Fedotova G.A.

REDUNDANCY AS PART OF THE RELIABILITY PROBLEM IN ELECTRIC-POWER INDUSTRY

The paper is devoted to the problem of redundancy of generating capacities of the Unified Electric Power System (UES) of Russia. The paper has considered approaches to the solution of the problem used during the Soviet period, and now, peculiarities of redundancy in market conditions. General principles for redundancy used in Russia and abroad in a vertically integrated hierarchical structure of electric power management in a market environment are presented in this paper. Recommendations are given for completion of various individual norms regulating the procedure of selection and deployment of redundant capacities in the UES, and for the development of optimization models for solving problems of redundancy in a multiregional power systems association.

Keywords: *electric power engineering, redundancy of power generation capacity, balance dependability, energy market, competitive selection of power.*

Introduction to the problem and basic principles of redundancy

Redundancy is one of the most important means to improve the dependability of power systems at all temporary levels of control of electric power systems (EPS). It provides partial compensation for reduced dependability of EPS arising due to equipment failure, disorders of fuel supply of thermal power-station (TPS) and water supply of hydro power plants (HPP), the deviations of the actual operating conditions of EPS from predictable ones. The problem of determining the optimal size and placement of the power reserves in the united power system (UPS) with limited carrying capacity of intersystem electrical connections is very complex. Despite the fact that this issue has been dealt with more than half a century, to date there is no single standard approach to its solution [1-3]. With a fully centralized management of industry, there is a regulatory authority or regulatory vertically integrated company responsible for the selection and maintenance of redundancy for generating capacity sufficient to provide the required level of dependability. In a market environment, the market itself can decide what level of reserve capacity needed to ensure compliance with dependability regulations and how to deploy it in a power systems association. However, even in these models the redundancy management is not carried out without some kind of administrative interference. In terms of the energy market, approaches to selection and deployment of reserve power in the UPS vary depending on the type and structure of the market.

In electric power systems with a centralized market of power, which includes the UES of Russia, redundancy of generating capacity is accumulated by means of competitive selection of power (CSP), in accordance with the requirements and regulations of the energy market. The main functions on the formation of the power market rules and requirements to support the dependability of the UES of Russia are performed by the System Operator (SO) (Federal Law # 250 dated 04.11.2007). In conducting competitive power take-off, SO determines the need of power according to market areas and takes off the necessary amount of generating power taking into account constraints of the network capacity ensuring a sufficient level of dependability with the least cost. Basic economic principles to ensure the dependability of electric power systems (EPS) in Russia in the energy market are determined by the Federal Law "On Electric Power Industry" (Article 6, 9, 18, 20, 38, 39 [4]). In accordance with this law, management of dependability and redundancy in electric power industry should be based on the allocation of responsibility for their provision between the entities of relationships and coordination of the liability based on combination of government regulation and market mechanisms. Despite the diversity of approaches used for the power take-off and deployment of generating power redundancy in the world practice, they are all based on the following principles.

1. Redundancy is a technical and economic challenge, which solution is associated with both technical activities and the optimization of power redundancies on the basis of mathematical models. There are two main approaches to solving the problems of optimal redundancy: normative and cost-based ones. The normative approach is based on the selection of a power redundancy value in a power system association and its deployment on electric power systems (EPS) in order to ensure the balance dependability of the regulatory level in the UPS and dependability of consumer power supply. The cost-based approach consists in the optimization of redundancies based on economic criteria, including costs for creation of redundancies and damage from undersupply of electricity to consumers due to power shortage. Since insuring absolute dependability is economically inefficient, then the optimization of power redundancies in the EPS should be a balance between the costs of building and maintaining redundancies and damage to consumers from electricity shortages. Both approaches are used in Russia and abroad.

2. Tasks of redundancy are solved in a mutually coordinated fashion at the planning stages of power industry development and EPS operation. Planning management of the industry development involves the creation of redundancies of rated capacity of EPS and allocation of certain funds for their creation. In the operation of EPS, the redundancies are used for their intended purpose to ensure balance dependability of reliable supply of consumers with electric power of required quality. In this case, as far as redundancies are used effectively in the service conditions, they justify the cost of creating them at the planning stage of development.

3. To determine the optimal value and power redundancy deployment in power systems, estimation and probabilistic approaches are used. In international practice, probabilistic methods and models have a widespread use. They allow one to take into account the accident rate of generating and network equipment, random fluctuations in the load and prediction of its error, interruption of fuel supply, delays in putting new capacities into operation and other random factors affecting dependability.

4. The main difficulty in solving the problems of dependability and redundancy in power systems with limited network capacity of intersystem connections is the consideration of these limitations, time difference of the passage of peak loads and differences in their specific schedules. With regard to the modern conditions of functioning and development of power industry in Russia, the Federal Law "On Electric Power Industry" introduced the concept of free power flow areas (FPFA). The large number of such areas in the UES not always coinciding geographically with regional power systems has complicated the problem of these factors accounting.

With multiregional representation of the power association, the criteria for selecting the size and deployment of the power redundancies used in world practice, as well as the indicators of balance dependability are not adequately substantiated and are, as a rule, empirical. Therefore, to solve the problems of redundancy in Russia, any foreign technique cannot be used in its pure form. The scientifically grounded approach that takes into account the actual state of the industry and modern requirements for dependability, the specific development and operation of EPS in terms of the energy market is necessary. Prior to the reform of industry, there was a hierarchical system of control dependability and power redundancies in the UES. The relationship between producers and consumers of electric power were based on the fulfillment of obligations, regulations and instructions. The transition from a centralized system of management of electric power to the market with the legal and financial liability for the dependability level of all the structures associated with the production, transport, distribution and consumption of electricity, requires a reconsideration of provisioning of electric power generation systems, the revision of approaches to dependability ensuring. The traditional principles of dependability insuring and practice of take-off and employment of reserve generating capacity in the UES existing today in Russia should be corrected in the first place, in terms of criteria for decision-making in market conditions, and the requirements for types and levels of redundancies, with the current state of power plant equipment and electrical power networks taken into account [5].

Selection and deployment of redundancies of generating capacity in the UES of Russia at the planning stage of development of electric power industry

In managing the development of power industry, the problems of the selection and deployment of installed generating capacity of UES redundancies are solved at different time sections:

- when planning the development of electric-power industry (with a lead time of 7-15 years);
- when designing the development of UES (with a lead time of 5-10 years);
- for long-term functioning of the market of power (with a lead time of 4-5 years).

When planning the development of electric-power industry, the General scheme of power generating facilities deployment with details on the integrated power system is formed, and it is adjusted at least once every 3 years. Schemes and programs of UES development, united and regional energy systems determining balanced plans of generating capacity and electrical networks are developed [6]. One of the main problems at this stage is the selection of the quantity of redundancies of installed generating capacity in power systems or in areas of free power flow, providing the balance between production and consumption of electricity and power. The solution of this problem is based on a system of standards, on the indicators of balance dependability, on the carrying capacity of intersystem electrical connections, including those which are needed for the implementation of power redundancies, on fuel stores for a thermal power station, on water stores for a hydropower plant, etc.

To determine the required redundancy of generating capacity at this stage, the value of the required additional capacity in the UES as to the original level of the installed capacity should be estimated. In this case, the deployments of additional generating capacity, its structure and allocation should enable covering the projected load, taking into account the possible excess above the expected value, the ability to carry out scheduled repairs of generating equipment and power compensation derived from work because of total or partial failures. The need to introduce an additional installed capacity is determined by preparing long-term balance of electric power and energy. At the same time, this helps to solve such problems as prediction of load growth and electricity consumption, selection of the optimal structure of power newly set into operation, the determination of location and its basic parameters, sequence of construction, expansion, renovation and modernization of power plants. Prospective balances of power and energy in the UES are developed in view of conditions of regional energy power system joint operation in the UPS. In the separation of the UES into areas of free power flow, the balance sheets are made for the UES as a whole and for each region, which are then harmonized and specified. The required redundancies of power in regional EPS or free power flow areas (FPFA) are determined with network constraints taken into account. As a result, to meet the overall balance of UES power by technical and economic calculation, decisions are taken on the planning of new generating capacity in EPS and on strengthening of the carrying capacities of intersystem connections.

The values of the required redundancy of power in a power system association in the formation of the General layout of electric power facilities are taken by percentage of the load peaks. They are defined in the Methodological recommendations for the design of power systems development [7].

At the design stage, the degree of uncertainty in demand for electricity and the required increase in installed capacity to meet the demand is reduced due to the reduced lead-time decision making (5-10 years). In these circumstances, the adjustment of the level of the redundancy of generating capacities, power structures, generating redundancy and its spatial location is carried out. This involves checking prospective balance of power and energy, correcting the project of development in case of their violation; refinement of delivered energy volumes and, if necessary, change of their locations, refinement of characteristics of new power plants and network; correction of carrying capacity connections and assessment of the balance dependability level .

The value of power redundancy in power systems at this stage is calculated on the basis of special assessment calculations when considering various emergency situations with the functionality of its components (operational, repair and strategic) taken into account. In this case, the operational redundancy should provide normative dependability of load covering estimated by the probability of deficit-free operation of EPS. Repair redundancy should compensate the reduction of installed capacity of power systems associated with the withdrawal of the generating equipment to scheduled maintenance. Its value is determined by the period of the annual maximum load on the basis of the characteristics and design features of the equipment with the regulations on the frequency and duration of repairs. Strategic redundancy should compensate the imbalance of power because of its unexpected deviations from the prediction, mainly related to the inertia of energy construction and/or to advancing development of adjoining industries.

With the lead-time of 4-5 years during operation of long-term power market, the value and deployment of the power redundancies for FPFA are determined by the Regulations on the procedure for determining the value of demand for power and planned factors of power redundancy in the areas [8]. In accordance with this regulation, the value of demand for power is determined by the product of the projected annual supply of maximum hourly consumption of electricity in the area and the planned factor of redundant power after deduction of volumes of electric energy production by generating facilities that operate in the retail markets. Maximum hourly consumption of electricity in the area is defined by the System Operator based on the forecast of power consumption in the territories of the Russian Federation included in the program of UES development. The System Operator calculates the planned factor of power redundancy for FPFA as the sum of the indicator 1.17, the coefficient of under-utilization of capacity and the coefficient, taking into account the export of electric energy. Predictive factor of under-utilization of power is determined by the ratio of average monthly power reduction due to unscheduled repairs of generating equipment, to the value of the projected peak consumption in the corresponding area.

The current framework for planning power redundancy in Russia's power industry and the used norms regulating the procedure for selection of a value of necessary power redundancy and its deployment in the UES have been developed for the conditions of the centralized management of the industry [6-8]. In methodical recommendations for the design of power systems [7], the values of operational power redundancy depending on the structure of the installed equipment in electric power stations, its types, and individual power and accident rate, the probable value of deviation of the power balance of power systems from forecast are calculated based on normative values of these indicators taken as early as in the Soviet era. In the Regulation on the procedure for determining the value of demand for power and planned power redundancy factors in FPFA [8], the selection of the planned factor of power redundancy is not based on the direct analysis of balance dependability. These documents need to be improved in terms of the recording of power market functioning and current requirements for dependability. In particular:

1. The method used to divide into FPFAs is not sufficiently justified in terms of selecting the optimal redundancy in areas considering the dependability in case of the implementation of full value competitive take-off of powers.
2. Assignment of common indicator 1.17 to all areas of the market does not provide for the optimal choice of the value and deployment of the power redundancies as to the areas, because this does not take into account the differences of composition and structure of generating power in the areas, single powers and accident rates, relations with other regions and their carrying capacity abilities.
3. The use of valuation approaches in choosing the magnitude of power redundancies in the EPS does not allow taking into account random factors affecting the dependability. This task needs probabilistic methods and models. Such methods were used in the practice of planning the development of energy systems in our country during the Soviet period and are widely used abroad.

Consequently, the practice of selecting and deployment of redundancies of installed capacity, currently prevailing in Russia, does not provide sufficiently optimal solutions in terms of dependability. The methodology used is not economically feasible to determine the value of the power redundancies, taking into account dependability, the new economic conditions of the industry and the current state of the power equipment. The new scientifically reasonable approaches that meet international standards, taking into account the market relations in the industry, the modern forms of management of electric power and dependability requirements [5, 11], are required. They may be based on methods developed in the Soviet period, adapted to modern conditions. The approaches developed and used in the Soviet Union was based on the well-developed fundamental researches and was quite consistent with international standards, but was focused on a vertically integrated power industry with centralized control [9, 10]. In the past 20 years, they have not received the necessary development and practical use.

Statement of tasks for selection and deployment of power redundancies

As noted earlier, the choice of the optimal amount of redundancy and its territorial distribution in the UES of Russia in the areas of free power flow must be based on a compromise between the cost of its creation and support and damage brought to consumers of electric power shortages due to power shortage conditioned by power deficit. Improving the dependability of power systems by creating a redundancy of power requires an increase in reduced costs, including capital and operating costs. In this case the damage to consumers from the undersupply of electricity to consumers is reduced.

In general, the problem of optimizing the power redundancy in EPS consists in selection of such a reserve, which would provide the required dependability at minimum cost. Fig. 1 shows the dependence of the cost on creating and maintaining the power redundancy (A), the damage from short supply of electric power to consumers (B) and total reduced costs, taking into account the damage (C) from the amount of available redundancy of power. [9] The minimum of the curve of the total costs C corresponds to the optimal level of power redundancy.

The selection criterion for power redundancy in a single power supply system or in a free power flow area can be represented by a functional:

$$C = C_R + M[Y] \rightarrow \min, \tag{1}$$

where C is the reduced cost, C_R is the cost of creating and maintaining the redundancy of generating power in the area, $M[Y]$ is the expectation of damage from the uncertainty of power supply due to power shortage.

The task of selecting and deployment of power redundancies is much more complicated in power systems with poor inter-system connections. Such an association cannot meet the requirements of dependability in case of deficient areas present in its structure, even if the individual power systems or areas of free power flow meet the requirements of dependability or have power excess. The lack of power in deficient areas cannot be covered due to the limited capacity of external links. In order to bring this power system in accordance with the standard of dependability, it is necessary either to introduce additional powers in certain areas, or to strengthen the connection between areas. For this purpose you need to know what connections should be strengthened and in which areas it should be economically feasible to introduce additional powers according to requirements of dependability. To understand the dependence of the dependability level of power systems associations on redundancy volume in the areas and reserves of carrying capacity of inter-system connections, it is necessary to conduct studies to assess the balance dependability of the individual areas and in power systems associations as a whole taking into account the carrying capacities of links. The solution of this problem in condition of power market is associated with great difficulties, especially for large power systems associations, which is the case for the UES of Russia.

To achieve the required level of the balance dependability of a multiregional power system with poor electrical connections as an alternative to an increase in redundancies of generating power in the areas, the corresponding increase of network carrying capacity may be considered. Then the problem of optimal redundancy consists in the simultaneous optimization of redundancy of generating capacity in the areas and reserves of carrying capacity of connections between the areas. The following functional can be used as an optimization criterion:

$$C_{\sum} = \sum_{\mu=1}^{M} C_{R\mu} + \sum_{l=1}^{L} C_l + \sum_{\mu=1}^{M} M_{\mu}[Y] \rightarrow \min, \tag{2}$$

where: M is the number of areas in power system, L is the number of links between areas zones, $C_{\sum}$ is the total reduced costs in the power systems association, $C_{R\mu}$ is the cost of creating and maintaining redundancy of generating power in the μ-th area, C_l is the cost of increased carrying capacity of the l-th link, $M_{\mu}[Y]$ is the expectation of loss from uncertainty of power supply to consumers in the μ-th area.

There is a possibility for another approach when the criterion for selection and deployment of redundancy generation capacity consists in the minimum of total discounted costs, including the costs of creating redundancy of generating capacity and the strengthening of links, and the required level of dependability of consumer power supply is given according to limitation of norms. Then the amount of the power redundancy in each area of a multiregional power system will be selected under conditions of economically reasonable and technically necessary (regulatory) dependability, and selection criteria of power redundancy in power systems and its deployment on FPFA will have the following form:

$$C_{\sum} = \sum_{\mu=1}^{M} C_{R\mu} + \sum_{l=1}^{L} C_l \rightarrow \min, \pi_\mu \geq \pi_{norm}, \tag{3}$$

where π_μ and π_{norm} are the calculated value of the dependability index of power supply of consumers in the μ - th area and its normative value, respectively.

Using the criterion (3) for the selection and deployment of redundancy of generating power in the UPS in market conditions allows us to take most comprehensively into account the specifics of the relationship between the subjects of the energy market. With centralized management of power industry in Russia, the deployment of redundancies was based on the collective principle of mutual aid presented by EPS, when not only the redundancy of power, but the power shortage is distributed between power systems. Then the inclusion of the expectation of damage from undersupply of electricity to consumers in the functional (2) was qualified. In the market environment, the power shortage of other EPS cannot be distributed in power systems with excess energy. Each power system in the first place strives for ensuring the necessary level of its own dependability at the lowest cost and gaining maximize profit. Then it strives to fulfill contractual obligations to the adjacent power systems and only after that to give out the excess power to meet the power shortage in other systems on a commercial basis. With this approach, standards of dependability of power supply are required. Attempts to get them were made in the USSR [9], but since that time works in this direction are not carried out, therefore, optimization of redundancies according to the criterion (3) is still problematic.

Use of redundancies of generating power in the operation of EPS

In EPS operation, the issues of use of redundancies in view of their functionality and such properties as mobility and efficiency are of the main significance. At this stage the meaning of the problem consists in refining the redundancy of power in each region of free power flow and its redistribution between areas to provide the required level of dependability in the areas and in power system as a whole with the actual situation in power systems. Such redistribution in current conditions of EPS operation should be carried out through the market of power and system services. At the same time, operating redundancy to cover its own load with the required degree of dependability and repair redundancy to replace the power taken out for planned maintenance and reconstruction in each area should be provided. The close relationship of operational and maintenance components of the power redundancy allows affecting the value of the operational constituent ensuring dependability by optimizing the timing of repairs in the process of planning. Therefore, the task of redistribution of power redundancies should be solved together with the task of planning of generating equipment repairs associated with the reduction of dependability. Joint planning of repair of stations' electrical equipment and networks of inter-system connections provides additional opportunities to improve dependability through the use of system effects [12].

In conditions of the power market, the task of scheduling repairs deserves special attention in the context of the problem of redundancy in the operation of the power system. The separation of ownership and the introduction of market mechanisms in the process of management of electric power have led to the appearance of independent market entities with divergent interests that directly or indirectly affect the approaches to the planning of repairs. Power generating and distributing companies are interested in maximizing profits from the operation of the equipment installed in power plants and networks under their ownership. Consumers are interested in the minimum price for electricity; the system operator is interested in insuring the required dependability and profit-making, etc. In conditions of the power market, regardless of the selected criteria, the mechanism has to work that allows at the choice of timing of the planned repairs to coordinate the interests of all market participants [13].

Redistribution of redundancies of power generating between FPFA in the UES can be carried out with the help of optimization mathematical models for dependability criteria under the assumption that the amount of available redundancies in areas is defined and economically feasible in the planning stages of development [14]. Depending on the operating conditions and power systems' association and optimization purposes it is possible to use different criteria of dependability, such as the following ones.

- Ensuring equally possible dependability of power supply to consumers in the areas and over time.
- Achieving equal probability of upstate of power systems (in free power flow areas).
- Leveling operating power redundancy between areas and over time in proportion to the load.
- Ensuring maximum possible dependability of power supply to consumers in a power systems association taking into account the standards of dependability in the areas.

At the same time the level of dependability can be estimated by various indicators, including the indicator of the relative provision of electricity to consumers, the probability of upstate of power systems, etc. The selected dependability index should be normalized, it should have a simple physical meaning and be sufficiently sensitive to various disturbances, leading to a decrease in dependability (emergency power reduction, casual load growth, taking out the equipment for repair) and to activities that increase the dependability (putting into operation of new equipment, increasing the carrying capacity of links, redundancy).

Along with the criteria of dependability, theoretically it is possible to find the solution of the problem considered on the basis of cost criteria. Then, through the efficient use of power redundancies, it is possible to provide a minimum of total costs, including the costs for the use and maintenance of power redundancies, the costs for fuel and repairs, as well as damage caused by undersupply of electricity to consumers. Practically, this approach is difficult to implement, and one of the main problems of the use of cost-based criteria is the lack of adequate economic information and/or its inaccessibility. Besides, the prediction of prices for fuel and repair, costs for the maintenance of power redundancies, electricity tariffs and damages from undersupply of electricity to consumers in the power market is a complicated task.

Conclusion

Thus, approaches and methods for selecting and deployment of redundancies generating power of EPS in Russia existing and used today do not meet a modern organizational structure of the industry. At present, the Guidelines for the design of power supply systems based on a common approach to the design of development of power systems, including economic justification redundancy level of installed power, remain in force. These guidelines were developed in 2003 and orientated on a vertically integrated hierarchical structure of the industry with centralized management. Recommended levels of redundancies in the UPS comprising the UES of Russia, due to heavy aging power plants equipment and networks, require further updating.

There is a need to refine the Regulations on the procedure for determining the amount of power demand, selection and deployment of power redundancies in the division of the UES into areas of free power flow and determining the planned factor of the power redundancy in FPFAs to meet the requirements of dependability.

With regard to the market system of power industry development, there is no methodology for power redundancy based on internationally accepted principles and approaches. To select the amount and deployment of the power redundancies even at the planning stage of UES development it is necessary to use not estimating approaches, but optimization models based on probabilistic methods. Since the principles of selection and deployment of power redundancies in Russia and abroad coincide on basic positions, the available international developments to address this issue can be used in Russia under condition of their adaptation to the peculiarities of the Russian power market.

The above stated principles and approaches to redundancy of generating power and ensuring dependability are mostly traditional. At present, under conditions of information technology developments, the new approaches are applied to power systems development based on modern methods and controls aimed at reducing the breakdown rate of equipment, failures of control systems, and the probability of system failures and required redundancies of generating power.

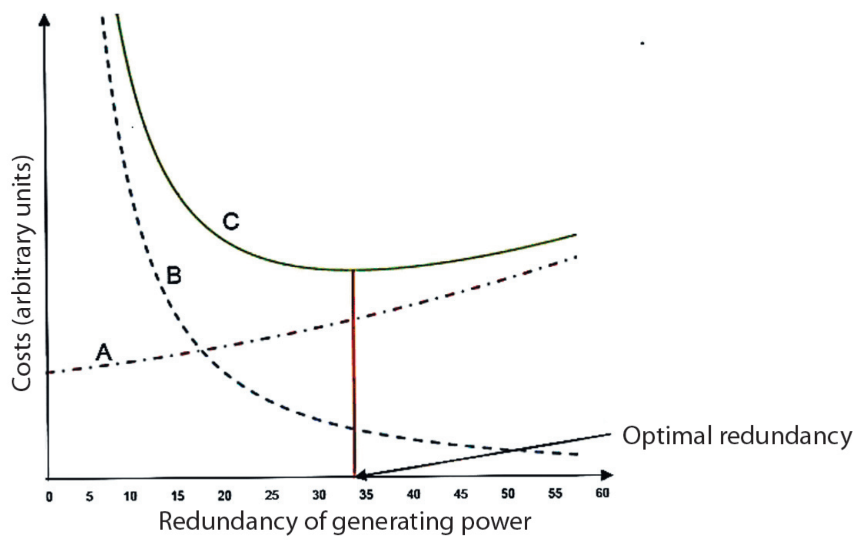

Fig. 1. Selection of optimal redundancy

References

1. **Billington, Roy and Ronald N. Allan.** Dependability Evaluation of Power Systems, Second Edition, Plenum Press, New York and London. 1996.

2. ABB, LOLE Resource Adequacy Methodology, Presentation to the New England Installed Capacity Requirement Stakeholder Meeting. November, 18, 2005. http://www.isonewengland.org/committees/comm_wkgrps/othr/icsp/mtrls/2005/nov182005/lole_resource_adequacy_methodology.pdf

3. **Johannes Pfeifenberger, Kathleen Spees, Adam Schumacher.** A Comparison of PJM's RPM with Alternative Energy and Capacity Market Designs. A report by The Brattle Group prepared for PJM Interconnection. September, 2009.

4. About power industry. Federal Law of the Russian Federation dated 26.03.2003 # 35.

5. The concept of dependability ensuring in power industry. Moscow: Russian Ministry of Energy, 2011. 170.

6. About designs and programs for the long-term development of power industry. Government regulation # 823 dated 17.10.2009.

7. Guidelines for the design of power systems. The Order of the Ministry of Energy of Russia # 281 dated 30.06.03 (SD 153-34.20.118-2003).

8. About approval of the Regulation on the procedure for determining the amount of power demand for long-term power take-off on a competitive basis in the wholesale market of electric power and the procedure for determining the planned coefficients of power redundancy in areas (groups of areas) of free flow of electrical power. The Order of the Ministry of Energy of the Russian Federation # 431 dated September 7, 2010.

9. **Rudenko Yu. N., Cheltsov M.B.** Dependability and redundancy in power systems. Novosibirsk: Nauka. 1974. p. 263.

10. **Rudenko Yu. N. Ushakov I.A.** The dependability of power systems. Novosibirsk: Nauka. 1989. p.328.

11. **Chukreev Yu., Chukreev M. Yu.** Ensuring dependability in managing the development of power systems for the conditions of the power industry reform. / / Proceedings of the Russian Academy of Sciences. Energy. 2008. # 4. p. 39-48.

12. The dependability of power systems and their equipment. Reference book vol. 2. The dependability of electric power systems, Energoatomizdat. 2000. 568p.

13. **Voropai N.I., Fedotova G.A.** Planning for repairs of power generation equipment in the market environment, taking into account dependability. / / Automation and telemechanics. 2010. # 7. p. 179-184.

14. **Fedotova G., Voropai N.** Optimization of dependability of power supply to consumers. / / E-journal “Dependability: Theory & Applications”. Vol. 2. June 2007. Number 2. P. 57-68. Available: http://www.gnedenko-forum.org/Journal/index.htm