lines either should not be considered or should be considered in the corresponding calculation intervals in combination with emergency maintenance (by increasing the relative duration of maintenance downtime).

3. Equipment failures in the model are not divided into sudden and predicted. It is considered that all types of reserves (spinning and standing) are used and the system failure is determined by a general or local excess of load of the whole generated power. It is assumed that the reserve available in the system is divided into spinning and standing in accordance with the ratio of sudden failures to predicted ones. In this case sudden failures are eliminated by the primary spinning reserve, and predicted failures with different lead time – by the spinning reserve of the following orders and the standing reserve until they are completely exhausted.

4. Power deficit (and therefore, power undersupply) is determined by the global or local

deficit of generating capacity. Such forms of deficit as frequency decrease in the system or voltage decrease in consumer buses are not analyzed.

5. In the developed model the specific of operating conditions of hydro power plants, pumped-storage power plants and thermal power plants are taken into account by specifying the initial data on these facilities (corresponding distribution functions of their states and probabilities of resource supply, including energy resources.

6. Maximum transfer capabilities of individual transmission lines are taken as constant and independent of the system operation, however different (if necessary) for each calculation interval. The total transfer capabilities of ties between the nodes are determined additively as the functions of transmission line states (operable and inoperable). However, it is possible to specify the relationship between the transfer capabilities of ties and the state of constituent transmission lines more accurately by the corresponding distribution functions.

7. To optimize the calculated states we apply the interior point method [6], and suggest using one of the four models [7] which provide the sought results on the basis of:

- the first Kirchhoff law,
- power losses in the networks,
-technical and economic characteristics of electricity production and transmission,
- functioning of the wholesale electricity and capacity markets, and – the specified strategies to limit consumers under the given bilateral constraints on the flows in transmission lines.

Let us enumerate the main features of these models for optimization of the calculated states:

1) a model which makes it possible to minimize power deficit in terms of only the first Kirchhoff law and distribute the total system power deficit among the nodes in proportion to their loads (estimation of system deficit only);

2) a model which provides unique distribution of the total power deficit among nodes in terms of power losses in ties between the nodes (also estimation of system deficit only);

3) a model which considers technical and economic indices of electricity production and transmission costs and provides the distribution of the total power deficit among nodes in terms of power losses in ties among the nodes (estimation of deficit and deficit-free states of the system);

4) a model which is analogous to the third model, but additionally considers the specific features of electric power system operation in the wholesale market environment.

Depending on the model used, we consider either the sets of post-emergency deficit conditions only or, in order to take into account fuel consumption and the impact of wholesale markets on the electric power system operation, all possible operating conditions (statistically, of course). The consideration of all the electric power system states (deficit and deficit-free) provides additional possibilities for the estimation of the load distribution functions in transmission lines. These distribution functions represent the data necessary for the reasonable selection of transfer capability of ties among the subsystems. In the course of optimization of the calculated states, the reliability can be studied in terms of different ways of mutual assistance among the power companies, depending on their contractual relations.

It has to be mentioned that practically all the operating conditions should be calculated for the case of the reliability analysis within the studies of electric power system survivability and energy security, since in this case major disturbances are considered (global fuel undersupply, low-water years, large-scale failures of plant capacities and large intersystem ties, etc.).

8. The developed model suggests using a simple principle effective from the viewpoint of the authors. The principle considers the constraints on all the resources, and first of all, the constraints on primary energy resources for different power plants (water in hydro power plant storages, fuel at thermal power plants). To this end, it is necessary to have reported or statistical data on the probabilities of certain supply of the resources. The multiplication of a generating capacity state distribution series of a power plant by a resource supply distribution series at the plant gives us the resultant series of operable plant capacities provided with resources. The use of these resultant

series for all the plants makes it possible to determine the probability distribution function of load supply, depending on the distribution functions of resources supplied and capacities available.

9. When choosing the type of backup generating capacity and electric energy we take into account that, on the one hand, each individual power company should have a certain minimum level of their own backup, and on the other hand, the total level of backup should exceed the one obtained in the calculations for technological reserves (reserve for current, overhaul, and medium maintenance, reserve for modernization and equipment reconstruction, and operating reserve).

The minimum level of technological backup is determined by the specified standard of power supply reliability for a power company in the case of its isolated operation. Such standards are known for the USA, for example ($\mathcal{P}$ not less than 0.9, where $\mathcal{P}$ – probability of deficit-free operation). There is no such a standard for Russia, nevertheless the model is adapted to the evaluation of the required power reserve level in each electric power system for its isolated operating conditions at a specified $\mathcal{P}$.

Here we present the most significant and specific assumptions and possibilities. The reliability theory has some other assumptions and propositions as well (for instance, equipment failure independence, disregard for different failure rates of operating and repaired equipment, etc.).

Required initial data***: the calculation scheme of the electric power system (equivalent subsystems and ties among them); probabilities of emergency downtimes of generating units or transmission lines; annual duration of overhaul and medium maintenance of the indicated electric power system components (standard); scope of current maintenance of the electric power system components during the year (standard); unit commitment and parameters of generating units for each node and each calculation interval during the year (the calculation period equals 1 year); transfer capabilities of ties between the nodes in both directions; characteristic daily load curves for each node, duration (number of working days) of the corresponding load periods, into which the interval is divided (for example, the load on working and non-working days); mean square deviation of loads from the projected curves; probabilities of the necessary resource supply to generating capacities; electricity rates, total and variable costs of production and transmission, if the calculated operating conditions are optimized using a corresponding model that considers the electricity markets. To optimize the calculated states of electric power system in terms of reliability with the model which takes into consideration the wholesale market conditions we need the data on specific discounted costs of the electric power system equipment at nodes and in ties and compensation costs (specific damages)*** $\mathbf{y}_0$ ***in case of power undersupply to consumers at nodes.***

In the formation of a calculation scheme of the electric power system, to determine reliability we should take into account the probability of random division of the system into subsystems (nodes). The scheme should be composed so that selecting the nodes we could detect the "weak" ties and take into consideration the territorial and organizational hierarchy of the electric power system.

The accuracy of the calculations depends on how fully and accurately the model considers the factors of the electric power system operation which influence its reliability. The software can provide almost any extent of factor consideration and accuracy of calculations within the accepted assumptions.

Sought information. As a result of the calculations we determine the following reliability indices in subsystems and in the whole system for each calculation interval (months, quarters) and for the year: probability of failure-free operation of the system (node) $\mathcal{P}$; mean value of power undersupply to consumers W^{und}; power availability ratio[1] π; damages caused by electricity

[1] Relative satisfaction of demand for electricity (the ratio of supply to demand)

undersupply D. The values of calculated technological reserves at nodes and in the entire system are: reserve for overhaul (medium) maintenance; reserve for current maintenance; operating reserve; total value of reserves of all types. The model calculates the distribution functions of power deficit and the energy reliability characteristics of the ties.

Here the energy reliability characteristic of the tie is the function of power flow distribution in the given tie under the electric power system operating conditions and with the specified equipment reliability characteristics. The indicated function determines the character of an interconnection between the two adjacent subsystems and the possible mutual assistance in terms of the rest of the system. The considered energy reliability characteristic is a quantitative reliability characteristic that determines the actual efficiency of using the corresponding tie in the given conditions. Therefore, the energy reliability characteristic can be applied in the mutual coordination of reliability calculations at different territorial levels of electric power system.

The dual (objectively reasonable) estimates of deficit of the main resources (generating capacity at nodes and transfer capabilities of ties) are also calculated to provide the reliability of power supply to consumers. The estimates characterize the “contribution” of the generating capacities of each node and the transfer capabilities of each tie to the electric power system reliability and allow the optimization of reliability under the scheduled operating conditions of the system. Apart from the reliability indices the software calculates their mean square deviations σW^{und} and $\sigma\pi$.

3. MATHEMATICAL STATEMENT OF THE PROBLEM

In accordance with the given statement of the problem we represent the calculation scheme of the electric power system as a connected graph, whose vertices (nodes) correspond to the equivalent calculation subsystems, and edges - to the transmission lines. The considered calculation period T_{p}, which usually equals one year, is divided into S intervals, where the given electricity consumption curves and unit commitment and parameters of the equipment are fixed. Let us determine the reliability indices in the following way:

for nodes $(m=\overline{1,M})$:

a) in interval $(s=\overline{1,S})$

- probability of failure-free operation

$$\mathcal{P}_{ms}=1-Q_{ms}=1-\frac{1}{\tau_s}\sum_{\varphi=1}^{\Phi_s}\sum_{\eta=1}^{L}\sum_{k=1}^{K_s}q^{\text{def}}_{m\varphi\eta k}\cdot\tau_\varphi\ ; \tag{1}$$

- average power undersupply to consumers (kWh)

$$W^{\text{und}}_{ms}=\sum_{\varphi=1}^{\Phi_s}\sum_{\eta=1}^{L}\sum_{k=1}^{K_s}P^{\text{def}}_{m\varphi\eta k}\cdot q^{\text{def}}_{m\varphi\eta k}\cdot\tau_\varphi\ ; \tag{2}$$

- power availability ratio

$$\pi_{ms}=1-W^{\text{und}}_{ms}/W_{ms}=1-W^{\text{und}}_{ms}/\sum_{\varphi=1}^{\Phi_s}P^{\text{L}}_{m\varphi}\cdot\tau_\varphi\ ; \tag{3}$$

b) period $T_{\text{p}}=\sum_{s=1}^{S}\tau_S$ has the same indices (averaged)

$$\mathcal{P}_m=1-Q_m=1-\frac{1}{T_{\text{p}}}\sum_{s=1}^{S}Q_{ms}\cdot\tau_S\ ; \tag{4}$$

$$W^{\text{und}}_m=\sum_{s=1}^{S}W^{\text{und}}_{ms}\ ; \tag{5}$$

$$\pi_m = 1 - W_m^{\text{und}} / W_m = 1 - W_m^{\text{und}} / \sum_{s=1}^{S} W_{ms} \; ; \tag{6}$$

for the system:

a) at each interval *s* indices $\mathcal{P}_{\text{c}s}$, $W_{\text{c}s}^{\text{und}}$ and $\pi_{\text{c}s}$ are calculated by analogy with (1)–(3);

b) for period T_p indices $\mathcal{P}_\text{c}$, W_c^{und} and π_c are calculated by analogy with (4)–(6).

To calculate the system indices we should determine the values $q_{\text{c}\varphi\eta k}^{\text{def}}, P_{\text{c}\varphi\eta k}^{\text{def}}, Q_{\text{c}s}$ and Q_c, analogous to the values $q_{m\varphi\eta k}^{\text{def}}, P_{m\varphi\eta k}^{\text{def}}, Q_{ms}$ and Q_m in (1)–(6).

In (1)–(6) $Q_{ms}, Q_m, Q_{\text{c}s}, Q_\text{c}$ are the relative probabilities of power supply interruption; $\tau_s = \sum_{\varphi=1}^{\Phi_s} \tau_\varphi$ – length of the interval *s*; φ, Φ_s – current number and quantity of calculation periods at interval *s*, which are determined by constant values of average load $P_{m\varphi}^{\text{L}}$ at all nodes (in terms of consumption for the system auxiliaries and losses in distribution networks); τ_φ – length of the φ-th subperiod in hours; η, H – current number and quantity of calculated random values of irregular load components; k, K_s – current number and quantity of random system states, determined by the k_{ms}-th random values of generating capacities at nodes and the k_{ns}-th random states of transmission lines in ties; $q_{m\varphi\eta k}^{\text{def}}, q_{\text{c}\varphi\eta k}^{\text{def}}$ – probabilities of power deficit $P_{m\varphi\eta k}^{\text{def}}$ and $P_{\text{c}\varphi\eta k}^{\text{def}}$ in the $\varphi\eta k$-th calculated conditions; W_{ms}, W_m, $W_{\text{c}s}$, W_c – required electricity outputs at the *m*-th node and in the entire system (c), at the *s*-th interval and in the calculation period T_p, respectively.

Probabilities of power deficit are determined as:

$$q_{m\varphi\eta k}^{\text{def}} = \begin{cases} q_{\varphi\eta} \cdot q_k, & if \;\; \Delta P_{m\varphi\eta k}^{\text{o}} > 0, \\ 0, & if \;\; \Delta P_{m\varphi\eta k}^{\text{o}} \le 0; \end{cases} \tag{7}$$

$$q_{\text{c}\varphi\eta k}^{\text{def}} = \begin{cases} q_{\varphi\eta} \cdot q_k, & if \;\; \Delta P_{\text{c}\varphi\eta k}^{\text{o}} > 0, \\ 0, & if \;\; \Delta P_{\text{c}\varphi\eta k}^{\text{o}} \le 0; \end{cases} \tag{8}$$

where $q_{\varphi\eta}$ – probability of the η-th random load deviation at nodes in the φ-th period; q_k – probability of the k-th state of the system equipment.

The optimal (minimized) value of load $\Delta P_{\text{c}\varphi\eta\kappa}^{\text{o}}$, which is not supplied throughout the entire system, is calculated by the corresponding values $\Delta P_{m\varphi\eta k}^{\text{o}}$ at each of *M* nodes:

$$\Delta P_{\text{c}\varphi\eta\kappa}^{\text{o}} = \sum_{m=1}^{M} \Delta P_{m\varphi\eta\kappa}^{\text{o}} \; ; \tag{9}$$

$$P_{m\varphi\eta k}^{\text{def}} = \begin{cases} \Delta P_{m\varphi\eta k}^{\text{o}}, & if \;\; \Delta P_{m\varphi\eta k}^{\text{o}} > 0, \\ 0, & if \;\; \Delta P_{m\varphi\eta k}^{\text{o}} \le 0; \end{cases} \tag{10}$$

$$P_{\text{c}\varphi\eta k}^{\text{def}} = \sum_{m=1}^{M} P_{m\varphi\eta k}^{\text{def}} \; . \tag{11}$$

The values required for the calculation of $\Delta P_{m\varphi\eta k}^{\text{o}}$ such as the values of the calculated random deviations of loads $P_{\text{rand}\varphi\eta_m}^{\text{L}}$ from their average values $P_{m\varphi}^{\text{L}}$ and generation $P_{k_{ms}}^{\text{G}}$ at nodes, as well as the values of transfer capabilities of ties $\overline{P}k_{ns}$, $\underline{P}k_{ns}$ $(n=\overline{1,N})$, where n, N – number of the tie and quantity of ties among the nodes in the calculation scheme, respectively) are determined using the corresponding distribution functions by the Monte-Carlo method.

The indicated distribution functions are specified or calculated on the basis of the given law of random load distribution, unit commitment and parameters of the equipment at nodes and in ties for each calculation interval s:

$$q_{\varphi\eta_m}(P^{\mathrm{L}}_{\mathrm{rand}\,\varphi\,\eta_m}) = F(P^{\mathrm{L}}_{m\varphi}, \sigma^{\mathrm{L}}_m), \qquad m=\overline{1,M}; \tag{12}$$

$$q_{k_{ms}}(P^{\mathrm{G}}_{k_{ms}}) = F(P^{\mathrm{G}}_{i_{ms}}, q_{i_{ms}} \,|\, i_{ms}=\overline{1,I_{ms}}), \quad m=\overline{1,M}; \tag{13}$$

$$q_{k_{ns}}(\underline{P}k_{ns}, \overline{P}k_{ns}) = F(\underline{P}_{i_{ns}}, \overline{P}_{i_{ns}}, q_{i_{ns}} \,|\, i_{ns}=\overline{1,I_{ns}}), \; n=\overline{1,N}, \tag{14}$$

where σ^{L}_m – mean-square deviation of load in per unit from values $P^{\mathrm{L}}_{m\varphi}$ (the distribution law is taken as normal); $P^{\mathrm{G}}_{k_{ms}} = P^{\mathrm{G}}_{\mathrm{av}\,ms} - P^{\mathrm{G}}_{\mathrm{em}\,k_{ms}}$ – the calculated k_{ms}-th value of the total generating capacity, which is not under the conditions of emergency downtime; $P^{\mathrm{G}}_{i_{ms}}$, $q_{i_{ms}}$ – available capacity and probability of the emergency downtime of the i_{ms}-th power unit; i_{ms}, I_{ms} – current number and quantity of power units (or calculated stages of the generating capacity); $\overline{P}_{i_{ns}}$, $\underline{P}_{i_{ns}}$ – limits of transfer capability of the i_{ns}-th transmission line in the directions assumed as positive and negative (direct and inverse), respectively; $q_{i_{ns}}$ – probability of downtime of the i_{ns}-th transmission line:

$$q_{i_{ns}} = \begin{cases} q_{\mathrm{em}\,i_{ns}} & \text{scheduled maintenance of transmission line is not considered;} \\ q_{\mathrm{em}\,i_{ns}} + q_{\mathrm{sch}\,i_{ns}} & \text{scheduled maintenance of transmission line is considered,} \end{cases}$$

where $q_{\mathrm{em}\,i_{ns}}$, $q_{\mathrm{sch}\,i_{ns}}$ – probabilities of outages of the i_{ns}-th transmission line in emergency and scheduled maintenance, respectively; i_{ns}, I_{ns} – current number and total quantity of transmission lines in the n-th tie in the s-th interval.

Optimal values of power deficit $P^{\mathrm{def}}_{m\varphi\eta k}(\Delta P^{\mathrm{o}}_{m\varphi\eta k})$ are determined by optimizing the calculated states of the electric power system, depending on the adopted strategy to constrain consumers, electricity market conditions, etc. [6, 7]. In the simplest case, when power deficit is distributed among nodes in proportion to the load power the function:

$$\sum_{m=1}^{M} C_m \Delta P^{\mathrm{L}}_{m\varphi\eta k} \Rightarrow \min, \tag{15}$$

where

$$\Delta P^{\mathrm{L}}_{m\varphi\eta k} = P^{\mathrm{L}}_{m\varphi} + \Delta P^{\mathrm{L}}_{\mathrm{rand}\,\varphi\,\eta_m} - \Delta P^{\mathrm{G}}_{m\varphi\eta k} > 0 \tag{16}$$

provided the following conditions and constraints are met in order to obtain physically and technically feasible solutions

$$P^{\mathrm{L}}_{m\varphi\eta k} - P^{\mathrm{G}}_{m\varphi\eta k} + \sum_{n=1}^{N_m} P_{n\varphi\eta k} = 0 \tag{17}$$

for $m=\overline{1,M}$; $\varphi=\overline{1,\Phi_s}$; $\eta=\overline{1,\mathrm{H}}$; $k=\overline{1,K_s}$; $s=\overline{1,S}$.

Here C_m – coefficients determining the significance of loads at nodes; $P^{\mathrm{L}}_{m\varphi\eta k}$, $\Delta P^{\mathrm{L}}_{m\varphi\eta k}$ –

values of supplied and unsupplied load, respectively; $P^{G}_{m\varphi\eta k}$ – value of the used generating capacity; $P_{n\varphi\eta k}$ – power flow in tie (here the positive direction is taken as the power flow from the given node to the neighboring ones; and the negative direction is represented by the power flow from the neighboring nodes to the given one); N_m – number of ties adjacent to the *m*-th node.

The components of balance equations (17) are determined as follows:

$$\begin{aligned} &0 \le P^{G}_{m\varphi\eta k} \le P^{G}_{\text{op}\,k_{ms}} \\ &0 \le P^{L}_{m\varphi\,\eta k} \le P^{L}_{m\varphi} + \Delta P^{L}_{\text{rand}\,\varphi\,\eta_m} \end{aligned}, \tag{18}$$

where

$$P^{G}_{\text{op}\,k_{ms}} = P^{G}_{k_{ms}} - P^{G}_{\text{sch}\,ms}, \qquad k_{ms} = \overline{1, K}_{ms}; \tag{19}$$

$$\underline{P}^{L}_{k_{ns}} \le P^{L}_{n\varphi\eta k} \le \overline{P}^{L}_{k_{ns}}, \qquad k_{ns} = \overline{1, K}_{ns}. \tag{20}$$

Here $\Delta P^{L}_{\text{rand}\;\varphi\,\eta_m}$ – from expression (16), $P^{G}_{\text{op}\,k_{ms}}$ – operating generating capacity; $P^{G}_{\text{sch}\;ms}$ – generating capacity under scheduled maintenance.

The available capacity at each node $P^{G}_{\text{av}\;ms}$ (for the calculation of $P^{G}_{k_{ms}}$) at each interval *s* is determined by the given initial data on the equipment:

$$P^{G}_{\text{av}\;ms} = \sum_{i_{ms}=1}^{I_{ms}} P^{G}_{i_{ms}}. \tag{21}$$

The scheduled maintenance of generating equipment $P^{G}_{\text{sch}\;ms}$ is taken into consideration in the following way[2]:

$$P^{G}_{\text{sch}\;ms} = P^{G}_{\text{cur}\;ms} + P^{G}_{\text{ov}\;ms}; \tag{22}$$

$$P^{G}_{\text{cur}\;ms} = \sum_{i_{ms}=1}^{I_{ms}} \overline{\alpha}_{\text{cur}\,i_{ms}} \cdot P^{G}_{i\;ms}; \tag{23}$$

$$P^{G}_{\text{ov}\;ms} = f_1(V_{\text{ov}\;m},\; F_{\text{dip}m}); \tag{24}$$

$$V_{\text{ov}\;m} = \Big(\sum_{i_m=1}^{I_m} \overline{\tau}_{ov\;i_m} \cdot P^{G}_{i_m}\Big)/k_{\text{dip}}; \tag{25}$$

$$F_{\text{dip}m} = f_2(P^{L}_{\max\;ms} \,/\, s = \overline{1, S}). \tag{26}$$

The current $P^{G}_{\text{cur}\;ms}$, and overhaul and medium $P^{G}_{\text{ov}\;ms}$ (22)–(26) maintenances are considered independently, using different techniques [8]. The common requirement for the consideration of these types of maintenance in the model is that the maintenance should definitely be carried out to the necessary degree.

In formulas (23)–(26):

$\overline{\alpha}_{\text{cur}\;i_{ms}}$ – norm (relative total duration) of scheduled current maintenance of the i_{ms}-th unit; $V_{\text{ov}m}$ – required “area” of overhaul maintenance of generating equipment at node (MW per day); $F_{\text{dip}m}$ –

[2] The software for this model realized Russian principles of scheduled equipment repairs.

dip area in the curve of the monthly node peak loads (MW per day); $\bar{\tau}_{\text{ov}i_m}$ – norm of scheduled overhaul and medium maintenance of the i_m-th unit (day/year); k_{dip} – coefficient of using the dip of the annual curve of monthly maximums for overhaul maintenance, in per units [8]; $P^{\text{L}}_{\max ms}$ – maximum load at the *m*-th node in the *s*-th interval.

The additional data obtained by solving the stated problem includes: probabilities of power deficit of different degrees (formulas (7), (8)); probabilities of power flows $P_{n\varphi\eta\kappa}$ (energy reliability characteristics) in ties, obtained while solving problem (15)–(20); dual estimates as a result of power deficit optimization in the electric power system.

Such data allow us to calculate mean square deviations of indices W^{und}, π; series of power deficit distribution among nodes and in the entire system for each *s*-th interval and for the whole calculation period T_{p}: $q^{\text{def}}_{ms}(P^{\text{def}}_{ms})$, $q^{\text{def}}_{m}(P^{\text{def}}_{m})$, $q^{\text{def}}_{\text{c}s}(P^{\text{def}}_{\text{c}s})$, $q^{\text{def}}_{\text{c}}(P^{\text{def}}_{\text{c}})$. These indices can change, depending on the duration of electric power system operation at different frequencies less than 50 Hz, if the coefficient of frequency-regulating effect of load is known: $\tau_f = F(f)$ for the entire system and its individual nodes at each *s*-th interval and within T_{p}. Also, using these data we can determine energy reliability characteristics of ties $q_{ns}(P_{ns})$, $q_n(P_n)$, and integral dual estimates for each node and tie.

The damage caused by power undersupply *D* at nodes and in the system for intervals *s* and for the whole calculation period are determined by multiplying the corresponding values of power undersupply W^{und}, calculated for the nodes and for the whole system, for individual calculation intervals and calculation period T_{p}, by the value of specific damage due to electricity undersupply d_0.

The extent to which power plants are provided with primary energy resources should be considered in the way described above in the paper (point 8 – specific features, assumptions and simplifications). If the corresponding kind of resource is not limited, the distribution series of the resource availability degenerates into the probability equal to 1. Using the obtained values $P^{\text{G}}_{m\varphi\eta k}$ and $q_{m\varphi\eta k}$ and knowing the specific consumption b_ν of the ν-th resource, we can estimate the required amount of the resource.

4. METHODS AND TECHNIQUES FOR SOLVING THE PROBLEM.

The problem of reliability assessment of a large scheme represents a complex "tree" of subproblems. By solving these subproblems we determine the values $q^{\text{def}}_{m\varphi\eta k}$ and $P^{\text{def}}_{m\varphi\eta k}$ as the basis for the calculation of the reliability indices.

The electric power system reliability indices are calculated using the following successive modules:

I. Module of the initial data preparation:

1. Input, analysis, and processing of the initial data.
2. Calculation of complex characteristics of the factors that determine the reliability of nodes and the whole system.

II. Probability module

3. Construction of load curves and the curves of scheduled maintenance of generating equipment for each node.
4. Calculation of distribution functions of the generating equipment states at each node.
5. Determination of possible states of electric ties in terms of the transmission line maintenance downtime.
6. Formation of a set of calculated states of generating equipment, transmission lines, and loads (in terms of random load variations) in the system.

III. Module of calculated state optimization:

7. Selection of an optimization model of calculated states
8. Optimization of a calculated state, including minimization of power deficit (determination of power deficit at nodes, economic indices, and flows in ties, and check of the resource availability).

IV. Module of calculation of reliability indices:

9. Calculation of energy reliability characteristics of ties at time intervals and within the calculation period T_{p}.
10. Calculation of reliability indices of nodes at time intervals and within the calculation period T_{p}.
11. Calculation of reliability indices of the system at time intervals and within the calculation period T_{p}.
12. Calculation of economic indices of the system at time intervals and within the calculation period T_{p} (depending on the chosen model in module III).
13. Processing of the calculation results.

Some subproblems are included in the general problem in the form of repeatedly used algorithms. For instance, stages 3–12 are calculated for all S intervals.

The different character of subproblems solved in the calculation of reliability indices explains the use of a variety of methods:

– method for calculating the distribution series of random states of components in the calculation scheme of a system on the basis of a generating function of the general replication theorem, and the addition and multiplication theorems of probabilities of different events;

– statistical testing method for the formation of the calculated system states;

– combinatorial methods of dividing the system states in terms of a given criterion;

– methods of linear and nonlinear programming for the optimization problem of calculated states in the electric power system (an interior point method [6]).

The problem is solved by the method of simulation modeling of electric power system operation during the calculation period. The states of loads and system equipment are played out by the Monte-Carlo method. The power distribution series of units at nodes and transmission lines in ties under emergency downtime conditions are calculated beforehand.

The advantages of the implemented algorithm over the analogous algorithms [4] are as follows:

1. The possibility of studying the systems of complex configuration with the ties of limited transfer capability.

2. The calculations do not require preliminary equivalenting of the unit commitment. This

reduces the efforts necessary for the initial data preparation and improves the accuracy of calculations, especially for the electric power system with numerous units of different types.

3. The reliability calculations can use both the given functions of equipment state distribution among nodes and ties and the functions calculated with the software on the basis of data on the reliability of certain system components.

4. The software allows the user to specify the initial data in different forms and with different accuracy. Apart from reliability indices and parameters of their dispersion, it is possible to calculate complex indices characterizing the specific properties and conditions of the electric power system operation that determine its reliability. The latter is especially important for the study of reliability properties of the electric power system.

5. The optimization of calculated states in terms of the operational strategy for the limitation of consumers makes it possible to obtain the indices of power supply reliability both for the entire system and for individual nodes.

6. The possibility of assessing the reliability indices within the whole calculation period and within individual intervals.

7. Energy reliability characteristics of the ties along with dual estimates at nodes and in ties make up the data for technical and economic analysis of the system performance.

8. The software consists of modules, which allows the user to easily change it in the course of improvement or modification.

5. REFERENCE DATA ON THE SOFTWARE AND ITS APPLICATION

The software package YANTAR is intended for the determination of reliability indices of the electric power system represented by a calculation scheme. The software is written in FORTRAN and operates in batch mode.

The software YANTAR can be considered a computational tool that implements a most complete model for the calculation of the selected reliability indices of electric power system. The solutions can be used for the engineering analysis and reliability optimization of the electric power system and constituent subsystems under the scheduled conditions of their operation.

The software can also be used as a standard for checking and correcting the applied and newly developed simplified models for considering the reliability factor when solving the control problems.

This software package can be used to solve the following problems:

- selection of all types of reserves of the electric power system generating capacity: reserves for scheduled (overhaul, medium, current) maintenance, operating reserve, commercial reserve;
- rational allocation of the chosen amount of total reserve across subsystems and power plants of the system in terms of transfer capabilities of the networks;
- calculation of power supply reliability by subsystem within the system (estimation of deficit-free operation probability, relative degree to which the consumers are provided with electricity, average annual value of electricity undersupply to consumers);
- power supply reliability assessment for a certain consumer in the given electric power system;
- assessment of the system-wide benefit in terms of the reliability factor in different variants on the expansion of the main electric power system structure (generation and network segments of the system, the resource supply segment);
- optimization of a commissioning period of new equipment in the electric power system in terms of the reliability factor.

Apart from the main factors, we can take into account the following aspects of the expansion and operation of the electric power system: the burn-in and aging of equipment (by correspondingly specifying the statistical values of equipment failure rate for certain calculation periods); special schemes of equipment operation (two-boiler single-turbine units, special connection schemes of transmission lines and influence of the inner electric power system ties on the transfer capabilities of intersystem lines); seasonal and other types of unit commitment and characteristics of the system components, including the reliability characteristics; time zone shifts for different nodes of the electric power system, etc.

The estimation of reliability indices for different variants of the electric power system operation in combination with the cost estimation makes it possible to select the best variant.

The comparative analysis of the electric power system reliability allows us not only to choose the best variant on the system expansion, but also to solve the second indicated problem. The latter is possible owing to the software-based calculation of nodal reliability indices both for the whole calculation period and for individual intervals. This makes it possible to assess the operating conditions at different nodes of the system and the nature of changes in their reliability in time. In the course of the analysis we identify the nodes of the system with insufficient power supply reliability and then, using the dual estimates and various engineering computations, improve the reliability of both specified nodes and the whole system, since the system reliability is conditioned by the reliability of its nodes.

In the last decade the software package YANTAR has been used to make a great number of reliability calculations for different schemes. These are the schemes of the Unified Power System of the USSR; Unified Power System of Russia; Integrated Power System of the East; interstate interconnections between the Electric Power Systems of the Far East of Russia and Japan; Integrated Power Systems of Siberia, North China and the East; Integrated Power Systems of the Far East of Russia, North Korea, and South Korea, etc. The reliability of the Unified Power System of Russia was studied in the course of construction of a 1150 kV transmission line in the territory of Russia, from the Integrated Power System of Siberia to the Ural Federal District. The survivability of the Unified Power System of Russia under the conditions of large-scale and long-term disturbances (gas undersupply, moratorium on nuclear power plants, isolated electric power system operation, low-water years for Russian rivers, etc.) was assessed. The performed calculations allowed us to consider the reliability factor when studying the schemes of electric power system expansion and operation [9 etc.].

6. CONCLUSIONS

1. The paper presents a conceptual problem statement and the main principles of constructing the algorithm and calculation procedures intended for the reliability assessment of modern complex electric power systems.
2. The research shows the differences between the developed software package YANTAR and other analogous software packages. Attention is given to the great practical experience in the application of this software to the calculations of the electric power system reliability of different levels in the analysis of various projects for the expansion of modern systems.
3. The YANTAR allows online synthesis of electric power system reliability, taking into account the technical and economic characteristics of the system equipment.

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