System Statement of Tasks of Calculating and Providing the Reliability of Heating Cogeneration Plants in Power Systems

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Abstract. A set of mathematical models for calculating the reliability indexes of structurally complex multifunctional combined installations in heat and power supply systems was developed. Reliability of energy supply is considered as required condition for the creation and operation of heat and power supply systems. The optimal value of the power supply system coefficient F is based on an economic assessment of the consumers' loss caused by the under-supply of electric power and additional system expenses for the creation and operation of an emergency capacity reserve. Rationing of RI of the industrial heat supply is based on the use of concept of technological margin of safety of technological processes. The definition of rationed RI values of heat supply of communal consumers is based on the air temperature level inside the heated premises. The complex allows solving a number of practical tasks for providing reliability of heat supply for consumers. A probabilistic model is developed for calculating the reliability indexes of combined multipurpose heat and power plants in heat-and-power supply systems. The complex of models and calculation programs can be used to solve a wide range of specific tasks of optimization of schemes and parameters of combined heat and power plants and systems, as well as determining the efficiency of various redundancy methods to ensure specified reliability of power supply.

1. General provisions
One of the required conditions for the creation and operation of heat and power supply systems is to ensure a specified (optimal) reliability of energy supply to consumers. Reliability is understood as ensuring the quality of electricity and electricity supply to consumers in accordance with energy consumption schedules over a certain period of time and avoiding dangerous situations.

CCP and heat-and-power supply systems (STE) on their basis are attributed to the class of structurally complex multi-functional reconstructed systems

The system statement of the tasks of calculating and providing reliability includes:

- Selection and justification of unit, complex and integral reliability indicators (RI) in accordance to the functional purpose of the researched thermal power plants;
- Development of probabilistic methods and models for the calculation of the RI elements of power equipment, heat power plants in general, and heat-and-power supply systems based on them;
- Justification of the rationed values of RI of heat and power supply systems;
Formulation and solution of the task of optimal distribution of RI between the elements of the heat energy installations;

Development of probabilistic methods and models for calculating the required emergency power reserve in the system to provide a set (rationed) RI value;

Development and justification of methods for increasing (optimizing) the RI of thermal power plants in general;

Formulation and solution of tasks of economically most advantageous methods for increasing the reliability of heat power installations.

Let us consider some aspects of solving systems of these problems.

2. Selection and justification of RI of installations and systems

The known complex and integral indicators of reliability often do not allow to correctly solve problems of maintaining the reliability of power supply of consumers. For refinement of them proposed a probabilistic system index is suggested – the efficiency coefficient of the functioning of $K_{ef}(t)$, which takes into account both operational failures, including partial failures, and functional failures at time $t$.

$$
K_{ef}(t) = P\{t, N_p \geq N_s\} \cdot P\{t, N_s \geq N_{as}\}
$$

(1)

Where $P\{t, N_p \geq N_s\}$ is the probability that at the moment of time $t$ the level of working capacity of $N_p$ will not be below some given level $N_s$; $P\{t, N_s \geq N_{as}\}$ - the probability that the power level $N_s$ will not be below the required level. The first cofactor of the expression (1) is defined by the structure of the STE, the RI of its individual elements, as well as commonly used reservation methods, etc. The second cofactor is defined by the schedules of electrical and thermal energy consumption. The application of this index determines the possibility and expediency of decomposition methods application when calculating the reliability of structurally complex STEs, allows analyzing STE both from the position of its structure and from the point of view of providing energy consumption schedule.

3. Rationing of RI of power supply systems

The optimal value of the power supply system coefficient $F$ is based on an economic assessment of the consumers' loss caused by the under-supply of electric power and additional system expenses for the creation and operation of an emergency capacity reserve. Rationing of RI of the industrial heat supply is based on the use of concept of technological margin of safety of technological processes. The definition of rationed RI values of heat supply of communal consumers is based on the air temperature level inside the heated premises. Herewith, failures of heat supply systems are ranged in accordance to the disturbance of heat supply during the coldest period of the heating season at air temperature inside the premises: 1 rank of failure – $t \leq 0^\circ C$; 2 rank - $t < 10^\circ C$; 3 rank - $t < 15^\circ C$; 4 rank - $t < 20^\circ C$. The rationed values of RI of the heat supply system for the first and second failure ranks are the probabilities of reaching the corresponding temperatures and are equal to $P_1 = 0.97$ and $P_2 = 0.86$ [1]. The third and fourth failure ranks do not lead to large material damage, but identify the extent of comfort living. Consequently, the third and fourth failure ranks are rationed by the values of the system efficiency coefficients, which are, respectively, $k_{E3} = 0.97$ and $k_{E4} = 0.89$ [1].

4. Probabilistic model for the calculation of the RI elements of power equipment

Deterministic methods for calculating the RI of power equipment elements, based on the calculation of relative or absolute strength and durability reserves, have been widely used, but do not take into account a number of real operational factors. In actual operating conditions of power equipment the calculation of the RI of power equipment elements should be based on probabilistic methods that allow for statistical dispersion of the strength and loading characteristics using the theory of random variables and random functions [2, 3].
The basis of the mathematical model for calculating the reliability of WHRB and its failure-free operation is:

- WHRB is divided into zones, each one contributes to the probability of failure: economizing, evaporating and overheating zones;
- Effective voltages are random variables, the spread of which with respect to the expected mathematical value is determined by many factors [4];
- Operational characteristics of the materials used (long-term strength limit and endurance limit) are random variables distributed according to normal or log-normal laws;
- The assessment of failure-free operation is carried out from the condition of determining the probability of not exceeding the effective voltages over the permissible values in each design section.

The failure-free performance should be understood as the probability of not exceeding the loading value

\[ X(t) = \{ x_1, \ldots, x_i, \ldots, x_j, t \} \]

strength limit value \( Y(t) = \{ y_1, \ldots, y_j, \ldots, y_j, t \} \) that is, the random working capacity function (WCF) \( Z(t) = X(t) - Y(t) \) hits a range of negative values. If there are \( m \{ m = 1, \hat{m} \} \) zones in WHRB with the same reliability, and the failure-free performance of each is characterized by \( n \{ n = 1, \hat{n} \} \) WCF, then the condition of a failure-free operation will be written as

\[ Z_{n,m}(t) = \left[ \min \left\{ Y_{nk}(t) - X_{nk}(t) \right\} \right]_{m > 0}, m \in \hat{m}; n \in \hat{n} \]  \hspace{1cm} (2)

Where \( k \) is the number of analysed WHRB zones.

In a general case when several WFC determine failure-free performance, that is, when \( \hat{n} > 1 \) , the probability of the failure-free operation will be written as

\[ P(t) = P[Z_{n,m}(t) > 0], m \in \hat{m} \]  \hspace{1cm} (3)

If WCF \( Z_{n,m}(t) \) are independent, then

\[ P(t) = \prod_{m=1}^{\hat{m}} \prod_{n=1}^{\hat{n}} P_{n,m} \{ Z_{n,m}(t) > 0 \} \]  \hspace{1cm} (4)

The value \( P_{n,m} \{ Z_{n,m}(t) > 0 \} \) is found with formula

\[ P_{n,m} \{ Z_{n,m}(t) > 0 \} = P[Z_{n,m}(t) > 0]P_{n,m} \{ Z_{n,m}(t) > 0 \} = P[Z_{n,m}(t) > 0] \exp \{ -\nu_{n,m} t \} \]  \hspace{1cm} (5)

Where the value \( P[Z_{n,m}(t) > 0] \) describes the probability that the random value of the effective voltage will not exceed permissible values at time \( t \), and value \( P_{n,m} = \exp \{ -\nu_{n,m} t \} \) corresponds to the probability that the random WCF \( Z_{n,m}(t) \) will not be ejected into the negative range of values during a period of time \( t \).

The probability that for the \( m \)th section of the WCF (omitting index \( m \)) the effective voltages \( \sigma(t) \) will exceed the permissible \( \bar{\sigma}(t) \) will be defined as

\[ F[\sigma(t) > \bar{\sigma}(t)] = \iint f(\sigma, \bar{\sigma}, t) d\sigma d\bar{\sigma} \]  \hspace{1cm} (6)

Where \( f(\sigma, \bar{\sigma}, t) \) is joint differential probability-distribution function of reduced voltage and long-term strength.

Since the condition for operability of the WHRB parts has the form of

\[ \xi(t) = \sigma(t) - \bar{\sigma}(t) < 0 \] ,

then, using it to define integration ranges (10), we get
In the event of values $\sigma$ and $\bar{\sigma}$ being distributed according to the normal laws, the probability of failure-free operation will be written as

$$P\{\sigma < \bar{\sigma}, t\} = 0.5 - \Phi\left(\frac{M(\sigma(t)) - M(\bar{\sigma}(t))}{\sqrt{S^2(\sigma(t)) + S^2(\bar{\sigma}(t))}}\right)$$

(8)

Where $\Phi[\beta]$ is Laplace’s function; $M(\sigma(t)), M(\bar{\sigma}(t)), S^2(\sigma(t)), S^2(\bar{\sigma}(t))$ are, correspondingly, expected values and dispersions of operating stationary and ultimate stress at the moment of time $t$ [5].

5. Method of calculating the structural reliability of heating CCPs

For combined thermal-clamping gas-vapor CHPP, generally designed for electric power, process steam and hot water generation, the correlation of produced energy types is inherent. This leads to the necessity of calculating the interdependent RIs for the release of each type of generated energy.

This method is based on the Markov model of the evolution of system’s conditions, which is based on a description of its functioning by means of a Markov process with a discrete set of conditions and continuous time. The basis for the use of the Markov model is the adoption of exponential laws for the distribution of operative and recovery time.

Real thermal-clamping CCTs are structurally complex systems. Therefore, to calculate the RI of CCT, its structural scheme is represented as a $(i = 1, n)$ consistently connected aggregate blocks, each of which contains $L_i = M_i + P_i$ elements, where $M_i$ and $P_i$ are respectively the number of working and reserve elements of the $i$-th Block. The matrix of possible plant conditions is represented as a set of vertices and arcs. The condition vertices are described by $(n + k)$-dimensional graph of the form

$$\{X^i_1, X^i_2, \ldots, X^i_n, X^j_r, \ldots, Q^j_r, N^j_r, B^j_r\} = \{X^i_n, N^j_r, Q^j_r, B^j_r\}$$

$z = 1, Z ; i = 1, n ; r = 1, R$

(9)

Where $Z$ is the number of possible plant’s conditions; $n$ – number of selected aggregate blocks; $R$-number of heat carriers produced by the plant; $X^i$ - number of failed elements of the $i$-th block in state $z$; $Q^j_r, N^j_r$ - respectively, the output capacity of the $r$ type of heat carrier in condition $Z$ and electric power; $B^j_r$ - firing rate in CCT for producing electric and heat power.

Procedures for the formation of a set of conditions of a power plant, the matrix of transition intensities, and solutions of a system of differential (algebraic) equations for the change in the probability of conditions are formalized and presented as a set of calculated programs [5,6]. To each possible condition of the plant correspond to certain the levels of working capacity of the power plant for the release of electric $N^j_r$ and thermal $Q^j_r$ energy correspond. Presenting the required conditions for the operation of the CCT in the form of a deterministic piecewise constant function $N^j_r(j = 1, G)$ and $Q^j_r(j = 1, G)$, the set of CCT’s conditions can be divided into subsets. One of them $\left\{z \in S^+\right\}$ can be described by operability levels $N^j_r \geq N^j_r$ and $Q^j_r < Q^j_r$.

Probability of finding a plant in the aggregate condition $S^+$, i.e. the availability coefficient for producing electrical power and thermal output in relation to a fixed working capacity level for a period of time $t$ is determined by the formulas

$$p_u(t) = K^+ (N^j_r, t) = \sum_{z \in S^+} P^z (N^j_r > N^j_r, t) = 1 - \sum_{z < S^+} P^z (N^j_r < N^j_r, t)$$

(10)
Mean integral values of availability factors for the period $T$ are

$$K_{\phi}^{\phi}(N_s) = \frac{1}{T} \int_{0}^{T} K_{\phi}^{\phi}(N_s, t)dt, \quad K_{\phi}^{\phi}(Q_s) = \frac{1}{T} \int_{0}^{T} K_{\phi}^{\phi}(Q_s, t)dt$$

(12)

The average value of the CCT failure flow parameter is determined as the sum of the multiplied probabilities of failures of the operability to the intensity of the system transitions from the range of the corresponding operable conditions $S^+$ to the inoperative condition $S^-$, i.e.

$$\omega_{\phi}^{\phi}(t) = \sum_{z \in S^+} \left[ P_{z}(t) \sum_{z \in S^-} \lambda_{zj} \right], \quad \omega_{\phi}^{\phi}(t) = \sum_{z \in S^+} \left[ P_{z}(t) \sum_{z \in S^-} \lambda_{zj} \right]$$

(13)

The subset of states $S^+$ contains conditions with varied available power ($N_s, N_p, N_n$) and productivity ($Q_s, Q_p, Q_n$). To account for partial failures of the power plant, it is possible to calculate the availability rate by formulas

$$K_{\phi}^{\phi}(t) = \sum_{z \in S^+} P_z(t) \bar{N}_{\phi}^{\phi}, \quad K_{\phi}^{\phi}(t) = \sum_{z \in S^+} P_z(t) \bar{Q}_{\phi}^{\phi}$$

(14)

Where $\bar{N}_{\phi}^{\phi}, \bar{Q}_{\phi}^{\phi}$ is the relative electrical and thermal power capacity of the power plant in the $z$-th condition.

The developed method for calculating reliability indexes of CCT and power supply systems based on them, was used to solve the problems of providing a specified (optimal) level of system reliability by using the optimal redundancy method.

6. Conclusion

- A probabilistic model is developed for calculating the reliability indexes of combined multipurpose heat and power plants in heat-and-power supply systems. The complex of models and calculation programs can be used to solve a wide range of specific tasks of optimization of schemes and parameters of combined heat and power plants and systems, as well as determining the efficiency of various redundancy methods to ensure specified reliability of power supply.
- It was established that reliability indexes of multipurpose combined plants are interdependent. Calculation of reliability indexes of thermal-clamping plants should be made for each type of energy produces to consumers.

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