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The reliability and availability evaluation of repairable district heating networks under changeable external conditions

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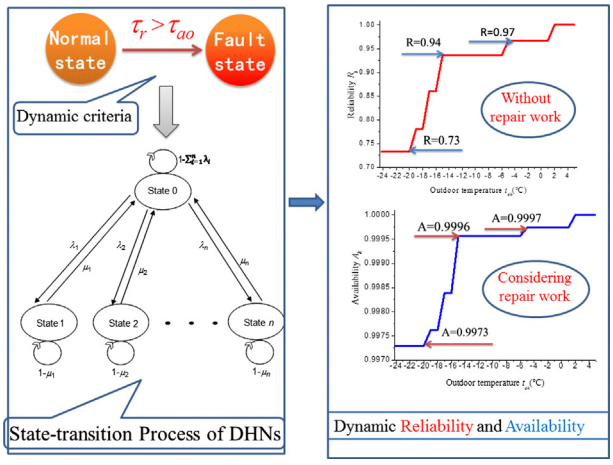
HIGHLIGHTS

- The hypothesis of constant outside temperature in reliability analysis is modified.
- The dynamic state-determination criterion for repairable DHNs is proposed.
- The outside temperature has significant influence on the reliability of DHNs.
- Changing laws of the reliability and availability for DHNs are identified.

GRAPHICAL ABSTRACT



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ABSTRACT

The conventional reliability evaluation of district heating networks is generally based on restrictive assumptions aiming to simplify the reliability assessment process, e.g., the hypothesis of the unrepairable system and constant outside temperature. Due to such simplifications, the reliability indices retain constant and unchangeable during the heating season, which is infeasible to reveal the changeability of reliability of heating networks. Concerning such deficiencies, this paper presents a novel study to modify these assumptions, and further analyze the influence of changeable outside temperature on the reliability of heating networks based on the state-space method. In this study, in terms of the dynamic state-determination criterion, structural and functional reliability indices are proposed to evaluate dynamic reliability of heating networks. In reality, the realistic state-determination is the critical foundation of reliability evaluation, which directly determines the accuracy of the reliability assessment. Hence, the dynamic state-determination criterion is introduced in this study, concerning both the external and internal conditions of consumers. Combined with the state probabilities, functional reliability indices consider two functional parameters, i.e., the heat power and the indoor temperature, to reflect the changeability of heat-supply ability and the resultant effects of failures on internal status of consumers under changeable external conditions. As a pilot study, the proposed reliability evaluation indices are applied to a real looped heating network in Harbin, China. The results indicate that the outside temperature significantly affects the reliability of heating networks. It is observed that the reliability and availability demonstrate a ladder growth with the increasing of outside temperature. According to

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the changeability of reliability, the weaknesses and the key components of the system can be figured out. Therefore, advanced preventive measures can be taken to reduce failures of components and improve the reliability of heating networks.

1. Introduction

Compared with individual heating modes, district heating schemes exhibit two basic advantages of energy conservation and mitigation of air pollution [1–3]. With the rapid revolutions of district heating systems, the heating scales and areas are much larger than ever before. The urban district heating areas in China have grown from 11.1×10^8 to 51.8×10^8 m^2 within ten years. For Beijing area, the total district heating areas have reached to 5×10^8 m^2 in 2014, and the total length of district heating pipelines is 1.2×10^4 km, two-times growth compared with the length in 2005 [4]. As the fast development of district heat-supply system, the heating networks tend to become much more complex and diverse [5]. However, failures of heating networks are inevitable, leading to negative effects on the society and economy. Zou et al. [6] collected failure data of 12 thermal enterprises from 2002 to 2006 in Heilongjiang Province, the coldest climate area of Mainland China, from which the total number of failures was recorded as 1134, among these failures, the faults of pipes, valves and compensators were 631, 274 and 114 respectively. Furthermore, failures of heating networks have hazard effects on residential consumers, and may threaten health or even life of people because of interruptions of heat supply. In turn, this also leads to serious social and economic problems. Solving these problems is possible through the application of the reliability assessment. Because quantitative and accurate reliability evaluation of heating networks could not only determine weak sections of networks, but provide critical guidance for maintenance and optimization of the network in the design and operation phases.

The high failure rates of heating networks in China are mainly due to deficiencies of reliability design and evaluation of heat supply systems. In 1960s, the Russian researcher Ionin firstly proposed failure-free working index R using the Boolean truth method to evaluate the reliability of heating networks [7], in which, R is the ratio of real heating loads to the ordered heating loads, expressed as Eq. (1):

$$R = 1 - \sum_{i=1}^{n} \frac{\Delta Q_i}{Q_0} \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \left(1 - e^{-\sum_{i=1}^{n} \lambda_i t} \right) \quad (1)$$

where Q_0 represents the ordered heating loads, MW; ΔQ_i, the insufficient heating loads caused by the failure of component i, MW; λ_i, the failure rate of component i; t, the total heating time, a; n, the total number of components.

Though revealing the reliability of heating networks in some content, the index is based on restrictive assumptions that are not in consistent with the realistic features of heating networks, as listed in Table 1.

Table 1
Comparison of hypotheses for index R and features of heating networks.

No.	Assumptions	Realistic characteristics
1	Annually unrepairable system	Repairable system
2	Constant outside temperature	Dynamic outside temperature
3	Failures are determined just by disconnection with networks	Failure states rely on thermal conditions of heating networks
4	Without consideration of thermal inertia of networks	Heating networks and buildings both have thermal inertia

In order to reflect the reliability more accurately, researchers have tried to modify these assumptions. Aiming to modify the hypothesis of annually unrepairable system, Cai and Liu [8] regarded the heat-supply system as monthly unrepairable system, and thought the failure- duration is monthly to evaluate the reliability. Zhan and Zou [9,10] investigated that failures of the system varied with months during the heating time, and proposed the coefficient of failure frequency spectrum to modify the annual reliability index. In 2008, Wang et al. [11] used the state-space method to analyze and calculate the steady-state reliability indices of repairable heating systems, e.g. the static heat supply ratio, the availability and reliability of consumers, which is a systematic reliability evaluation of heating networks.

Besides these modifications, researchers also conduct the reliability analysis combined with the attributes and properties of heating systems. Myrefelt [12] calculated the functional availability indices of the heat supply system concerning the indoor temperature under failure conditions with the probabilistic theory. Babiarz and Blokus-Roszkowska [13] used the semi-Markov model to analyze and calculate the steady-state probabilities of six states defined by outside air temperature. Valinčius et al. [14] assessed the failure reliability of district heating networks integrated with the thermal-hydraulic analysis. Stennikov et al. [15] proposed the availability and free-failure probability of consumers to determine if the indoor temperature of consumers reaches the designed level or the minimum allowable level respectively. Concerning the connectivity of heating networks under abnormal conditions, Wang and Zou [16] investigated the connection reliability based on the graphic method, and analyzed the effects of pipe structures on the connectivity reliability of heating networks.

Through reviewing the reliability evaluation approaches, it has been found that these reliability indices are basically under the premise of annually and monthly constant outside temperature without consideration of dynamic factors. In fact, the changeable external conditions and the quality of repair and maintenance have significant influence on thermal loads and internal conditions of consumers. In references [17–19], the influence of outside temperature on the heat power of the system and indoor temperature of consumers is analyzed and investigated. Hence, the heat-supply quality and thermal comfort of consumers are related to the changeable outside temperature.

In order to reflect the changeable laws of reliability during heating time, this study presents a comprehensive, dynamic reliability evaluation model of repairable heat-supply system based on the state-space method with consideration of dynamic external conditions. Furthermore, the influence of outside temperature on the reliability of heating networks is specifically analyzed. The changeability of reliability can be detected when failures randomly occur under changeable outside temperature, and hazards on the internal conditions of consumers can be justified as well. According to the changing laws, the key components and weak heating period can be figured out. Furthermore, effectively preventive measures can be taken to improve the reliability of heating networks and to militate against the effects of failures on consumers.

This paper contains several sections. The dynamic criterion of state determination is proposed for repairable district heating net-