MODELS AND METHODS FOR ESTIMATION AND OPTIMIZATION OF ELECTRIC POWER SYSTEM RELIABILITY

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ABSTRACT

The paper presents the results of the review of methods and models of an estimation and optimization of electric power systems (EPS) reliability. There are classification and characteristic of existing probabilistic methods used for an estimation of EPS reliability in the paper. The methodology of model for an estimation of systems reliability of EPS is described. Theoretical bases of system reliability optimization of EPS are stated. The description of the software YANTAR for estimation of EPS systems reliability is given.

1. INTRODUCTION

Providing reliability of electric power system (EPS) is a complex multifaceted problem to be solved at different levels of territorial, temporal, and technological hierarchy of control. The reliability models are mainly intended to obtain the reliability indices that could be directly or indirectly applied to make decisions on ensuring reliability of the entire power system and its facilities. The problems of EPS reliability can be considered in terms of both estimation and optimization.

Reliability of power systems and their facilities is a complex property. It should be considered as a set of some single properties that are essential for a certain object. This makes the problem of analysis and synthesis of EPS reliability increasingly more complicated. It does not seem possible to create some unified model for solving all reliability problems, i.e.:

- at all stages of control (while forecasting, designing, making decisions on expansion, for long-term, short-term and current control of operation);
- at all territorial levels (from a piece of equipment to a unit, facility and system of various degree of integration: regional, national, etc.);
- for all production stages (primary energy resources, generation, transportation, conversion and distribution of electric energy), division of reliability problems by production stage is topical due to replacement of vertically integrated systems by partly horizontally integrated sectors of the industry as a result of emerging market relations in the electric power industry;
- for all individual properties (security, longevity, failure-free operation, maintainability, stabilability, survivability, controllability and storability).

Levels and stages of reliability problem solving may considerably vary in accuracy and completeness. Moreover, the models applied to solve one and the same problem may differ in completeness and accuracy in terms of initial data representation and solutions to be obtained. Thus, the decomposition of a unified universal model into a great number of models that solve partial problems of reliability is objectively conditioned. However, the need arises to coordinate solutions to the partial reliability problems.

The specific and unique nature of EPS in the majority of cases does not allow the use of mathematical models and algorithms intended for calculation of reliability indices that are suggested in the general theory of reliability. This theory is sufficiently well developed yet for a limited class of systems. These models can not completely reflect the technology particularities of electric power systems, the great number of functions to be performed by them, numerous purposes they are intended for, their multiple probable states and dominating number of partial failures. This is why special mathematical models are developed to estimate reliability of electric power system facilities.

The problem of power system reliability estimation is formulated and solved depending on:

- the research goal;
- the time constraints (on-line and for a long-term perspective);
- the assumed calculated scheme (the degree of equivalenting);
- the validity and forms of initial information representation;
- the nomenclature of reliability indices to be calculated;
- the requirements for accuracy of results to be obtained;
- the applied mathematical tools.

There are a lot of techniques and methods for calculating reliability of EPS and its facilities in the national and international practice [1-4]. Along with a great number of “nuances” that make them distinct they also have certain elements of commonality and similar principal approaches. The diversity of mathematical models and methods makes it useful to analyze their specific features and potential capabilities in order to reveal the areas of their primary application.

2. CHARACTERISTIC OF MODELS INTENDED TO ESTIMATE (SYNTHESIZE) RELIABILITY OF FACILITIES (SYSTEMS) IN ELECTRIC POWER INDUSTRY

For methodological purposes all the models that are intended to estimate (synthesize) reliability of the EPS facilities can be classified in terms of their application in accordance with the criteria presented in Table 1.

Solving the control problems of EPS and its facilities in terms of reliability, the reliability indices are calculated either within an individual (independent) problem or in the process of solving the main problem.

Individual models intended for reliability estimation (synthesis) that are applied when solving individual problems on EPS expansion and operation make it possible to limit ourselves to a rough preliminary consideration of reliability (i.e. apply indirect standards and rules for considering reliability factor) but with further mandatory analysis of obtained solutions in terms of reliability. Here the values of reliability indices are specified only for the best variants identified.

There can be another way of applying reliability models. The reliability optimization can be implemented as a software, in which an independent model can be represented by a submodule for reliability estimation of a variant of the considered EPS scheme. This certainly requires that the model should be satisfactorily fast, accurate and sufficiently complete. Such a model can be used within the software either in each iteration or at the final stage of formation of some variant.

Table 1. Classification of reliability models of power systems and their facilities

Type of model	Extent to which influencing factors are taken into account	Accuracy of considered factors representation	Speed of software applied	Purpose of model
Independent reliability model	Virtually completely	Most accurate representation	Low or average	Study of reliability properties of EPSs and their facilities, as well as properties of respective models
	Sufficiently completely	Sufficiently accurate	Average	Comparative analysis of reliability of variants of synthesis of facilities to be controlled ------------------------ Reliability optimization of EPSs and their facilities
Reliability model as part of optimization model for solving a specific control problem	Sufficiently completely	Approximate	Sufficiently high	Reliability estimation in the process of optimization calculation
	Insufficiently	Approximate, even rough	High	Approximated consideration for reliability in optimization model

Independent models are essential when **studying** reliability as a property of facilities and systems in the electric power industry. Along with comparative analysis of the variants these models can be used in two more aspects shown in Table 1. The studies conducted give an opportunity to formulate new problems in a more substantiated way.

3. CHARACTERISTIC OF THE MAIN METHODS APPLIED TO ESTIMATE RELIABILITY OF ELECTRIC POWER FACILITIES AND SYSTEMS (Table 2)

The methods underlying the models intended for estimation of reliability of power systems and their facilities are known in the general theory of reliability, but their application in this case is somewhat different.

The studies on reliability are characterized by application of a great number of various methods.

When solving any problem, including the problem of EPS reliability estimation, the preference for the method to be applied should be determined by the content of the problem solved. Here, in every case the objective is to obtain a sufficiently fast and convenient computational software that generates satisfactory results.

All the methods can be classified by several principal features. And first of all in terms of information support and the mathematical tool applied for estimation of reliability indices.

The following two **groups** of methods are suggested: the methods for experimental reliability estimation (group A), and the methods for reliability calculation and forecasting (group B) (Table 2, column 1).

Methods for experimental estimation of reliability (**group A**) are based on the study of results obtained during special tests (”tests for reliability”) that are carried out at facilities themselves or their physical analogues. Special tests are taken to mean the process of determining or checking reliability indices by experiment. The main objective of such tests is to create an information basis (i.e. to obtain more complete and reliable data on the facility as a physical reality, however, the representativeness of the data is limited). Experimental determination and check of reliability indices can be carried out at all stages of control: designing, manufacturing and operating, but not for all facilities. The database in question can be used for calculation methods intended for analysis and synthesis of reliability or for industrial control of the reliability level to be provided.

A special place in this group is occupied by the methods for studies to be conducted while carrying out the tests of physical-chemical and other causes of failures that require multi-purpose experiments under certain conditions.

Table 2. Classification of methods for determination of reliability indices of power systems and their facilities

Groups	Classes	Types			Primary application
A. Methods of experimental reliability estimation	I. Tests for reliability of a real facility	1. Long-term tests			Determination and check of EPS equipment reliability
		2. Accelerated tests			
B. Methods of calculation-based reliability determination	II. Methods that do not require modeling a facility by component	3. Retrospective methods			Short-term EPS operation scheduling
		4. Extrapolation methods			Prospective and long-term expansion planning of power systems and their facilities
		5. Expert methods			
	III. Methods based on modeling a studied facility by component	6. Deterministic methods	6.1. Methods of physical simulation		At all territorial levels temporal stages of control of EPS expansion and operation as a main or an auxiliary tool
			6.2. Criterion ***n–i***		
			6.3. Method of the worst case		
			6.4. Standardization		
		7. Probabilistic methods	7.1. Analytical methods based on representation of real stochastic phenomena by	a) random events	
				b) random processes	
			7.2. Statistical methods based on representation of real stochastic phenomena by	a) random events b) random processes	

Methods for reliability calculation (group B) are used to determine numerical characteristics of reliability of an object to be studied under known structure, operating conditions and reliability indices of its components.

The methods are divided into **classes** depending on the methodological principles and mathematical tools applied (Table 2, column 2):

I. *Tests for reliability* are subdivided into long-term and accelerated (Table 2, columns 2 and 3). The main principle of long-term tests is restoration of real conditions of facility operation. Accelerated tests are characterized by short-term facility operation under large loads with a view to receive the required information on reliability in the maximum possible short period of time (compared to the operating conditions).

II. *Methods that do not require a detailed* (by-component) modeling of the facility:

- The retrospective methods are based on generalization of the previous experience;
- The extrapolation methods are based on the analysis and forecasting of the existing trends;
- The expert methods are based on the knowledge, experience and intuition of experts.

These methods are used in forecasting to estimate numerical reliability indices of a facility under conditions of incomplete certainty of both quantitative reliability characteristics of components constituting the facility and conditions of its operation.

III. *Methods based on the by-component modeling* of an object to be studied. These methods are subdivided into the so called deterministic and probabilistic. The probabilistic methods include: **analytical** methods based on 1) functional relationships in the form of mathematical dependences, 2) analytical expressions of probabilistic processes, 3) complete or reduced search of potential states of an object, and "**statistical**" methods that are based on the Monte-Carlo method and pseudostatistical methods of LPι programming type, etc. On the other hand the probabilistic methods can be based on representation of stochastic phenomena by random events or random processes. This class also includes the methods of physical simulation that require mostly by-component representation of a complex facility.

Further we will present a short characteristic of the methods in terms of their types and areas of primary application (Table 2, columns 3 and 4).

Methods of group A (Table 2) are not widely used for well-known reasons (unique nature and other specific features of EPS). Special tests for reliability require either very long tests of a small number of components, or short tests of a rather large amount of equipment (facilities). For most of electric power facilities none of the foregoing is acceptable for economic reasons and for the reason of uniqueness of certain types of equipment (facility). According to the rules existing in the electric power industry development tests of facilities are carried out to reveal and eliminate design shortcomings rather than estimate reliability.

However, the method of long-term tests is applied in the electric power industry in the form of analysis of operation experience (statistical data) of real facilities (systems) and their equipment. For these reason EPS should have information systems and reliability services, besides, great and laborious work should be carried out to collect, process, store and use the data on reliability of electric power facilities.

Application of accelerated tests in electric power industry is limited by the level of simple equipment and individual nodes, and components of more complex equipment.

Methods of group B are preferred for use in the models for reliability estimation of power systems and their facilities because of their commonality, rigor and lesser dependence on subjective factors. These methods are used at all territorial and temporal levels as a main or an auxiliary tool.

The methods that do not require by-component modeling of an object to be studied are divided into the following types (Table 2, p.II (3,4,5):

II.3. The retrospective methods are calculation methods intended for reliability estimation. They are based on the analysis of previous operating experience of a facility and reasonable use of this experience to forecast the conditions of its expansion. In doing so most often the experimental planning method and regression analysis are applied.

These methods can be applied provided the properties and structure of an object are sufficiently stable over time, which is generally characteristic of power systems and their facilities. The primary application area of these methods is analysis of power systems or their individual components operation, which is aimed at prospective and long-term planning of their expansion.

II.4. The extrapolation methods are the methods intended for forecasting reliability. They are based on the analysis of change in reliability indices of the facility operation depending on change in its individual parameters or operating conditions. These methods are widely applied to forecast reliability of EPS equipment. They are also sometimes applied to estimate reliability of facilities, subsystems and entire systems. The methods suggest using representative statistical data that are collected over a long-term period of time or concern a large number of facilities. However, power systems as objects to be studied change over time in a very complex way, therefore there are problems with accuracy of the results obtained, particularly when reliability of EPS facilities is estimated for a remote future.

II.5 Application of the expert methods is sensible in the cases where the process of determining reliability can not be formalized or the data on the facility expansion are very much uncertain.

The methods based on the by-component modeling of an object to be studied are divided into two large classes: deterministic and probabilistic (Table 2, p.III 6,7).

III.6. The deterministic methods are the methods and criteria for analysis and synthesis of reliability of a facility (system) which do not suggest modeling the probabilistic characteristics of failures of the facility components but are rather intended for analysis of the facility capability to resist any disturbance from an a priori specified class, i.e. operation of the facility after such a disturbance should meet the required conditions and parameters. For power systems and their facilities these are admissible levels of voltage, frequency, equipment loading, shortage-free operation. We will dwell on some of the deterministic methods.

III.6.1. The methods of physical simulation can be applied for experimental estimation of reliability, particularly at a system level. However, this possibility so far has been used only for studying individual states or operating conditions of a system in deterministic form, for example when studying survivability. And it will hardly be widely used for probabilistic analysis due to complexity of such kind of experiments.

III.6.2. Reliability of a facility at failure of any i components (reliability by the **criterion (rule) n-i**) is the property of the facility to perform the main functions, when i = 1, 2, 3 … components out of ***n*** fail. Here loading of all components should lie within the admissible limits, and state variables should not go beyond the standard ranges, however, decrease in the efficiency of facility operation is as a rule allowed (increase in fuel consumption, power losses, etc.)

III.6.3. The "worst case" method suggests that a facility should perform its functions in the situation where mix and parameters of its components, taking into account operating conditions, have limiting values.

III.6.4. Standardization suggests that reliability factor is taken into account by applying the rules and reliability indices specified for structure and parameters of a facility.

III.7. The probabilistic methods are the methods and criteria that can be used to estimate how often and for how long a facility (system) will be unavailable due to failures of its components. This estimation should certainly include modeling of probabilistic processes in the system and probabilistic characteristics of failures of components. The probabilistic approaches are considered to provide more versatile, deep and accurate characteristics of facility reliability as compared to the deterministic methods, however they are more complex and labor intensive.

III.7.1. The analytical methods of reliability calculation employ as a rule the main principles of probability theory, combinatorial analysis, algebra, logics, queuing theory, etc.

The analytical methods, with available mathematical description of functional relationships between individual factors, allow one to solve any problem related to estimation of reliability in the electric power industry with a required accuracy. The absolute advantage of these methods over the other methods in practical application is diminished by the following factors: the absence of description of functional relationships or its awkwardness in some cases; "the curse of dimensionality" that makes it impossible sometimes to carry out computations even with modern computers within an acceptable time; difficulties, related to computation of some indices.

III.7.2. The statistical methods are the methods intended for calculation of reliability on the basis of statistical modeling, where the main processes of the facility operation, including stochastic ones are represented by a probabilistic model tested many times. These methods are in fact the methods of "mathematical test for reliability".

The statistical methods are used in the cases where there are obstacles to application of the analytical methods. In these methods the factors that determine EPS reliability are taken into account relatively easily and the constraints on the form of distribution laws of the considered events are not imposed. The required accuracy of the obtained results is sometimes achieved through a considerable increase in the number of experiments which decreases the merit of these methods. The research dealing with search of new techniques and methods of "playing" various states remains urgent.

The methods (analytical and statistical) that are based on representation of probabilistic phenomena in the form of *random events* are used in the reliability models more often than the methods based on the notion of random process. This is explained by the fact that many phenomena in EPS can be described at the level of random events, and the mathematical tools for random events are better developed and simpler.

Nevertheless, the reliability models employ the analytical and statistical methods that are based on representation of real stochastic phenomena *by random processes*, for example, the analytical methods based on combinatorial approach, the Markov and semi-Markov circuits, and the statistical methods based on statistical modeling. The methods based on the analysis of random processes in combination with statistical modeling on fast computers make it possible to obtain a more complete and sometimes more accurate information on reliability of a studied facility, which is necessary due to constant expansion and complication of power systems.

Classification of the methods could be continued at a lower hierarchical level. However, the practical value of this classification will not be high. At this level we would have to characterize a constantly expanding set of applied methods that differ in formalization of techniques intended for representation of operating conditions, structure of systems, characteristics of components, and simplifications and assumptions made.

For example, the following modifications of the analytical methods are observed:

- *the logic-and-probabilistic methods* (functions of the algebra of logic, table logic method, the "fault tree" method), in which the structure of facility and specific features of its operation are described by means of the algebra of logic and reliability is calculated with the help of probability theory. The table logic method is a partial case for the method of random events, based on making up tables or matrices of relations between operating conditions of a facility, failures of its components and failures of the entire facility;
- *the method of structural schemes (flowcharts)* employs the conditional graphical representation of system components and relations among them (a structural scheme). The reliability indices are calculated with the help of graph theory or by sequential equivalenting.
- *the phase-space method* studies a random operation process of a complex facility on the phase space, i.e. a set of states that differ in the mix of faultless and faulty components;
- *the Markov process method* (*the state-space method)* is a particular case of the phase-space method, in which the process of object operation is described by a system of differential equations for transitions of components from one state to another;
- *the network method (the method of minimum paths and cutsets)*;
- *the topological methods,*

etc.

The statistical methods include:

- *the functionally statistical method,* in which the system operation process is described by the probabilistic model tested on computer many times;
- *the logically statistical method,* in which the system structure and specific features of its operation are described by means of the Boolean algebra and reliability is calculated by statistical modeling;

etc.

The methods for reliability calculation also differ by whether or not they consider the equipment restorability, whether they consider only the time instants of *failure* occurrence or *failure states* of an object. Besides they differ by optimization methods of deficient conditions, etc.

Note that classification of the methods in Table 2 is formal and abstract in a sense. In practice one and the same model can combine different methods, each being applied to solve particular subproblems. Experience shows that such models prove to be most acceptable in terms of required accuracy and speed of calculations.

In recent past the described methods and models were applied only to study reliability in terms of failure-free operation and maintainability (restorability), however their use in the study of other single properties of reliability is becoming increasingly frequent.

When constructing corresponding models it should be remembered that the *single properties of reliability* that are important for EPS have different degrees of significance. Therefore, there should be a certain order in their studies.

This is not so important for operating systems and each property can be estimated (synthesized) separately. In designing, however, the order of providing single properties is essential. It is senseless, for example, to provide high survivability unless the required level of security, longevity, failure-free operation, maintainability and stabilability is provided.

It is known that:

- the single properties are interrelated and interdependent;
- the relative cost of ensuring a required level of certain single properties is different;
- with the single properties ranked in a proper order the cost of providing every subsequent

single property is lower if all previous properties are provided.

Hence, the rational sequence of single reliability properties of EPS should be as follows:

1. Security.
2. Longevity.
3. Failure-free operation.
4. Maintainability.
5. Stabilability.
6. Survivability.
7. Controllability.
8. Provision with resources.
9. Storability.

The temporal aspect of reliability is characterized by such notions as adequacy, security, current (switching) reliability, etc. The above described models and methods can also be applied to them, yet considering a specific character of the problem solved.

Reliability estimated on the basis of one or another model is "calculated" reliability that cannot exactly coincide with actual reliability of an object. It will only roughly correspond to it because of assumptions and simplifications made in the model. Therefore, from a set of models one should choose those which could have a status of "*normative models*". Application of such models in relevant calculations would make it possible to compare reliability of objects on a normative ("legal") basis.

4. THE MODEL FOR ESTIMATION OF FACILITY RELIABILITY

Generally, the model for estimation of facility reliability consists of three modules:

1. The module for probability estimation of the considered calculated object states.
2. The module for optimization of object operation in the calculated states determined in the first module.
3. The module for determination of reliability indices of an object by the data obtained in the first two modules.

All the above methods are applicable in the first module intended for solution of the reliability estimation problem.

In the module for optimization of operation (**module 2**) under liberalization of market in the electric power industry along with technical requirements it is necessary to take into account the contract obligations to be fulfilled by different production stages of the system (production, transmission, distribution) while interacting with each other. Reliability estimation in the system should be oriented to the market and profit and hence the corresponding reliability indices should be determined. This module is central in the reliability estimation model. Greater requirements are placed on it in terms of complete consideration of the main factors, accuracy and high speed.

The third module of the model has no special complexities and is an ordinary solver using the calculation results obtained in the first two modules.

For the horizontally integrated system of EPS control the reliability estimation problem can be supplemented by estimation of contribution made by each production stage of EPS to the system reliability. Since the number of economic entities taking part in the market is great solving this problem will make it possible to determine the boundaries of their responsibility for reliability and adjust reliability of individual production stages of EPS to the required system reliability index. Among the production stages of particular interest are the stages of the main EPS structure, namely the stage of electricity generation and transmission (a network stage).

5. RELIABILITY OPTIMIZATION OF LARGE EPSs

Consider **reliability optimization of large EPSs** in greater detail. Large EPSs are the systems, whose calculated schemes consist of sets of power nodes connected by transmission lines with limited transfer capabilities. Power nodes are represented by concentrated subsystems with generalized load and generating facilities, and the internal network in them does not impede power transmission from power sources to load buses in all possible conditions. Large EPSs (in particular, UPS of Russia or even interstate interconnections) make it possible to achieve a certain economic effect due to mutual assistance (in comparison with their isolated operation). The mutual assistance is provided owing to creation of intersystem lines with sufficient transfer capability. Therefore, the optimal value of generation capacity in the interconnection and its distribution among EPSs are determined jointly with transfer capabilities of tie lines.

The computational model for optimization of a large EPS expansion variant in terms of reliability is intended to choose the main structure of EPS and includes both the optimization of generation capacities and transfer capabilities of tie lines, and the stage of EPS provision with primary energy resources. In the general case the constraints on all types of resources (material, manpower, financial) should be taken into account.

The model should envisage two criteria to consider reliability. These are 1) technical and economic minimization of discounted costs of backing up capacity, primary energy resources and networks with account taken of compensation for the probable economic loss because of unreliable electricity supply to consumers and 2) provision of a standard reliability level.

Technical and economic optimization of reliability must be based on the following principles.

The optimal reliability level of the multi-nodal EPS corresponds to the minimum total discounted costs:

$$C_{\Sigma} = C^{G} + C^{L} + C^{E} + LOSS \rightarrow min, \quad (4)$$

where

$C^{G} = \sum_{m=1}^{M} C_m^G \cdot R_m^G,\ C^{L} = \sum_{n=1}^{N} C_n^L \cdot R_n^L,\ C^{E} = \sum_{m=1}^{M} C_m^E \cdot R_m^E$ – costs of generation capacity reserve at all M system nodes, costs of reinforcement of transfer capabilities of all N system lines and costs of reserves of primary energy resources, respectively;

C_m^G, C_n^L, C_m^E – specific costs for generation capacity reserve of the m-th node, for reinforcement of transfer capability of the n-th line and for reserves of primary energy resources, respectively;

R_m^G, R_n^L, R_m^E –value of generation capacity reserve at the m-th node, additional transfer capability of the n-th line, reserves of primary energy resources, respectively;

$LOSS = \sum_{m=1}^{M} loss_{re} \cdot E_m^{un}(R_m^G, R_n^L, R_m^E) \quad m=\overline{1,M},\ n=\overline{1,N}$ – total costs of the entire system to compensate for the economic loss because of average annual electricity undersupply to consumers at all M nodes of a system;

$loss_{re}$ – specific value of the averaged loss due to interruptions in electricity supply to consumers of the m-th node;

E_m^{un} – mean value of electricity undersupply to consumers of the m-th node.

Conditions of the minimum of functional (4) in this case are represented by the equality to zero of partial derivatives with respect to reserves for individual nodes R_m^{G}, R_m^{E} and tie lines $R_n^{Л}$

$$\frac{\partial C_{\Sigma}}{\partial R_m^G}=\frac{\partial C^G}{\partial R_m^G}+\frac{\partial LOSS}{\partial R_m^G}=C_m^G+\frac{\partial LOSS}{\partial R_m^G}=0,\quad m=\overline{1,M};$$
$$\frac{\partial C_{\Sigma}}{\partial R_m^E}=\frac{\partial C^E}{\partial R_m^E}+\frac{\partial LOSS}{\partial R_m^E}=C_m^E+\frac{\partial LOSS}{\partial R_m^E}=0,\quad m=\overline{1,M}; \qquad (5)$$
$$\frac{\partial C_{\Sigma}}{\partial R_n^L}=\frac{\partial C^L}{\partial R_n^L}+\frac{\partial LOSS}{\partial R_n^L}=C_n^L+\frac{\partial LOSS}{\partial R_n^L}=0,\quad n=\overline{1,N}.$$

The aim of the calculations is to obtain the values R_m^G, R_m^E and R_n^L for all nodes and lines, that meet condition (5).

In the optimization calculations based on set (standard) reliability indices the optimality criterion looks as follows.

The optimal reliability level corresponds to the minimum costs

$$C_{\Sigma}=C^G+C^L+C^E\rightarrow min \qquad (6)$$

at $\Pi_m=\Pi_{stand\ m}$, $m=\overline{1,M}$ or $\Pi_m\rightarrow max$ $m=\overline{1,M}$ at constraints on resources when provision of $\Pi_m=\Pi_{stand\ m}$, $m=\overline{1,M}$ is impossible, i.e. when the problem of optimal distribution of limited resources is solved.

Here Π – calculated reliability index, $\Pi_{stand\ m}$ – standard value of this index.

As in the first case (estimation of loss due to electricity undersupply) in the second case (direct use of standard reliability index) the calculation of reliability indices is a submodule of the optimization model of EPS.

Along with special optimization programs that contain a module for reliability estimation the independent interactive models can be used for reliability estimation for optimization purposes. In some cases this produces a positive effect (the number of iterations decreases, the accuracy of reliability indices increases).

Nowadays the estimation models applied in optimization programs should satisfy the requirements presented below.

The *estimation model* for calculation of EPS reliability indices is recommended when the temporal or resources constraints are insufficient to completely provide economically sound standards of redundancy and the choice of measures to provide reliability is so limited that only several alternative variants can be formed by expert. In such cases the estimation model is applied to technical analysis of the variants. The analysis results in calculation and comparison of the obtained reliability indices with the standards. As a rule, preference is given to the variant with a higher reliability level and lower costs.

A specialized estimation model should calculate reliability characteristics of large EPS that can be represented by any calculated scheme, in particular a mutiloop one with limited transfer capabilities of tie lines connecting nodes. The model should calculate current and capital maintenances. Also the calculated operating conditions generated in the model should be optimized.

The results obtained with such a model should include:

a) reliability indices;

b) the values of calculated reserves of different types;

c) the values of maximum load of tie lines for mutual redundancy of EPS and the functions of load distribution for these tie lines;

d) the values of required primary energy resources (water for HPP and fuel for TPP);

e) the estimates of deficiency of basic resources (generation capacity and primary energy resources at nodes and transfer capabilities of tie lines) for ensuring reliability.

The information obtained should allow an expert to thoroughly analyze the calculated reliability as a property of the concrete EPS in the considered specific conditions and detect available "bottlenecks" in EPS in terms of reliability.

Since the estimation program makes it possible to consider all possible system states and operating conditions, the obtained characteristics of power flows by tie lines represent sufficiently full information about their loading and do not require specification by analysis of calculated long-term and maximum conditions, as is the case with simplified techniques.

Characteristic of the software YANTAR to be considered as an example of EPS modeling for reliability calculation is presented below [5].

6. THE SOFTWARE YANTAR

6.1 The software goal

The software *YANTAR* is intended for reliability estimation in terms of failure-free operation and maintainability (restorability) of large EPS of any (radial, looped) multinode calculated scheme with limited transfer capabilities of tie lines among nodes. The problem is solved for the conditions of long-term planning of operation and expansion at the levels of Unified, interconnected and local power systems.

In the interactive mode the software YANTAR optimizes the value and allocation of generation capacity reserves, transfer capabilities of tie lines and reserves of energy resources in terms of reliability factor.

6.2 Required initial data

- The calculated EPS scheme (equivalent nodes and tie lines among them);
- Characteristic daily load curves at each node referred to common time, duration of the corresponding calculated intervals;
- Mean square deviations of loads from regular hourly values;
- Monthly maximum load curves by node;
- Composition and parameters of generation units for each node and each calculated interval;
- Composition and parameters of transmission lines for each line in each calculated interval;
- Probabilities of emergency outages of generators and transmission lines;
- Standards for current maintenance of EPS components during a year;
- Standards for capital and medium maintenance of the EPS components during a year;
- Limitations on the use of primary energy resources (fuel for TPP and water for HPP);
- Specific discounted costs of EPS equipment by node and by tie line;
- Compensation costs due to electricity undersupply to consumers by node.

6.3 Calculation results

The reliability indices for nodes and the whole system for each considered interval and the whole year are:

- Probability of shortage-free operation;
- The coefficient of electricity provision for consumers;
- Mathematical expectation of electricity undersupply;
- Mathematical expectation of power shortage.

The values of calculated reserves of different types for nodes and the entire system are:

- Reserve intended for capital (medium) maintenance;
- Reserve intended for current maintenance;
- Reserve for updating;
- Operating reserve;
- The total volume of reserves of all types;

Results of the calculation also include;

- The values of additional transfer capabilities of tie lines to provide mutual redundancy of EPS;
- The functions of load distribution among tie lines during a year;
- The values of required primary energy resources.
- The dual (objectively conditioned) estimates of deficiency of main resources (generation capacities and energy resources at nodes and transfer capabilities of tie lines) to ensure reliability of electricity supply to consumers.

6.4 *Solution method*

The problem is solved by the simulation modeling of EPS operation for the considered period (year). The series of capacity distribution among generators at nodes and transmission lines in tie lines are calculated for their emergency outages. Binomial expression is applied as generating function. The state of loads and capacities of system facilities are obtained by the Monte Carlo method. The calculated operating conditions are optimized by the interior point method [6], where a principle of minimization and distribution of capacity shortage among nodes is used as a functional. The principle is chosen in accordance with specific features of the problem from the following four variants [7]:

- in proportion to loads at nodes;
- in terms of power losses in transmission lines and damages caused by power undersupply by node;
- in terms of electricity price in regional markets and its production cost;
- in terms of electricity price in the spot and wholesale markets.

The model also calculates capacities and mix of units under current and capital (medium) maintenance in each calculated interval by the known techniques.

The module for optimization of the calculated EPS state in which account is taken of the wholesale electricity market characteristics is described as an example.

The operation optimization problem can be formulated as follows:

For the known values of available generation capacity, specific costs of electricity generation, required levels of load supply and coefficients of load significance at nodes, specified transfer capabilities of tie lines and coefficients of power losses in them, as well as for the values of electricity tariffs for the internal market of each power node and external wholesale markets

determine the value of loading of generating facilities and the values of load covered at nodes according to the given optimality criterion in terms of constraints on the ranges of possible changes in generation capacity and loads at nodes, power flows over tie lines and power balances to be met at nodes in terms of power losses in the networks.

Mathematical formulation of the problem and a method suggested for its solution.

The calculated scheme of EPS is represented as a connected graph with M nodes (vertices) and N ties (arcs) among the nodes. Each node is characterized by the amount of required load $\overline{P}_m^l$ and the value of operable generation capacity $\overline{P}_m^g$, and each tie – by the transfer capabilities in the direct and reverse directions $\overline{P}_n$ and $\underline{P}_n$ respectively, and by the loss factor $K_{loss\,n}$.

Denote the covered load power at the m-th node by P_m^l, the generation capacity participating in load meeting by P_m^g, the flow along the n-th tie by P_n. The optimization problem functional of any (deficit and deficit-free) system condition is described by the following expression:

$$\max \sum_{m=1}^{M} (c_m P_m^g + c_e \sum_{n \in N_0} P_n + g_m \Delta P_m^g - d_m P_m^g - f \Delta P_m^g) \tag{1}$$

subject to:

$$\sum_{n=1}^{N} (a_{mn} P_n + b_{mn} k_{loss\,n} P_n^2) + P_m^l - P_m^g = 0$$

$$0 \le P_m^g \le \overline{P}_m^g \qquad m = \overline{1, M} \tag{2}$$

$$0 \le P_m^l \le \overline{P}_m^l$$

$$\underline{P}_n \le P_n \le \overline{P}_n, \qquad n = \overline{1, N}, \tag{3}$$

where $\Delta P_m^l = \overline{P}_m^l - P_m^l$ – power deficit at the m-th node;

$\Delta P_m^g = \overline{P}_m^g - P_m^g$ – excess of generation capacity at the m-th node;

a_{mn} – elements of the matrix A of ties.

b_{mn} – elements of the matrix B, such that

$$b_{mn} = \begin{cases} 1, & if \quad P_n < 0; \\ 0, & if \; a_{mn} \quad P_n \ge 0. \end{cases}$$

N_0 – set of ties, which are used by the m-th node to sell (buy) the electricity of the higher-level wholesale market as compared to the local (internal) market.

In functional (1) there are the following technical and economic coefficients:

c_m – price of electricity supplied to consumers at node m (Rub/kWh);

c_e – electricity price in the wholesale interregional market (Rub/kWh);

d_m – costs on production of 1 kWh of electricity at the corresponding node (Rub/kWh);

g_m – cost of fuel used for generation of 1 kWh of electricity (Rub/kWh);

f_m – specific loss, compensation costs or penalties due to electricity undersupply (Rub/kWh).

In functional (1) dimensionality is violated, as far as the costs per 1 kWh are multiplied by the capacity (kW), this being its specific feature. The time for existence of this condition that is common for all functional components is factorized and determined beyond the considered optimization block of the software package.

In general the optimal solution can be obtained for real relations between the functional coefficients $f_m > c_m$, $c_m > d_m$, $d_m > g_m$ in the majority of system nodes.

Based on the calculation of operating conditions that were made with the model we can obtain:

- Price of electricity supplied to consumers;
- Loss due to electricity undersupply;
- Electricity production costs;
    - Economic benefit for the entire system and for nodes;

- Commercial benefit (profit) for the entire system and for nodes (power companies).

The form of functional (1) may vary depending on conditions of the competitive market operation and a set of its players.

The results of the analysis of all calculated conditions are used to calculate reliability indices (p.3).

The software is developed in Windows OS in the Fortran programming language in batch mode. The maximum parameters of the calculated scheme are 100 nodes and 160 tie lines.

7. CONCLUSION

Objectively there should be a great number of reliability models. This is associated with a great number of control problems solved in terms of reliability at different territorial, temporal and production levels.

Vertically integrated systems focus on technical and economic aspects of control.

For the liberalized market environment the models should be supplemented by the methods for solving financial problems, the problems of competition among numerous independent market players, etc.

Thus, the need arises to solve the problem of coordination of reliability solutions for different levels and stages.

8. REFERENCES

1. G.F. Kovalev, P.A. Malkin (1981) Software for optimization and estimation of reliability when designing electric power systems. SEI SO AN SSSR, Russian Metodicheskie voprosy issledovaniya nadezhnosti bolshikh sistem energetiki. Iss.22. – Irkutsk:,. – P.7-16 (in)

2. Methods and Techniques for Reliability Assessment of Interconnected Systems / Prepared by CIGRE T.F. 38.03.11. July 1997. – 60 pp.

3. R Billinton, R Allan. Reliability evaluation of power systems: transl. from English. – M.: Energoatomizdat, 1988. – 288 p.

4. J. Endrenyi. Reliability modeling in electric power systems; transl. from English /Ed by Yu. N.Rudenko. – V: Energoatomizdat, 1983. – 180p.

5. Dikin I.I., 1967, “Iterative solution of problems of linear quadratic programming”, Soviet Math, Dokl. 8.3, pp. 674–675.

6. G.F.Kovalev, L.M.Lebedeva. A set of models for optimization of operating conditions of calculated states in reliability estimation of electric power systems. Preprint No.7. ISEM SO RAN, - Irkutsk: ISEM SO RAN, 2000. – 73 p. (in Russian)

7. Reference book on design of electric power systems./ V.V.Ershevich, A.N.Zeiliger, G.A.Illarionov et al. Ed. by S.S.Rokotyan and I.M. Shapiro. – M.: Energoatomizdat, 1985. – 352 p. (in Russian).