# **ECONSTOR** Make Your Publications Visible.

A Service of

ZBW

Leibniz-Informationszentrum Wirtschaft Leibniz Information Centre for Economics

Postnikov, Ivan; Stennikov, Valery

## Article

# Modifications of probabilistic models of states evolution for reliability analysis of district heating systems

**Energy Reports** 

### **Provided in Cooperation with:** Elsevier

*Suggested Citation:* Postnikov, Ivan; Stennikov, Valery (2020) : Modifications of probabilistic models of states evolution for reliability analysis of district heating systems, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 293-298, https://doi.org/10.1016/j.egyr.2019.11.077

This Version is available at: https://hdl.handle.net/10419/243892

#### Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

#### Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



ND https://creativecommons.org/licenses/by-nc-nd/4.0/







Available online at www.sciencedirect.com



Energy Reports 6 (2020) 293-298



### The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019), September 20–23, 2019, Okinawa, Japan

# Modifications of probabilistic models of states evolution for reliability analysis of district heating systems

# Ivan Postnikov\*, Valery Stennikov

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

Received 4 October 2019; accepted 22 November 2019

#### Abstract

The analysis and synthesis of reliability of energy systems, particularly district heating systems (DHS), is based on probabilistic modeling of different system states and events connecting these states (usually, these are failures and restoration of system components). The paper deals with the problem of modeling the probabilities of DHS states based on a Markov random process under conditions that can be characteristic for actual systems: joint and dependent failures of several components. For this purpose, it probabilistic models of the evolution of events in DHS taking into account non-ordinary events and dependent between them are developed. The methodology is based on the theory of Markov random processes and the basic laws of probability theory. The formation principles of developed models are illustrated by the state graphs. Numerical studies were carried out, the results of which allows determine some properties and application limits of developed models. (© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

*Keywords:* District heating system; Reliability analysis; Probabilistic models; States evolution; Markov random processes; Rate of transition; Failure and restoration rates; Non-ordinary and depending events; Reliability indices; Availability factor

#### 1. Introduction

Mathematical apparatus of reliability theory for simple and complex systems includes a large number of methods: logistics and probabilistic, decomposition, asymptotic, heuristic, statistical, analytical, and analytical and statistical ones in [1–7]. Solution of many reliability problems for technical systems, including district heating systems (DHS) is based on the analytical methods that use data on failures and restoration of system components, methods based on the theory of Markov random processes being among most popular ones by Barlow and Proschan [1], M.Ross [2], Polovko and Gurov [3], Sennova and Sidler [4], Lisnianski et al. [5] and Rudenko et al. [6]. Operation of DHS from the standpoint of probabilistic description is characterized by a sequence of failures and recoveries occurring with

\* Corresponding author. *E-mail address:* postnikov@isem.irk.ru (I. Postnikov).

https://doi.org/10.1016/j.egyr.2019.11.077

<sup>2352-4847/© 2019</sup> Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/ licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

a certain frequency at all the stages of heat production and distribution processes. In the simplest case (at minimum constraints) the sequence of events at DHS is described as a simple occurrence of events associated with conditions of ordinariness, independence and time invariance (stationary) of probabilities of DHS states, and by exponential distribution laws of time for any possible system states. At the same time, in the operation of actual systems, simultaneous events may occur, for example, parallel failures of several system components. Also dependent events can occur, for example, failures of technologically related components. This paper presents probabilistic models based on Markov process to take into account these factors. The main purpose of taking into account these factors is to improve the adequacy of results of modeling to the actual conditions of systems operating.

#### 2. Methods

#### 2.1. Simple stationary Markov model

A stationary Markov model of DHS is represented by the following system of linear algebraic equations (Kolmogorov equations for steady-state conditions) in [8–10]:

$$p_{s} \sum_{z \in E_{1}} \nu_{sz} = \sum_{z \in E_{2}} p_{z} \nu_{zs}, \ s \in E,$$
(1)

where s and z – numbers of states;  $p_s$  and  $p_z$  – state probability; E – all the possible states;  $E_1$  – a subset of states that allow immediate (without intermediate states) transition from state s;  $E_2$  – a subset of states that allow immediate transition into state s;  $v_{sz}$  – rate of transitions from states s into z, where  $z \in E_1$ ;  $v_{zs}$  – rate of transitions from states s into z, where  $z \in E_2$ .

All the transitions between states are related either to failures or restorations of components, therefore, at reliability calculations all the values of  $v_{sz}$  and  $v_{zs}$  correspond either to failure or restoration rates of DHS components, that are usually denoted by symbols  $\lambda$  and  $\mu$ , accordingly. Further two modifications of this model are presented.

#### 2.2. Model with non-ordinary events

7

During operation of such complex system as DHS included subsystems such as heat network, sources (district and distributed), storages etc., a large number of different processes run in parallel, and simultaneous failures of several components are expected to be more probable than within separate DHS subsystems. In case of mutual independence of events the probability of their coincidence is a product of their probabilities by Polovko and Gurov [3], Linton [11] and Garrett [12]. Rate of non-ordinary transitions between DHS states is determined as a product of components failure and restoration rates, subject to their independence:

$$\nu_{sw} = \prod_{k \in E_w} \lambda_k \prod_{l \in E_s} \mu_l, \quad s \in E, \quad w \in E_1^*, \tag{2}$$

where  $v_{sw}$  – rate of non-ordinary transition from state *s* into state *w*;  $E_1^*$  and *w* – a set of states or each state separately the complex may convert into from state *s* due to coincidence of separate events;  $\lambda_k$  and  $\mu_l$  – failure and restoration rates of components *k* and *l* respectively;  $E_w$  – a set of components failed states in case of state *w* occurrence;  $E_s$  – a set of components failed states in case of state *s* occurrence.

Depending on the number of considered simultaneous events, consideration is given to several levels of nonordinary events occurrence, each being associated with a certain type of relations between states. The set  $E_1^*$ describing a set of rates  $v_{sw}$  for all the states *s* is constructed for each level separately. The above conditions being taken account of, the stationary Markov model of DHS operation for a non-ordinary sequence of events (transitions between states) in an aggregate form is expressed as:

$$p_{s}\left(\sum_{z\in E_{1}}v_{sz} + \sum_{u\in U}\sum_{w\in E_{1}^{*}}v_{swu}\right) = \sum_{z\in E_{2}}p_{z}v_{zs} + \sum_{u\in U}\sum_{w\in E_{2}^{*}}p_{w}v_{wsu}, s\in E,$$
(3)

where  $v_{swu}$  and  $v_{wsu}$  – rates of non-ordinary transitions from state s to state w and back for the uth level of events non-ordinariness; U – the number of considered non-ordinariness levels;  $p_w$  and  $E_2^*$  – probability and a set of states from which the complex may go over to state s due to simultaneous occurrence of several events. A graph of non-ordinary transitions between failure states of four (for example) DHS components that corresponds to dual events only is given in Fig. 1-a, b. Each directed line of the graph (in one direction) implies one out of three possible combinations: two failures and two restorations, or one failure and one restoration of components simultaneously. The scheme of graph construction is given in Fig. 1-c, where rates of dual transitions from the state corresponding to failure of two components 1 and 2 into any other probable state are shown on the directed lines.



Fig. 1. A graph of dual events between DHS states: (a), (b) two groups of transitions corresponding to the structure of dual events; (c) scheme of constructing a graph of non-ordinary transitions.

#### 2.3. Model with dependent events

During DHS operation the dependent events may occur along with simultaneous occurrence of several events. A set of DHS states in this case is developed using conventional probabilities by Polovko and Gurov [3], Linton [11] and Garrett [12]. Let us consider component *i* with the failure rate  $\lambda_i$ ; in case of its failure the conventional probability of the component *k* failure equals  $\varphi_{k/i}$ . It is obvious that conventional probability of failure varies within  $0 \le \varphi_{k/i} \le 1$  depending on conditions of operation and scheme of components connection. Rate of dependent failure of component *k* in case of the element *i* failure will be equal to  $\lambda_{k/i}$  and is determined by the value of conventional probability  $\varphi_{k/i}$ :

$$\begin{cases} \lambda_{k/i} = \lambda_k (1 + \varphi_{k/i}) & if \quad 0 \le \varphi_{k/i} < 1, \\ \lambda_{k/i} = \lambda_i & if \quad \varphi_{k/i} = 1. \end{cases}$$
(4)

Rate of non-ordinary failure of  $\lambda_{ik/i}$ , provided that rate of a dependent failure is described by Eqs. (4), is determined similarly to two independent events:

$$\begin{cases} \lambda_{ik/i} = \lambda_i \lambda_k (1 + \varphi_{k/i}) & if \quad 0 \le \varphi_{k/i} < 1, \\ \lambda_{ik/i} = \lambda_i & if \quad \varphi_{k/i} = 1. \end{cases}$$
(5)

Joint use of model for non-ordinary events (3), subject to the use of Eqs. (4)–(5) for determining the rates of dependent events, allows the stationary Markov model of DHS operation with account of both factors to be presented in the following way:

$$p_{s}\left(\sum_{z \in E_{1}} \nu_{sz}(2 \pm \zeta_{z/s}) + \sum_{u \in U} \sum_{w \in E_{1}^{*}} \nu_{swu}(2 \pm \zeta_{w/s})\right)$$
  
=  $\sum_{z \in E_{2}} p_{z}\nu_{zs}(2 \pm \zeta_{s/z}) + \sum_{u \in U} \sum_{w \in E_{2}^{*}} p_{w}\nu_{wsu}(2 \pm \zeta_{s/w}), \quad s \in E$  (6)

$$\begin{array}{l}
0 \leq \zeta_{z/s} < 1, \ \nu_{sz} > \nu_{sz/s}; & 0 \leq \zeta_{w/s} < 1, \ \nu_{swu} > \nu_{swu/s}; \\
0 \leq \zeta_{s/z} < 1, \ \nu_{zs} > \nu_{zs/z}; & 0 \leq \zeta_{s/w} < 1, \ \nu_{wsu} > \nu_{wsu/w};
\end{array}$$
(7)

where  $\zeta_{z/s}$  and  $\zeta_{s/z}$  – conventional probabilities of ordinary transitions of a set from states z to s and back, accordingly;  $\zeta_{w/s}$  and  $\zeta_{s/w}$  – conventional probabilities of non-ordinary transitions of a set from states w into s and back, accordingly;  $v_{sz/s}$  and  $v_{zs/z}$  – rates of dependent transitions from state s into state z and back;  $v_{swu/s}$ ,  $v_{wsu/w}$  – similar indicators for non-ordinary transitions. Each value of  $\zeta_{z/s}$  is associated either with a failure (then  $\zeta_{z/s} = \varphi_{k/i}$ ) or restoration (then  $\zeta_{z/s} = \gamma_{k/i}$ , where k, i are some DHS components). Fig. 2 shows a fragment of the graph of DHS states that reflects construction process of the events structure under availability of dependent failures and restorations on the example of considered components, formulas and symbols introduced.



Fig. 2. A fragment of the DHS state graph with account of dependent events.

#### 3. Results of numerical study

Test computations of aggregate DHS schemes with account of both considered factors (non-ordinary and dependent events) were performed. Fig. 3-a shows the dependence of the average ratio of states probabilities of considered DHS scheme calculated for an ordinary occurrence of events to probabilities calculated for an non-ordinary (in given case double) occurrence of events, on failure rates of system components when they change from 0.0001 to 0.1 1/h. The dependence for probability of the state "0" (full operability) is highlighted by line with square dots. As can be seen from the diagram in Fig. 3-a, significant deviations of probabilities of states correspond to the failure rate values more 0.01 1/h (for example, probability ratio is 14% for the failure rate is 0.1 1/h). For components of actual operating DHSs, as a rule, failure rates are significantly lower than 0.01 1/h, therefore, non-ordinary events can be neglected for most practical calculations of DHS reliability (however, there are exceptions noted in the conclusions).

The stationary availability factor (AF) in the general case is calculated as the sum of probabilities of operating states by Barlow and Proschan [1], M.Ross [2], Polovko and Gurov [3], Sennova and Sidler [4], and in the simplified case corresponds to the probability of full operating state  $-p_0$ . Based on the relationship between the AF and the total time of interruption of heating to consumers of DHS in [4], it is possible to compare the change of its values in the transition from an ordinary to non-ordinary events model. Thus, an increase in the value of  $p_0$  1.5% (for failure rates 0.01 1/h in Fig. 3) corresponds to a decrease of heating time by about 70 h, which is 30% of its admissible level, equal to 230 h (corresponds to AF of 0.96 under the annual heating period of 5700 h).

The dependence of the AF for test DHS on conventional probabilities of dependent events and on the level of DHS components reliability parameters (failure rates) is presented in Fig. 3-b. This diagram shows qualitative relations and allows some conclusions to modeling the dependent events at DHS reliability computation. Thus, the results of calculations show that the reducing of AF is insignificant under a minimal change of failure rates (to the level 0.0002 1/h) in the range of conditional probabilities from 0 to 0.2, compared to their further growth (Fig. 3-b).

Characteristics obtained reflect the decrease in heating reliability against the initial level due to interdependence between DHS components failures rates and dependent events through conventional probabilities. This would allow assessment of required redundancy in the system for the cases of probable emergencies caused by dependent failures (with account of forced outages of components) in the given range of input data for modeling. Such, Fig. 3-c presents the interruption time of designed heating to consumer during annual heating period when changing the conventional probabilities of dependent events. Shown in Fig. 3-c diagram on the one hand, allows us to determine a rational admissible area of conventional probabilities of dependent events, within which the change in reliability is insignificant and can be neglected dependent events.

On the other hand, diagram in Fig. 3-c makes it possible to determine the degree of possible decrease in the reliability of heating to consumers under the impact of dependent events whose probability cannot be accurately assessment. So, for example, in Fig. 3-c, the bottom curve of solid area of the diagram corresponds to the failure



Fig. 3. Results of numerical study: (a) dependence of the relation of states probabilities for test DHS in the case of ordinary and non-ordinary events on failure rates of system components; (b) Dependence of the AF for test DHS on conventional probabilities of dependent events and on the level of DHS components reliability parameters (failure rates); (c) Interruption time of designed heating to consumer during annual heating period when changing the conventional probabilities of dependent events.

rate 0.0001 1/h and the conventional probability of dependent failures 0.45, at which the total time of heating interruption for annual heating period will increase by 500 h/year.

By use of similar characteristics, it is possible to assessment the necessary time and capacity redundancy, providing compensation from possible interruptions of heating to consumers caused by dependent failures of system components.

#### 4. Discussion and conclusion

When solving of reliability problems (analysis and synthesis) for DHS, the mathematical modeling of probabilities of states for different operation modes is carried out, as a rule, on the basis of Markov random processes. In the common case, the probabilistic random process model is described by the simple occurrence of events, which are characterized by ordinary (at the same time there is no more than one failure or restoration) and independence. However, with the operation of actual systems, both non-ordinary as well as dependent events may occur. In this regard, the modeling of such events improve the accuracy of probabilistic describing of operating the system. An approach to the formalization of probabilistic models for DHS into account simultaneous of several events using the rule (law) of their combination under mutual independence is proposed. Dependence between some certain events is taken into account using conventional probabilities of the occurrence of one event when occurrence of another.

Accounting for non-ordinary events usually there are no significant changes in the probabilities values of system states, since according to the condition of multiplying probabilities the larger the number of simultaneous failures contains an event, the less its probability. According to test calculations, changes in the probabilities of states when taking into account non-ordinary events increase with increasing failure rates of system components and reach practically significant values (more than 2%) with greatly high levels of failure rates (more than 0.01 1/h). In this regard, for the majority of practical reliability calculations for the actual systems, the non-ordinary events can be ignored. At the same time, such rare events associated with simultaneous failures lead to "cascade" accidents and complete long-term heating interruptions of consumers. Local assessment of such events is necessary for the decreasing of potential damages by the ensuring of required redundancy and restoration time.

Also, accounting the non-ordinary and dependent events is important for DHS units included components with low reliability (failure rate more than 0.01 1/h) or operating under conditions that significantly reduce the reliability

of equipment operation. This is for example some pipeline sections of heat network, whose service life significant exceeds the admissible standards, or components under the high external loads.

Based on the results of probabilistic modeling, characteristics that allow us assessment the degree of possible (expected) decrease the reliability of heating to consumers under the impact of factors connected with dependent events whose probability cannot be accurately determined (including external factors) were obtained. These characteristics can be used for a preliminary assessment of the necessary redundancy to compensate for the possible heat undersupply to consumers caused by dependent failures of system components including the forced outages.

In any case, the use of models with non-ordinary and/or dependent events should be justified by influence of these factors on the reliability analysis result under operating conditions of considered system. It is also necessary to take into account the high uncertainty of this factors stochastic analyzing of which is very difficult, and that can lead to some deviants in the calculating of reliability indices. In addition, it is recommended that some rare (with low probability) events with significant consequences of failures should be considered separately from the general probabilistic model of system, and their influence should be considered when assessing the survivability of the system, which is the subject of special studies.

#### Acknowledgments

The research was performed at Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences under the support of Russian Science Foundation (Grant No. 17-19-01209).

#### References

- [1] Barlow R, Proschan F. Mathematical theory of reliability. New York: John Wiley and Sons; 1965.
- [2] M.Ross Sheldon. Introduction to probability models (twelfth edition). Los Angeles, CA: University of Southern California; 2019.
- [3] Polovko AM, Gurov SV. Fundamentals of reliability theory. St. Petersburg: BHV-Petersburg; 2006.
- [4] Sennova EV, Sidler VG. Mathematical modeling and optimization of expanding heat supply systems. Novosibirsk: Nauka; 1985.
- [5] Lisnianski A, Elmakias D, Hanoch BH. A multi-state Markov model for a short-term reliability analysis of a power generating unit. Reliab Eng Syst Saf 2012;98:1–6.
- [6] Rudenko YN, Ushakov IA, Cherkesov GN. Theoretical and methodical aspects of reliability analysis of energy systems. In: Energy reviews scientific and engineering problems of energy system reliability. New York: Harwood Acad. Publishers; 1984.
- [7] Li Na, Xiaoliang Wang, Zhenhu Zhu, Chao Gua. Reliability evaluation of power system based on isodisperse important sampling method and dynamic parallel calculation. Energy Proceedia 2019;156:343–8.
- [8] Postnikov Ivan, Stennikov Valery, Mednikova Ekaterina, Penkovskii Andrey. Methodology for optimization of component reliability of heat supply systems. Appl Energy 2018;227:365–74.
- [9] Stennikov VA, Postnikov IV. Methodological support for a comprehensive analysis of fuel and heat supply reliability. In: Vasant P, Voropai NI, editors. Sustaining power resources through energy optimization and engineering. Hershey PA: Engineering Science Reference (an imprint of IGI Global); 2016.
- [10] Stennikov VA, Postnikov IV. Methods for the integrated reliability analysis of heat supply. Power Technol Eng 2014;47(6):446-53.
- [11] Linton Oliver. Chapter 1 probability theory. In: Probability, statistics and econometrics. United Kingdom: University of Cambridge. Elsevier Inc; 2017.
- [12] Garrett SJ. Chapter 9 probability theory. In: Introduction to actuarial and financial mathematical methods. Academic Press, Elsevier Inc.; 2015.