Methodology for Comprehensive Hierarchical Reliability Assessment and its Application to Heating System Operation and Expansion

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Abstract— **This paper highlights the importance of a comprehensive hierarchical approach to the heating system reliability analysis. The core idea behind it is to integrate the methods and models used to assess the reliability of individual subsystems constituting heating systems, such as thermal energy sources and heat networks. This assessment accounts for a range of significant internal (systemic) and external factors. The main principles, provisions, and components of the methodology for the comprehensive hierarchical reliability analysis of heating systems are given. The methodology is employed in the key tasks related to assessing and ensuring (synthesizing) the operation of the studied systems. Building on the methodological approaches, models, and algorithms designed for the said analysis, this study introduces formulations, methods, models, and computational tools for new tasks of the long-term advancement of modern heating systems. These systems encompass both district and distributed thermal energy generation, featuring prosumer subsystems. The paper synthesizes the findings from the recent studies conducted by the contributing authors.**

Index Terms — **Comprehensive hierarchical reliability analysis, ensuring reliability, heat supply effectiveness, heating system, Markov random process, nodal cost of thermal energy, nodal reliability indices, radius of cost-effective heat supply, reliability, the theory of hydraulic circuits.**

I. Introduction

The monograph [1] presents an extensive review of the literature on methods designed to study the reliability of heating systems (HSs) and their subsystems, such as thermal energy sources (TESs) and heat networks (HNs). The analysis of research in the field of HS reliability reveals that in the current scientific, methodological, design, and operational practice, various reliability tasks are addressed separately for TESs and HNs in accordance with their technological structure. It also involves quantitative identification of various reliability properties for these subsystems and their components without exploring integral synergetic effects. In addition, analysis of the heat supply reliability fails to consider potential disruptions in the fuel supply to TESs (possible fuel shortages). Dividing the tasks overlooks the systemic characteristics of the heating system and ignores mutual interdependencies between individual system components that affect the overall reliability of heat supply. These characteristics become most evident when several TESs operate concurrently within a single heating system and when district-distributed and integrated heating systems are designed with technologically diverse components interconnected horizontally and vertically through complex connections.

Thus, the technological connectivity, continuity, and mutual influence of the thermal energy production and distribution processes in the heating system, as well as the fuel supply to TESs, justify a comprehensive hierarchical approach to the study of their reliability. This approach aims primarily to determine the integral impact of all

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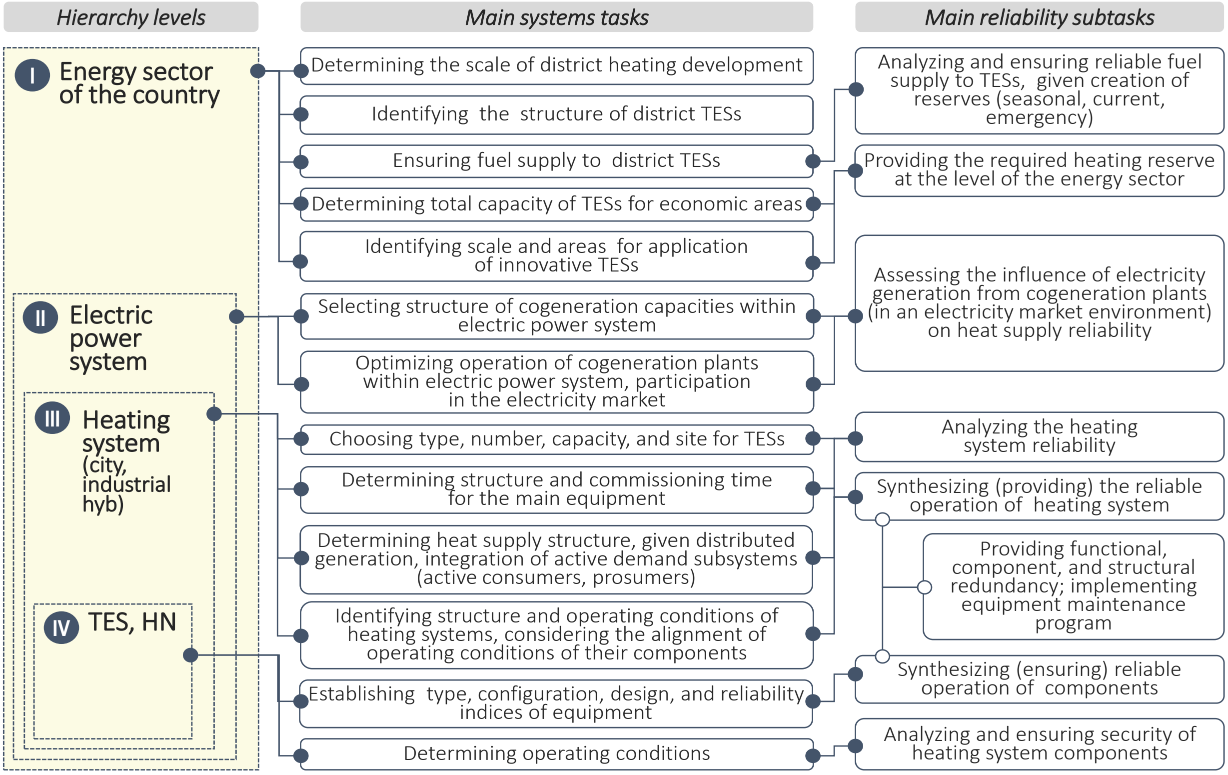

Fig 1. Main reliability tasks in managing the heating system expansion across various hierarchical levels.

subsystems on the reliability of heat delivery to consumers. Another important task is the decomposition of reliability, i.e., a quantitative assessment of the extent to which each of the considered subsystems and their components affect the level of heat supply reliability. The methodology of the comprehensive hierarchical analysis of the heating system reliability and its practical applications are described in [2–5]. These approaches underlie the methodology developed to ensure the component reliability of heating systems [6, 7]. This study identifies the reliability tasks within the overall framework of tasks related to heating system operation and expansion management. This paper discusses the study focusing on enhancing methods and models for comprehensive hierarchical reliability analysis of heating systems. It examines how the enhanced methods can be applied to various tasks within the studied systems, including those aimed at ensuring their reliability and some associated tasks, since addressing them holistically provides a more effective system result.

II. RELIABILITY TASKS WITHIN THE OVERALL STRUCTURE OF OPERATION AND EXPANSION MANAGEMENT TASKS OF MODERN HEATING SYSTEMS

The main system-wide tasks of the heating system expansion and the reliability subtasks identified within them are considered at four levels of the system hierarchy presented in Fig. 1. The structure of tasks given in [8] serves as the basis for this scheme. At level I (the energy sector of the country and regions), the scale of heating system expansion in the country and individual regions is optimized within the study of the energy sector, which links the heating system expansion within the country with the evolution of the energy sector structure and determines their interdependence. The study of the reliability subtasks at this level involves analyzing and ensuring reliability of fuel supply to TESs with the creation of reserves, providing the necessary functional reserves for thermal capacity and supplying consumers with thermal energy at the level of the energy sector.

Level II (electric power systems (EPSs)) covers two sets of tasks: analyzing the total capacities and operating conditions of power plants, including thermal power plants, planning their development for the next 5 to 15 years, as well as assessing the feasibility of introducing new types of equipment. When considering the heating system reliability, it is essential to evaluate how the electricity generation from cogeneration power plants, operating within the electric power system and within the heating system, affects the reliability of supplying thermal loads connected to them.

Level III (heating systems of a city or an industrial hub) involves selecting a strategy for the optimal expansion of the system to accommodate various types of fuel. It also includes calculating the optimal capacity, structure, and timing of the main TES equipment introduction, along with specifying routes and parameters of heating mains. The tasks are specified depending on the timeframe in which the system is considered, including future development within heating systems (10–15 years), since this is the stage where the number, type, capacity, and sites for district TESs are selected. The heating system topology is optimized enabling the implementation of prosumer subsystems and other technological and structural transformations. This level focuses on analyzing and ensuring the reliability of heating systems, finding solutions on their functional and topological redundancy,

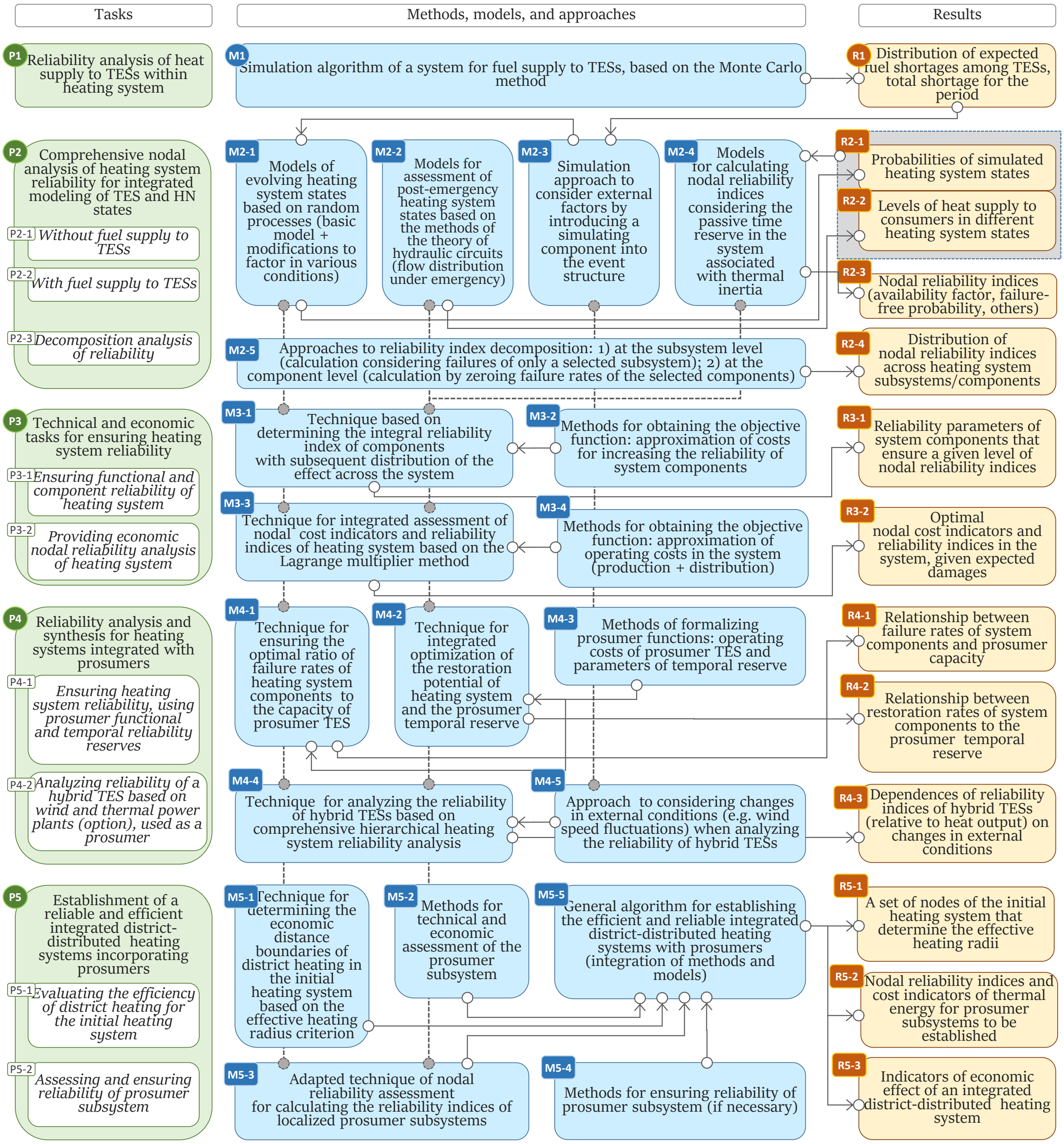

Fig 2. Hierarchical reliability analysis methodology for heating system operation and expansion management.

scheduling of equipment maintenance, and others.

Level IV (TES and HN) comprises an optimal selection of types, configurations, and parameters of components or subsystems within heating systems, i.e., TESs and HNs; as well as the expansion and planning of their operations. The tasks of reliability analysis and synthesis are similar to those of the level of heating systems, but include decomposition for individual subsystems. Additionally, the operational reliability of facilities related to the optimal control under emergency conditions is addressed.

The reliability analysis and synthesis tasks within the framework of the evolving methodology for comprehensive hierarchical reliability analysis of the fuel supply systems relate to Levels III and IV (fuel supply systems and subsystems). Analyzing and ensuring fuel supply reliability are a multiscale task that spans all levels of systems and the entire energy sector. However, when it comes to TESs functioning within heating systems, this task is considered at Levels I, III, and IV. When formulating strategies for reliability tasks within the broader context of the fuel supply system operation and expansion, it is crucial to consider the mutual influence of the results yielded at different levels, ensuring their iterative interaction to obtain balanced solutions based on forward and backward hierarchical connections.

III. Development Of Methods for a Comprehensive Hierarchical Analysis of Heating System Reliability and Their Application to Enhance Heating Systems

The tasks involved in developing the methodology for comprehensive hierarchical reliability analysis of heating systems are illustrated by a block diagram. This diagram is divided into three parts – formulations of tasks, methods, and results obtained. The entire set of tasks is divided into 5 blocks, as shown in Fig. 2.

Block 1 (P1). Reliability analysis of fuel supply to TESs operating within heating systems. This analysis utilizes the proposed methodological approach for assessing expected fuel shortages at TESs.

The approach is based on the statistical testing method (the Monte Carlo method) using actual data on fuel supply and demand. An algorithm is designed to assess the reliability of the heating system, which factors in various modeling conditions, with a particular emphasis on creating current reserves and ensuring fuel interchangeability. By implementing various fuel supply scenarios, the distribution of expected fuel undersupply to TESs is determined for specified time intervals, and that of the total shortage for the period. The results obtained hold independent significance and can serve as a basis for assessing a potential reduction in thermal energy supply from the TES in the heating system under study to be employed in the next block of tasks. Studies on Block 1 are given in [9, 10].

Block 2 (P2). Comprehensive nodal analysis of the heating system reliability by simultaneously modeling the TES and HN states. The group of TES states contains those corresponding to a reduction in productivity and thermal energy supply resulting from expected fuel shortages determined in Block 1. The research methodology encompasses the following methodological tools: models of the heating system state evolution obtained on the basis of Markov random processes; models for assessing post-emergency conditions in the heating systems based on the methods of the theory of hydraulic circuits (THCs); a simulation approach for considering various external factors by introducing a simulating component (SC) into the event structure; models for calculating nodal reliability indices (RI) that factor in the passive time reserve in the system, which is associated with the thermal inertia of heat pipelines and buildings. Two groups of intermediate results (probabilities of states of the simulated heating system and levels of heating delivery to consumers in these states) are jointly used to obtain the final result in the form of a vector of nodal reliability indices (availability factor, reliability of failure–free operation, others), which identify the distribution of reliability among consumers of the system under study. This stage involves formulating methodological principles for determining the main nodal reliability indices, designing models for calculating reliability indices based on the integration of the results of stochastic and physical-technical modeling of states corresponding to failures of TES and HN components, including the states corresponding to disruptions in the fuel supply to TESs. In this stage, methodological approaches to the physical-technical assessment of emergency conditions of the heating systems are given, which facilitates the assessment of the consequences of modeled failures. Based on the adopted regulatory requirements for the values of reliability indices, groups of consumers with heat supply disruptions are identified. Reliability decomposition reveals the contribution of subsystems and components, allowing for the assessment of the distribution of nodal reliability indices among the heating system subsystems and/or their components. The scientific and methodological developments of Block 2 are presented in [2–5, 11, 12]. The methodological tools developed in Block 2 are interconnected with all subsequent Blocks addressing reliability tasks, since they are used to various degrees of detail at all stages of calculating nodal reliability indices. Figure 2 demonstrates this relationship by dotted lines.

Block 3 (P3). Heating system reliability in technical and economic tasks that include 1) ensuring the functional and component reliability of the heating system and 2) economic nodal analysis of the heating system reliability. Within the first task, a methodology was designed to ensure the functional and component reliability of the heating system. The idea behind it is to distribute the integral reliability parameter (failure or recovery rate) preliminarily calculated to meet the requirements for the reliability indices among the system components following the technical and economic criterion. The nodal analysis employs the methodology devised to jointly model and evaluate the nodal reliability indices and costs of the heating system based on the Lagrange multiplier method. The obtained indices make it possible to determine the optimal operating conditions of the system according to the economic criterion, given the reliability in the range of acceptable technical conditions, and to identify the system's "bottlenecks" corresponding to the maximum economic losses resulting from a heat supply disruption. Both tasks require determining the values of the objective functions associated in the first case with the reliability costs (component redundancy) and in the second case - with the operating costs in the system. These functions are normally obtained using approximation methods of the corresponding cost parameters. Methodological developments for the tasks of Block 3 are discussed in [6, 7, 13, 14].

Block 4 (P4). Analysis and synthesis of reliability of heating systems integrated with prosumers. This block presents new application areas for the methods of heating system reliability analysis and synthesis, considering the technologies for integrated energy systems. Methods are proposed to address heating system reliability and management from an integrated system perspective. The focus is on the integration of thermal energy prosumers with their distributed self-generation into the technological structure of heating systems. The self-generation has the function of enhancing the efficiency and reliability of the systems. The research employs methodological tools developed for the comprehensive hierarchical reliability analysis of heating systems. Methods are devised to analyze the reliability of a hybrid energy source that integrates a wind farm and a thermal power plant, specifically focusing on thermal energy production, while factoring in the influence of stochastic fluctuations in wind speed. Computational experiments are conducted on a test heating system and hybrid energy source to demonstrate the application of the proposed methods and models. The results of the study conducted within Block 4 are presented in [15–22].

Block 5 (P5). Designing reliable and efficient district-distributed heating systems (DDHSs) with integrated prosumers. Several methods are proposed for analyzing and ensuring the reliability and efficiency of DDHSs. The proposed methods and models are utilized to devise an algorithm for designing DDHSs incorporating prosumers to cover the load that goes beyond the boundary of the district heating cost-effectiveness, which is calculated following the criterion of the effective heat supply range (EHSR). The results from the practical study based on the developed methodology and using an operating heating system to exemplify, are presented. They encompass the identification of the district heating cost-effectiveness areas for the system at issue, technical and economic evaluation for the integration of distributed thermal energy sources at the boundaries of EHSR, the reliability assessment and analysis of activities to ensure reliability within the distributed heating sector. The results for Block 5 are presented in [23–28], some of the studies are at the stage of preparation for publication.

IV. CONCLUSION

The paper focuses on the key reliability tasks of heating systems and their components, emphasizing their relationship with the main system-wide tasks that need to be addressed during the expansion of these systems across various hierarchical levels and timeframes. The study has established that almost all hierarchical levels – from the energy sector of the country and region to the level of each thermal power plant – involve the assessment of heating system reliability and activities to ensure it. The findings suggest that when establishing a methodology to address the reliability tasks of heating systems within the broader context of their operation and expansion, it is essential to take account of the interdependence of the results obtained at different levels and ensure their iterative interaction to generate balanced solutions based on forward and backward hierarchical connections.

The paper presents a general structure of the proposed methodology for comprehensive hierarchical analysis of heating system reliability and demonstrates the application of the corresponding methods to various reliability tasks addressed during the expansion of the studied systems. A general characteristic of the methods employed is given. Overall, the structure of the study rests on the classical theory of systems studies in the energy sector, which was pioneered and advanced at the Melentiev Energy Systems Institute SB RAS. The key methodological principle of the research is the symbiotic nature of tasks and methods developed to address them at various stages and hierarchical levels of the studied objects.

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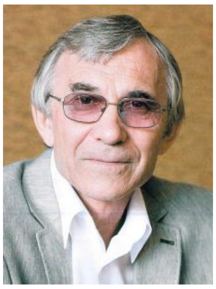

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