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Methodology for optimization of component reliability of heat supply systems

Ivan Postnikov*, Valery Stennikov, Ekaterina Mednikova, Andrey Penkovskii

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Science (ESI SB RAS), ESI SB RAS, Lermontov St., 130, Irkutsk 664033, Russia

HIGHLIGHTS

- Presented methodology for optimization of component reliability of heat supply system.
- Presented mathematical models for determine optimal reliability parameters.
- Considered case study illustrating applying of models and methods.

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ABSTRACT

The paper suggests a methodology to determine optimal reliability parameters (failure and restoration rates) of heat supply system components, which provide the required level of heat supply reliability. The methodological approach consists in the economically rational distribution of the total effect of reliability improvement among the system components, which is calculated using the average reliability parameters of the components. This task, along with the task to ensure structural reliability, is one of the key reliability tasks within a more general problem of optimal synthesis of heat supply systems and is urgent for both the systems under design and the existing insufficiently reliable systems.

The methodology of solving the stated problem is based on the methods of the theory of hydraulic circuits, nodal reliability indices of heat supply, models of Markov random process and general regularities of cogeneration and 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. The results of the practical research based on the calculation experiment that confirms the viability of the presented methodology for the schemes of real heat supply systems are presented.

The advantages of the proposed methodology compared to the existing approaches to solving this problem consist in joint optimization of the component reliability of heat source and heat network schemes, integration of procedures for the reduction in failure rates and the improvement in restoration rates of the components in one calculation pattern of search for the optimal system reliability, the absence of the need to conduct iterative calculations when using the average reliability parameters of components, considering the required levels of reliability indices.

1. Introduction

Heat supply 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 heat supply systems (HSS) 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 HSS, HN, HS and energy sources in general. These methods can be divided into analytical ones [1–13] based mainly on the Markov or semi-Markov processes, logical-and-probabilistic methods and methods of statistical modeling [1,14–19].

The methods of the first group [1–13] treat heat sources as a combination of functionally connected components integrated into a scheme for reliability calculation. Application of the Markov model for the reliability analysis of complex heat source schemes is conditioned by a high dimension of systems of equations of a random process, whose solving is not difficult on the current computers. However, in some cases the decomposition method that is known from the theory of technical system reliability is used to reduce the volume of calculations

* Corresponding author.
E-mail addresses: postnikov@isem.irk.ru (I. Postnikov), sva@isem.irk.ru (V. Stennikov), yakimetse@isem.irk.ru (E. Mednikova), penkoffsky@isem.irk.ru (A. Penkovskii).

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Nomenclature

Reliability indices

K_j nodal availability factor (AF)
K_j^0 standard value of AF
R_j nodal failure-free operation probability (FOP)
R_j^0 standard value of FOP

Sets

i number of system component
I set of system components
$I(s)$ subset of system components failure or restoration of which corresponds directly (without intermediary states) to transit from state s to some other state z
$I(z)$ subset of system components failure or restoration of which corresponds directly (without intermediary states) to transit from state z to some other state s
$I'(s)$ set of system components failure of which corresponds directly (i.e. without intermediary states) to transit to some state s
j number of consumer
J set of consumers
s,z numbers of system state
E complete set of system states
$E(s)$ subset of system states from which the system can directly (without intermediary states), transit to state s
$E(p)$ complete set of system states except for state $s = 0$
E_i set of system states from which the system can make a transition related to the failure and restoration of component i

Variables

p_0 probability of totally operable system state
p_s,p_z probability of system state s and z respectively
λ_i failure rate of component i (1/h)
μ_i restoration rate of component i (1/h)
$\overline{\lambda}_{jR}$ average rate of the system component failures determined when the requirements for FOP are met (1/h)
$\overline{\lambda}_{j(RK)}$ average failure rate which is determined with respect to consumer j when meeting the requirements for FOP and AF (1/h)
$\overline{\mu}_{j(RK)}$ average restoration rate which is determined with respect to consumer j when meeting the requirements for FOP and AF (1/h)
τ_0 duration of the heating period (h)
τ_{sj} part of the heating period within which state s is a failed state for consumer j (h)
$\overline{\tau}_{sj(K)}$ average index τ_{sj} which satisfies the required value of AF (h)
q_{sj} level of heat supply to consumer j at system state s (GJ/h)
q_{0j} design heat loads of consumer j (GJ/h)
q_{bj} heat loads of consumer j at the beginning of the heating period (GJ/h)
q_{avj} heat loads of consumer j average for the heating period (GJ/h)
$\overline{q}_{sj}$ relative heat supply to consumer j at system state s (GJ/h)
$\alpha_j,\omega_j,\delta_j$ heat load curve irregularity factor of a consumer
φ_j coefficient of specific heat losses in building of consumer j (GJ/(h °C))
t_{sj} current (actual) internal air temperature at consumer j in the system state s (°C)
t_{ex} current external air temperature (°C)
$t_{j\min}$ minimum admissible internal air temperature for consumer j (°C)
t_{exsj} external air temperature under which the consumer time redundancy will be equal to the restoration time of its rated heat supply (°C)
β heat storage coefficient of buildings (h)

Constraints

$\lambda_i^{\min}$ and $\lambda_i^{\max}$ minimal and maximal available values of failure rate for component i (1/h)
$\mu_i^{\min}$ and $\mu_i^{\max}$ minimal and maximal available values of restoration rate for component i (1/h)

Matrices and vectors

$\mathbf{A}_s$ incidence matrix of linearly independent nodes in the network for system state s
$\mathbf{x}$ vector of heat carrier flow rates in the network sections (t/h)
$\mathbf{g}_s$ vector of heat carrier flow rates at the nodes of the calculated scheme (t/h)
$\overline{\mathbf{A}}_s^T$ transpose of matrix $\overline{\mathbf{A}}$ ($\overline{\mathbf{A}}$ – total incidence matrix of nodes and branches in the network scheme)
$\mathbf{p}$ total vector of pressures at nodes of the network (mwc)
$\mathbf{h},\mathbf{H}$ vectors of head losses and operating heads in the branches, respectively (mwc)
$\mathbf{S}$ diagonal matrix of hydraulic resistances of branches (m/h^{2}t^2)
$\mathbf{X}$ absolute values of flow rates in branches (t/h)

Functions

$f_{\lambda i}(\lambda_i)$ cost function of ensuring (reducing) failure rates of system components (million roubles)
$f_{\mu i}(\mu_i)$ cost function of ensuring (increasing) restoration rates of system components (million roubles)

and construct more compact models. In particular, according to the technique for heat source reliability analysis in the initial scheme to be calculated is divided into individual and independent subsystems (blocks of elements or branches) and the reliability indices are calculated based on some specified algorithm for each subsystem. Then the reliability indices of an entire HS are determined on the basis of simple dependences in terms of series connection of subsystems. Such an approach is applicable to the object, whose elements are connected by the technologically common process and considerably simplifies the calculation, though the assumption on independence of subsystems introduces some error.

Application of the semi-Markov processes allows the description of HS operation that is more close to real conditions. Their main difference from the Markov models lies in failure formulation. The latter for the models of the semi-Markov processes is understood as an event that involves not only a decreased volume of heat energy output by a heat source below the required one and its stay in such a condition for the time exceeding the time reserve that is needed basically for heat accumulation, hot water reserves and other factors. The authors of the approach [7] call it functionally technological. It suggests joint application of the probabilistic models of functioning and deterministic models of thermo-physical processes, which essentially complicates calculations, but results in a more accurate reliability characteristic.

The alternative methods for reliability assessment of HS are based