Estimation of reliability of TPS as a complex system using logical probabilistic methods

O E Kondrateva 1, A M Borovkova 1, P N Bayeva 1 and E B Cherkasskiy 2

1 National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14
2 OJSC "UNIPRO", Moscow, 123112, Presnenskaya naberezhnaya, 10, block B

Abstract. The existing regulatory requirements for reliability assessment and the economic necessity of this assessment are considered. Modern methods and approaches to assessing quantitative indicators of reliability of structurally complex systems, such as thermal power plants, are presented. The expediency of using software systems for calculating reliability based on the General logical-probabilistic method is proved. On the example of one power unit, the application of a domestic software package for modeling and calculating reliability and safety using logical-probabilistic research methods is clearly presented. The existing problems of forecasting reliability indicators after the technical impact are described.

Key words: reliability, quantitative indicators of reliability of structurally-difficult system, logical-probabilistic method, the technical condition index

1. Introduction
Continuous reliable electric and thermal power supply for consumers by thermal power plants (TPP) is the most important constituent of modern human environment life-support and it directly influences the public production functioning. The electrical power system (EPS) reliability is composed of that of two links as follows: reliability of the generation link defined as the plant generating capacity, and the grid link presented as all electric mains of the supergrid system. The grid link reliability ensuring is the important task, especially for Russian power grids having extended and weak connections, as well as scarce and redundant generation areas[1]. However, the generation link is the primary one and responsible for the load coverage. Therefore, ensuring its reliability is a priority task when ensuring the EPS reliability. In Russian Federation about 70% of all electric power is generated at TPP, and that is TPP reliability assessment that is important and actual task, since it plays a significant role when assessing EPS (electric power system) reliability across the country as a whole.

2. Economic aspects of reliability assessment
TPP reliability is understood as the property to maintain in time the ability to generate the electric and thermal power with certain parameters according to the required load schedule for the specified system of the equipment maintenance and repair[2]. And the required reliability level ensuring has two complementary aspects. On the one hand the economic constituent is important as the ability to generate the necessary amount of electric and thermal power is expressed in profit gaining for the energy generating companies. Emergency failure in operation of the powerful thermal energy equipment of TPP will not only cause serious damage to the entire EPS, and consequently to the consumer, but due
to the electric and thermal energy under-supply, will result in the companies profit reduction from their implementation, and significant costs for the failed equipment repair and recovery. Therefore, the actual practical task for the energy generating companies is to assess the production activity risk that includes the reliability and losses assessment if the reliability doesn't meet the required indices. The companies' costs for reserve, replacement and repair due to the technical condition shall be less than the damage expressed in monetary terms. To fulfill this condition it is necessary to correctly assess the damage caused by the under-supply of the energy. The reliability assessment and analysis allow providing for reserving the most significant equipment at the design stage, timely procurement of the components spare parts, predicting and scheduling the maintenance works and, above all, optimizing the investments in the available equipment to maintain its operability.

3. Requirements of regulatory documents

On the other hand the energy generating companies shall supply the electric and thermal energy according to the required load schedule provided by the regulations. The Order of Minenergo №676 approved the Procedure whereby the technical condition index $K_{ITC}$ of the main equipment and the electric mains of the power plants and the power grids is calculated. Such an assessment should be performed once a year, and on the basis of the result obtained (the numerical score value from 0-100) the system's technical condition kind, the necessary level of technical impact on the equipment, type of repair when making and updating the perspective (multi-year) schedules of repair, annual maintenance programme and measures complex on the technical retrofitting and upgrading are defined if the values don't meet the satisfactory indices (no less than 50).

And on the basis of the value obtained $K_{ITC}$ the failure probability of the functional assembly and the unit of the main technological equipment is calculated and the consequences assessment is carried out in compliance with the Order of Minenergo №123 taking into account the indices in Table 1 as follows:

| Table 1. The indices considered when assessing the consequences of the functional assembly failure |
|---|---|
| **Index** | **Definition** |
| $C_9$ | Equipment replacement cost without VAT, rub |
| $З_{ПУСК}$ | Launch costs (depending on additional fuel consumption and its price) |
| $У_3К$ | Actual and predicted costs on compensation of environmental damage |
| $У_3П$ | Actual and predicted costs on compensation of the personnel life injury due to the equipment failure |
| $У_3П$ | Actual and predicted costs on compensation of personnel health damage |
| $У_{неопл.мощн}$ | Actual and predicted loss due to the non-payment of the power plant available capacity |
| $У_{упущ.выгоды}$ | Actual and predicted loss due to the lost profit as a result of the electric and thermal power underproduction |
| $У_{комп.над}$ | Loss due to the compensation payment to consumers |
| $У_{тар.над}$ | Loss due to the tariff reduction |
| $C_{пр}$ | Other costs (for emergency elimination etc.) |

4. Quantitative indicators of reliability

To determine the quantitative indices of TPP reliability it should be presented as a system consisting of separate components with available statistic source data. For the recoverable components that are those with the lifetime consisting of the alternate periods of operation and recovery, which are the TPP components, the following quantitative indices are characteristic:

- $\omega(t)$ - failures flow parameter characterizing the number of the failed objects in the selected time period
- $T_0$ - time between failures of the facility;
- $T_n$ - mean time of the facility recovery;
- $K_g$ - availability factor characterising the probability that the facility will be operational, i.e. ready to bear design load at an arbitrary point of time excluding the periods of its scheduled outages;
- $K_{t,n}$ - utilization factor characterizing the relative share of time when the facility was in operating condition within the considering period of time excluding the scheduled outages;
- $K_p$ - forced outage factor characterizes the facility in disabled condition.

The system components damage rate statistics according to the results of their operation within the specified time gives the values of the failures flow $\omega(t)$, the component time of recovery $T_n$ and the time between failures $T_0$. The above-mentioned factors and the system failure probability can be calculated on the basis of those values.

5. Methods for evaluating reliability

Analytical, statistical or experimental methods can be used for calculations, and their comparative analysis is specified in Table 2.

Table 2. Reliability assessment methods

| Methods            | Advantages                                                                 | Disadvantages                                                                 |
|--------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| **Analytical**     | Allow the entire system reliability assessing by comparing the different operation schemes and calculation of the reliability quantitative indices at the early design stages. Allow researching the influence of the different factors on its system and its components and finding the general optimal solutions using the obtained analytical expressions. | Become difficult to implement at the system complex scheme requiring a complex mathematical tool. |
| **Statistical**    | Allow assessing the complex system, incapable for evaluation with the analytical assessment methods, by developing and researching the studied facility statistical model functioning. | The solution is presented as numerical statistical estimates, but not as the analytical solutions reflecting the different factors influence on its system and components. |
| **Experimental**   | The main way to determine or confirm the reliability level of the components and the entire system in practice. Allow assessing the reliability of the valid equipment which meet all technical conditions that provides insight into its degradation under the influence of various external and internal factors leading to failures. | It is assumed that some amount of the studied facility samples is available. Moreover, these samples should be valid and satisfy all technical conditions. The reliability assessment is inevitably associated with a certain (sometimes very significant) resource consumption of the tested samples. |

6. Application of the General logical-probabilistic method

The general logical-and-probabilistic method (GLPM) based on all above mentioned methods and having all their advantages can be considered as a perspective method of the reliability calculation. GLPM provides the complex systems reliability analysis with their structure described by means of the
mathematical tool of the binary logical algebra, and the quantitative assessment of the reliability is carried out with the probability theory. To fulfill the calculation it is necessary to convert an actual functional-structural diagram into the equivalent graphic diagram describing the contents and the power-generating unit components functioning condition. From the mathematical point of view, such a graphical representation of the system makes it possible to determine the system operating condition (direct approach) and the failure condition (reverse approach), as well as allow correctly representing all traditional kinds of the structural diagrams (block diagrams, fault trees, event trees, connectivity graphs with the cycles) and a fundamentally new class of the non-monotonic (incoherent) structural models of the studied systems different properties, that is a great advantage. For simulation and calculation of the quantitative reliability indices it is also necessary to use experimentally obtained source data. Moreover, GLPM has developed procedures of the source structural models conversion into the sought calculated mathematical models, that allow performing their algorithmization and computer implementation. In the general form, the GLPM algorithm can be represented by the block diagram as follows (Fig. 1):

![Logical function construction of the system operability](image)

Quantitative assessment and optimization of TPP operation reliability according to the above mentioned algorithm is a difficult task due to significant quantity of the systems components and variety of the relationships between the separate components. It is quite difficult to assess the reliability of such a system analytically "manually" at real facilities, since the assessment requires a lot of time and special additional training of the personnel. Moreover, it is not always possible to obtain visible and consistent results as well as the quantitative assessment of the reliability and optimal ways to increase it.

7. Software packages for calculating reliability
The task described above can be significantly simplified by applying the software packages of simulation and calculation of the reliability indices and the systems safety. Calculation made in the software packages allows quick changing and assessing the influence of certain parameters on the system reliability.

A comparative analysis of the most common domestic and foreign software packages of the reliability calculation implementing the GLPM methods is specified in Table 3[5].
| Software country of origin | Calculation of indices | Calculation method | Scope | Advantages/ disadvantages |
|----------------------------|------------------------|--------------------|-------|--------------------------|
| PK "Relex" (Relex software Corporation, USA) | Probability of no-failure operation; mean time between failures; the system failures intensity; availability factor; failures flow parameter | GLPM; Monte Carlo simulation; Markov model | Reliability and safety analysis of the controlling and technological systems, instrumentation products, computer engineering, transport, in defense equipment | Advantage: the wide range tasks solution; economic calculations feasibility; allows considering the type of reserve, probability and time of the reserve successful connection, the failure mechanism, the recovery strategy Disadvantages: high cost |
| PK "Risk spectrum" (Sweden) | Probability of no-failure operation; mean time between failures; mean time of recovery | GLPM | The probabilistic method of the power engineering facilities safety; the technology-related risk optimization and determination of the maintenance system optimal parameters for potentially hazardous facilities | Advantage: it is used at more than 50% of nuclear power plants all over the world Disadvantages: high cost |
| PK ASM ("ARBITR", RF) | Probability of no-failure operation; mean time between failures; mean time of recovery; probability of failure; significance and contribution of the components in the different reliability indices | GLPM | The power engineering facilities safety analysis; the technology-related risk optimization and determination of the maintenance system optimal parameters for potentially hazardous facilities | Advantage: ease of use; relatively low price |

The software packages analysis specified in Table 2 showed that all packages under consideration provide a possibility to solve the set task on the reliability assessment based on the algorithm proposed in Figure 1, so the choice of a specific one will depend more on the enterprise’s purchase costs.

8. An example of the calculation power unit
Consider the calculation stages at PK "ARBITR" of the structural-complex system reliability on the example of a TPP 200 MW steam power-generating unit.
It is necessary to build a functional integrity diagram showing all components of the system with the links between them based on the functional-structural diagram (Fig. 2):

Figure 2. The scheme of functional diagram

Figure 2 shows the functional vertices expressing the conditions for implementation of the specific components operability. For example, the functional vertex 3 corresponds to a TPP power generator that implements the operability in cases, firstly, of its own operability, as well as when ensuring operability of the excitation system and operability of the electric motor. The fictitious vertices showing the conditions of implementation of several components operability are also specified. For example, the fictitious vertex 30 shows that two of three condensation pumps should be in operating condition. All system comes down to the fictitious vertex 1 designating the operability of all system.

We obtain the quantitative reliability indices for the system under consideration (Fig. 3):

- The value obtained $K_G$ means that the power-generating unit, with a probability of 0.936, will be in operating condition at an arbitrary point of time
- The value $T_{vc}$ means that it will take the system 90 hours on average to recover when it fails
- The value $T_{oc}$ shows that the time between the operating condition and the failure will be 1338 hours
- The value $P_{vc}$ demonstrates that within the specified time between failures of the system (1 year = 8760 h) the probability of its no-failure operation is small and is 0.0014

It is noteworthy that in addition to its own quantitative indices of the power generating unit reliability, the software package allows assessing the significance and contribution of each constituent component in the structural reliability, as well as obtaining a clear graph of the system dependence on the first failure.

9. The existing problems of calculation

The software package using based on GLPM allows obtaining the integral indices of reliability, identifying the most dangerous equipment regarding failure, and determining the necessary technical measures aimed at maintaining the operational reliability of this equipment. The reliability of the data obtained in this case will depend on the correct use of the proposed algorithm and the correctness of forming of the array of the source data. According to the above mentioned, the mean time between
failures and the mean time of the components recovery obtained on the basis of the statistics analysis of the equipment failures and system shutdowns are taken as source data. However, once the calculation is carried out and all necessary measures are determined, the source data change, and the task arises to correctly predict the components source data change due to the technical measures. This is one of the key problems of the TPP equipment reliability assessing.

To solve this problem not only the system components damage rate statistics, but also the correct assessment of the equipment technical condition is needed. It is important that the above mentioned index of technical condition $K_{HTC}$ determines the type of the system technical condition and necessary level of technical impact on the equipment. Thus, the question arises: Is it possible, after carrying out the necessary technical measures, to calculate $K_{HTC}$ and compare the obtained value with the reliability indices necessary for the calculation? Such an approach would allow proceeding from $K_{HTC}$ to the reliability indices and obtaining the source data. However, at present the technical condition index, calculated by the existing procedure, includes not only physical condition indices, but also those of safety and thermal efficiency, that does not always allow obtaining reliable data on the technical condition to assess the equipment failure risk. The TPP components calculation $K_{HTC}$ based on the physical parameters determining only its operability would possibly become one of this problem solutions.

10. Conclusions
Thus, the TPP reliability assessment performed by the energy generating companies should be fulfilled considering the regulatory and technical requirements and for achieving the maximal economic indices of the activity. For such an assessment the logical-and-probabilistic methods can be used, adopted in the hardware system they allow obtaining the reliability quantitative indices and making a conclusion about how long and with what probability the system will be in operating condition.

To obtain the reliable calculation results with the help of GLPM, it is necessary to correctly predict the change in the reliability indices due to the performed technical impacts that can be achieved by competent comparison $K_{HTC}$ with the reliability indices.

Prediction of the equipment technical condition, calculation of the failures probability and its economic assessment allow proceeding to a risk-based approach in planning of technical impacts, preventing accidents in power engineering industry, and making planned and unscheduled costs for repair and re-equipment, that will allow the supplying companies responsible for the reliability of the power supply, as a whole, fulfilling their obligations on supplying electric and thermal power and gaining maximum profit.

References

[1] Krupenev D S 2010 Evaluation and synthesis of network reliability of the electric power system *Problems of energy* № 9-10, p. 28-40
[2] GOST 27.002-89.2002 Reliability in technology. Basic concept. Terms and definitions. - Moscow: IPK "publishing house of standards" 24 p.
[3] Order of the Ministry of energy of the Russian Federation No. 676 dated July 26, 2017 " on approval of the methodology for assessing the technical condition of the main technological equipment and power transmission lines of power stations and electric networks”
[4] Order of the Ministry of energy of the Russian Federation dated February 19, 2019 No. 123 " on approval of guidelines for calculating the probability of failure of a functional node and a unit of basic technological equipment and assessing the consequences of such failure”
[5] Stroganov A, Zhadnov V and Polessky S 2007 Review of software systems for calculating the reliability of complex technical systems *Components and technologies* № 5 p. 183-190
[6] Mozhaev A S 2006 General logical-probabilistic method of automated structural-logical modeling of reliability, safety and risk of complex systems "Security of Russia". Risk analysis and security issues. In four parts. Part 1. Fundamentals of analysis and regulation of safety. Moscow: MGF "Znanie" p. 243-293

[7] Baidyuk M A and Komarov G V 2019 Assessment of the technical condition and reliability of electric machines Izvestiya SPbGETU "LETI" № 3 p. 78-84

[8] Petukhov I S 2004 Automated system of structural and logical assessment of reliability and risk indicators of energy facilities Problems of Informatics in education, management, Economics and technology: Sat. St. iv of the all-Russian scientific and technical conference-Penza p. 154-156

[9] Gromov V N and Mozhaev A S 2000 Theoretical bases of the General logical-probabilistic method of automated system modeling. Saint Petersburg: publishing house of the Military engineering and technical University 145 p.