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Mathematical Models and Methods of the Analysis and Optimal Synthesis of the Developing Pipeline and Hydraulic Systems

Optimization of reliability parameters structure for district heating systems

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Abstract. The problem of reliability parameters distribution on the district heating system's scheme is considered. This is one of important part of the general problem of optimal synthesis of district heating systems and is urgent for both the systems under design and the existing insufficiently reliable systems. The concept of solving the problem is based on the average reliability parameters of components (failure and restoration rates) which determine the first approximation to the optimal solution. This parameters needs for the further distribution its average values among system components. Algorithm and mathematical models for determine of optimal reliability parameters of system components with provide the required level of heat supply reliability and minimal total costs on ensuring this level are developed. The methodology of solving the stated problem is based on the methods of the theory of hydraulic circuits, nodal reliability indices, models of Markov random process and general regularities of heat transfer processes. The methodology also takes into account changes in thermal loads during the heating period and time redundancy of consumers related to heat storage.

Keywords: district heating system; reliability optimization; nodal reliability indices; component reliability; failure and restoration rates; Markov random process.

1 Introduction

District heating systems (DHS) is the most important component in support of vital activity of population and development of all economic branches. High socio-economic significance of the heat supply sphere imposes heavy demands to reliability of DHS that combine heat supply sources (HS) and heat networks (HN) in the unified structure.

There exist different methods for the analysis and optimization of reliability of HS and energy sources in general. These methods can be divided into analytical ones [1–5] based mainly on the Markov or semi-Markov processes, logical-and-probabilistic methods and methods of statistical modeling [1, 6, 7].

The general principles of calculating reliability and redundancy of HN of large DHS were formulated in 1972 in [8]. The approach that is based on the evaluation of nodal reliability indices was developed later at Siberian Energy Institute, now it is Melentiev

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Energy Systems Institute of SB RAS [1, 9]. Along with the nodal approach to reliability assessment of HN there is another concept that is based on the integral reliability index [10]. Many aspects of HN reliability problems are common with similar tasks for other energy networks or pipeline systems (oil, gas, electricity etc.), e.g. [11–15].

It should be noted that all these methods relate to separate subsystems of DHS – HS or HN. This don't let to get a total system estimation of heat supply reliability. For deliverance of this shortcoming the authors worked out several methods and models for comprehensive (complex) analysis of DHS, e.g. [16–19]. This paper is devoted to optimization of component reliability as one of the major tasks of reliability synthesis of DHS.

2 Methodology for solving the problem of reliability parameters structure optimization for DHS

The specified values of reliability parameters of DHS components are improved or provided by reducing their *failure rates* and improving their *restoration rates* that is reduction in the restoration time. Statement of the optimization problem of reliability parameters structure optimization for DHS consists in determining the reliability parameters of it components (failure and restoration rates), which provide the required level of heat supply reliability at the minimum costs of ensuring these parameters and constraints on technically possible values. According to the methodology for DHS reliability analysis which is presented in [1], the required level of heat supply reliability is determined by the standard values of two nodal reliability indices: failure-free operation probability (FOP) R_j^0 and availability factor (AF) K_j^0, that are specified for all $j \in J$, where j – number of consumer, J – set of consumers.

Solving of the stated problem based on the concept of *average reliability parameter* of components. Average reliability parameter of components is taken to mean their failure or restoration rate that preliminarily has the same value for these components, which provides the required level of reliability indices. These parameters are determined by the formulas intended for the calculation of nodal reliability indices of DHS [1, 16, 19], Rossander equation that determines annual heat load curves of consumers [20], and some basic laws of district heating and thermal physical processes involved in DHS [20].

Thus, mathematical formulation for the optimization of reliability parameters of DHS components is follow:

$$F_{\text{obj}} = \sum_{n \in N} f_{n\lambda}(\lambda_n) + \sum_{n \in N} f_{n\mu}(\mu_n) \to \min; \tag{1}$$

$$\bar{\lambda}_j = \frac{1}{\tau_\text{o}}[\ln(1/R_{\text{o}j})] \times \left(1 - N_s(1 - K_{\text{o}j}) \Big/ \sum_{s \in E} L_s^{\sigma_j}\right)^{-1} \times \left(\sum_{s \in E} M_s^{\sigma_j}\right)^{-1}; \tag{2}$$

$$L_s = \frac{1}{1 - \omega_j}\left[1 - \frac{1}{q_{\text{o}j}}\left(q_{sj} + \varphi_j t_{sj} - \varphi_j \frac{C_1 - C_2 \exp B_j}{C_3(1 - \exp B_j)}\right)\right]; \tag{3}$$

$$M_s = \frac{1}{1 - \omega_j}\left(1 - \bar{q}_{sj} + \frac{\varphi_j t_{sj}}{q_{\text{o}j}} - \varphi_j \frac{C_1 - C_2 \exp B_j}{C_3 q_{\text{o}j}(1 - \exp B_j)}\right); \tag{4}$$

$$\bar{q}_{sj} = q_{\text{o}j} / q_{sj}, s \in E, j \in J; \tag{5}$$

$$C_1 = t_{\text{o}j}(1 - \bar{q}_{sj}), C_2 = t_{j\min} - t_{\text{o}j}\bar{q}_{sj}, C_3 = 1 - \bar{q}_{sj};\ B_j = 1/(\varepsilon_j \bar{\mu}_j),\ j \in J; \tag{6}$$

$$\overline{\lambda}_j \sum_{s\in E} p_s = \sum_{n\in N} \sum_{s\in E(n)} \lambda_n p_s,\ j\in J; \tag{7}$$

$$\overline{\mu}_j \sum_{s\in E} p_s = \sum_{n\in N} \sum_{s\in E(n)} \mu_n p_s,\ j\in J; \tag{8}$$

$$p_s\left(\sum_{n\in N(s)}\lambda_n + \sum_{n\in N(s)}\mu_n\right) = \sum_{z\in E(s)}\left(\sum_{n\in N(z)} p_z\lambda_n + \sum_{n\in N(z)} p_z\mu_n\right),\ s\in E; \tag{9}$$

$$\mathbf{A}\mathbf{x}_s = \mathbf{q}_s,\ s\in S; \tag{10}$$

$$\overline{\mathbf{A}}_s^{\mathrm{T}}\mathbf{p}_s = \mathbf{h}_s - \mathbf{H}_s,\ s\in S; \tag{11}$$

$$\mathbf{S}\mathbf{X}_s\mathbf{x}_s = \mathbf{h}_s,\ s\in S. \tag{12}$$

$$\lambda_n^{\min} \le \lambda_n \le \lambda_n^{\max},\ n\in N;\ \ \mu_n^{\min} \le \mu_n \le \mu_n^{\max},\ n\in N; \tag{13}$$

Here: $f_{n\lambda}(\lambda_n)$, $f_{n\mu}(\mu_n)$ – cost functions of ensuring reliability parameters of components, i.e. their failure and restoration rates, respectively, rub.; $\overline{\lambda}_j$ и $\overline{\mu}_j$ – average failure and restoration rates for consumer j, respectively, 1/h; τ_0 – time instant corresponding to a total number of hours of the considered (heating) period, h; N_s – the quantity of system states; s – number of system state; E – set of system states; ω_j, σ_j – irregularity factors of heat load curve of consumer j [20]; φ_j – coefficient of specific heat losses for consumer j, GJ/(h°C); t_{sj} – current (actual) internal air temperature for consumer j in system state s, °C; $\overline{q}_{sj}$ – relative heat supply to consumer j in system state s, GJ/h; t_{0j} – design temperature of internal air for consumer j, °C; $t_{j\min}$ – minimum admissible temperature of internal air for consumer j, °C; q_{sj} – level of heat supply to consumer j in system state s, GJ/h; ε_j – coefficient of thermal energy storage for consumer j, h; $L_s, M_s, C_1, C_2, C_3, B_j$ – assumed abbreviations of expressions; p_s – probability of system state s; n – number of system component; N – set of system components; $E(n)$ – is a subset of system states for which the system can transition because of failure or restoration of component n; λ_n, μ_n – failure or restoration rates of component n, 1/h; p_z – probability of the system state z (division of state into s and z is necessary to write the system of equations of random process); $N(s)$ – subset of system components whose failure or restoration corresponds to a direct transition of the system from state s to some other state z; $N(z)$ – subset of system components whose failure or repair corresponds to a direct transition of the systems from state z to some other state s; $E(s)$ – subset of the system states from which the system can transition to state s; $\mathbf{A}_s$ – incidence matrix of linearly independent nodes in the network under emergency system state s (considering failure of some component); $\overline{\mathbf{A}}_s^{\mathrm{T}}$ – full transposed node-branch incidence matrix; $\mathbf{x}_s$ – vector of heat carrier flow rates in the network sections (branches) under emergency system state s, t/h; $\mathbf{q}_s$ – vector of flow rates at network nodes under emergency system state s, t/h; $\mathbf{p}_s$ – vector of nodal pressures of HN under emergency state s, mm wc; $\mathbf{h}_s$ – vector of heat losses in the sections under the emergency system state s, mm wc; $\mathbf{H}_s$ –

vector of operating heads at sources in the emergency system state s, mm wc; $\mathbf{S}, \mathbf{X}_s$ – diagonal matrices of coefficients of hydraulic resistance of sections, m/(h2t2), made up from the values of hydraulic resistances of sections and absolute values of flow rates in them, t/h; $\lambda_n^{\min}, \lambda_n^{\max}$ – minimal and maximal available values of failure rate for component n (1/h); $\mu_n^{\min}, \mu_n^{\max}$ – minimal and maximal available values of restoration rate for component n (1/h).

The form of functions (1) and their quantitative parameters are determined by the methods of approximation on the basis of an analysis of the actual data mainly on the costs of equipment with different reliability characteristics and establishing and maintaining the emergency and restoration services. The rationale of using the Markov model (9) as well as the other aspects of using the tool of Markov random processes in the problems of DHS reliability are considered in more detail in [1, 16, 19]. The hydraulic conditions in HN are calculated by the methods of theory of hydraulic circuits [9] with using the nodal and matrix form of model of flow distribution (hydraulic conditions) in the network (10)–(12).

3 Case study

Consideration is given to DHS scheme presented in Fig. 1-a. The scheme consists of two district heat sources (HS1 and HS2), seven consumers (nodes 1–7) and circuit HN consisting of 18 sections (components). An aggregate scheme of components for both HS is demonstrated in Fig. 1-b,c and consists of boilers 19, 25; turbines 20, 26; network heaters 21, 23, 27, 29; network pumps 22, 24 and 28, 30.

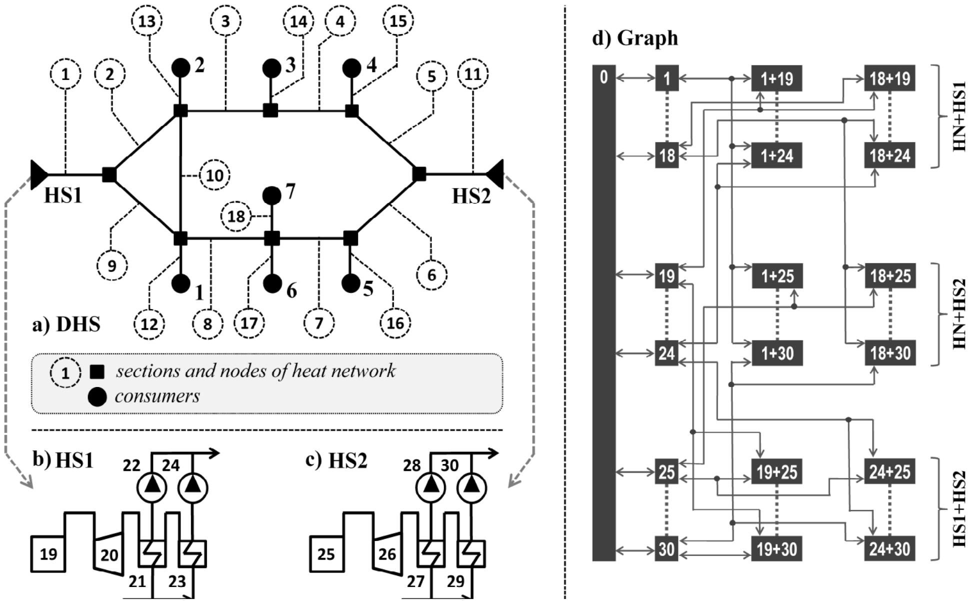

Fig. 1. Schemes of case study: a) general scheme of DHS; b) simplified scheme of HS1; c) simplified scheme of HS2; d) graph of DHS states and relation between them.

The random process of DHS operation is modeled for the following conditions: each component can be in two states – operable and failed, and the flow of events within one subsystem (HN, HS1 and HS2) is the simplest. The latter condition suggests a simultaneous failure of components only from different subsystems of DHS. Here we will confine ourselves to the consideration of the state when no more than 2 components fail at once. Thus, the set of states is formed by individual states of HN, HS1, HS2 and combinations of these states for HN+HS1, HN+HS2 and HS1+HS2. The graph of DHS states in a reduced form is presented in Fig. 1-d. The results of the calculation of probabilities of system states and post-emergency hydraulic conditions are not presented due to a large data array.

The reliability parameters of the DHS are optimized provided the following standard values of nodal reliability parameters [1] are met: for AF – 0,97 and FOP – 0,905. The following ranges of possible values of optimized reliability parameters of the DHS components are assumed: 0,0002–0,0025 1/h – for failure rate; 0,007–0,09 1/h – for restoration rate.

Results of search for an optimal solution on the choice of reliability parameters of DHS components with the required reliability level are presented on Fig. 2. The GAMS software package is used as a solver.

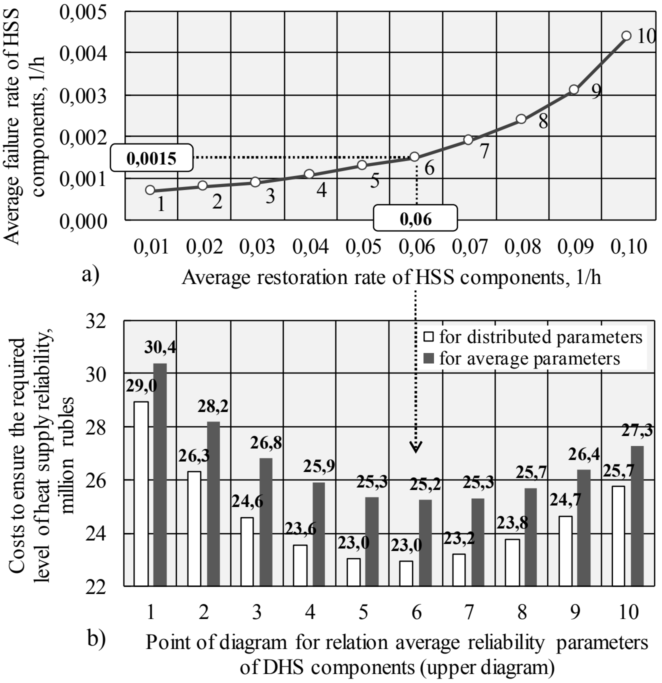

Fig. 2. Results of search for optimal reliability parameters of DHS components: a) relationship among average failure and restoration rates of DHS components; b) costs to ensure the required reliability level of heat supply to consumers.

The diagram on Fig. 2-a demonstrates the relationship between the average reliability parameters (failure and restoration rates) of the components. The diagrams on Fig. 2-b shows a change in the costs to ensure the required level of heat supply reliability depending on relationship of average reliability parameters for their optimal distributed among components and without this distribution. The solution obtained under the specified conditions corresponds to the reliability costs in the amount of 25,2 million rubles (per year) for average reliability parameters of components under the following values of average reliability parameters: failure rate – 0,0015 1/h, restoration rate – 0,06 1/h (point 6); and 23 million rubles for optimal distributed its average values among components. Thus, the economic effect with the optimal distribution of average reliability parameters among components is 2,3 million rubles or 9%.

4 Conclusions

The research suggests a methodology for the optimization of component reliability of DHS within the general problem of its reliability synthesis. The advantages of the proposed methodology compared to the existing approaches to solving this problem consist in joint optimization of the component reliability of HS and HN schemes, integration of procedures for the reduction in failure rates and the improvement in restoration rates of the components in the search of the optimal system reliability.

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