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Methods for optimization of time redundancy of prosumer in district heating systems

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Abstract

The paper deals with the problem of operating the reliability of prosumers as part of a district heating system, taking into account overload time redundancy that they possess. This time redundancy can be both passive, caused by heat accumulating effect and use of thermal energy storages, as well as an active time redundancy, which is provided by additional heating by its own heat source. Methods to determine the optimal level of this time redundancy of heat prosumer were developed based on search the minimal cost of ensuring required values of restoration rates of system components, taking into account the functions of prosumers. Methodology is based on the use of nodal reliability indices, models of Markov processes, aggregated model of heat transfer processes in heating of consumers, Rossander equation, models of the theory of hydraulic circuits.

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Keywords: District heating system; Prosumer; Intelligent integrated energy systems; Reliability; Time redundancy; Nodal reliability indices; Availability factor; Mathematical modeling; Optimization; Markov random process; Theory of hydraulic circuits

1. Introduction

Implementation the technologies of integrated and intelligent energy systems must significantly improve the technical and economic efficiency and reliability of energy supply to consumers by Hamada and Matsuhashia [1], Xiaqin et al. [2] and Elmohlawy et al. [3]. Today, problems of designing such energy systems, in particular, 4th generation district heating (4GDH) systems by Lund et al. [4], are the subject of a lot of studies, a rather large-scale overview of which is given in [5]. In this scientific and technical area of researches one of promising topic is the technological concept of prosumer.

A prosumer can have its own energy sources (including renewable energy sources), energy storages and/or other technological components that allow optimal control the energy consumption in order to improving efficiency and reliability of energy system in general. Currently, much attention is paid to different methodological and technological aspects of functioning prosumers in energy systems, and potential effects of its participation in energy

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Nomenclature

Sets

j	Number of consumer/prosumer (further consumer means both as consumer and prosumer)
J	Set of consumers including prosumers
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
s, z	Numbers of system states
E	Complete set of system states
E''_j	Subset of failure states for consumer j
E'_j	Subset of other (no failure) states for consumer j
$E(s)$	Subset of system states from which the system can directly (without intermediary states), transit to state s
N''	Number of states from subset E''_j

Variables

$t_{\text{ex}sj}$	External (air) temperature under which the prosumer time redundancy will be equal to the restoration time of rated heat supply, °C
t_{sj}	Current inside (air) temperature at consumer j in system state s , °C
t_{oj}	Designed inside temperature for consumer j , °C
$t_{j\text{min}}$	Minimal admissible inside temperature for consumer j , °C
\bar{q}_{sj}	Relative heat supply to consumer j at system state s
q_{oj}	Design heat loads of consumer j , MW
q_{bj}	Heat loads of consumer j at the beginning of the heating period, MW
$q_{\text{av}j}$	Heat loads of consumer j , average for the heating period, MW
q_{sj}^{SYS}	Part of heat load of consumer j , supplied from the system (by district HS) in system state s , MW
q'_j	Heat capacity of own HS for prosumer j , MW
$\alpha_j, \omega_j, \delta_j$	Heat load curve irregularity factors of consumer j (from Rossander equation)
φ_j	Coefficient of specific heat losses in building of consumer j , MW/°C
ε_j	Heat accumulating coefficient for consumer j , h
$\Delta\varepsilon_j$	Additional time redundancy of prosumer j , h (caused by the use of their heat sources and/or storages), h
$\bar{\mu}_j$	Integrated (average) restoration rate of system components relation to consumer j , 1/h
p_s, p_z	Probability of system state s and z respectively
λ_i	Failure rate of component i , 1/h

supply are assessed. At the same time, the overwhelming part of these works is focused on electric power systems (EPS), for example in [6–9], and only in recent years a prosumer concept is considered for district heating systems (DHS) by Brange et al. [10], Brand et al. [11], Kauko et al. [12], including studies of the author of this work – Postnikov et al. [13,14], Postnikov and Stennikov [15].

Further in the paper a prosumers of heat energy connected to DHS is considered. These prosumers can have own distributed heat sources (HS): in this case we can call such systems as district-distributed heating systems

(DDHS). Own HS of prosumer provides an additional energy and time redundancy, which allows to reduce heat undersupply in failure states of the system, as well as reduce the load on district/centralized HS and improve quality and reliability of heating for both consumers and DHS in general. This study is devoted to problem of determining the optimal level of time redundancy of prosumer for ensure reliability of its heating, as well as ensure the reliability of system whole (reliability of heating to all consumers) taking into account prosumer functions.

2. Methods

2.1. Modeling of time redundancy of prosumer

Possible variants of heating interruption consequences for consumer and prosumer are illustrated by diagrams in Fig. 1. With termination of heat supply from the system (failure of heating) and without its restoration, the inside temperature decrease from designed value t_{oj} to level of external temperature t_{ex} . Due to heat accumulation effect, this process takes place gradually. During the time τ_3 after system failure repairs are made and heat supply is restored, but inside temperature increases gradually from t_2 to admissible value $t_{j\ min}$ (depending on consumer category) by time point τ_5 . Thus, undersupply of heat energy for consumer is proportional to area of figure A-B-C.

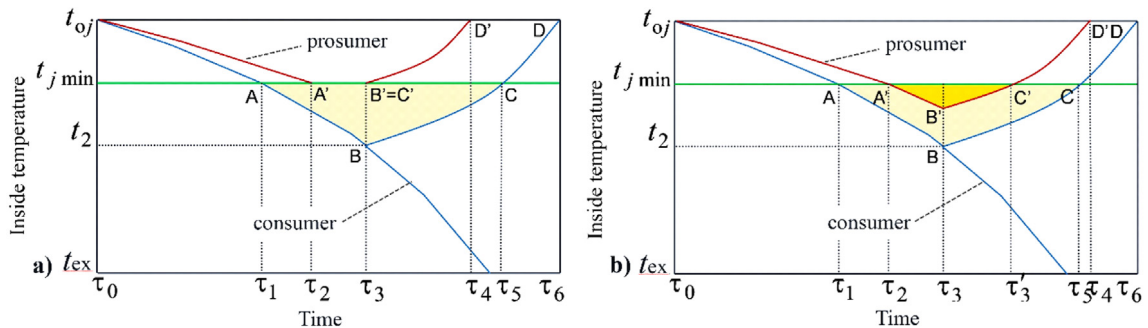


Fig. 1. Decrease of inside temperature in case of heating interruption for (ordinary) consumer and prosumer: (a) without heating failure to prosumer; (b) with heating failure to prosumer (but with less damage in comparison to ordinary consumer).

For a prosumer with an additional redundancy (in energy and time) we can exclude undersupply of heat energy (diagram “a”), or significantly reduce it (diagram “b”, undersupply is proportional to the area of figure A'-B'-C'), depending on ratio of prosumer load, time of heat supply interruption and capacity of additional redundancy of prosumer. Designed heating is restored by time period τ_6 for consumer and τ_4 for prosumer on diagram “a” or “b” depending on capacity of redundancy.

Time redundancy of prosumer accounted for using the following expression for external temperature under which prosumer time redundancy will be equal to the restoration time of rated heat supply by [16]:

$$t_{exsj} = \frac{t_{oj}(1 - \bar{q}_{sj}) - (t_{j\ min} - t_{oj}\bar{q}_{sj}) \exp B_j}{(1 - \bar{q}_{sj})(1 - \exp B_j)}, \quad (1)$$

where

$$\bar{q}_{sj} = q_{oj}/(q_{sj}^{sys} + q'_j), \quad (2)$$

$$B_j = 1/[(\varepsilon_j + \Delta\varepsilon_j)\bar{\mu}_j]. \quad (3)$$

Index q'_j can be fixed and correspond to a rated (required) value of capacity of the prosumer HS. Also this index can be variable and take into account the components failures decreasing the performance of the HS.

2.2. Models for determine of integrated restoration rate of system components in relation to reliability requirements into account additional time redundancy of prosumer

Requirements to reliability of heat supply to consumers can be set on the basis of different reliability indices (RI) by Sennova et al. [16]. In framework of this study, one of the main comprehensive RI, the nodal availability factor

(AF), is used. Using the expression (1), traditional dependence for determining of AF from [16] and the Rossander equation [17], which allows calculating the heat load of consumers at any time point during heating period, the following model was obtained to determine the nodal AF for consumer taking into account its heat accumulation effect:

$$K_j = 1 - \sum_{s \in E} p_s \left[\frac{1}{1 - \omega_j} \left(1 - t_{sj} \left(\frac{\varphi_j}{q_{oj}} - \frac{1}{t_{sj}} \left(\frac{C_1 - C_2 \exp B_j}{C_3(1 - \exp B_j)} \right) \right) \right) \right]^{\alpha_j}, \tag{4}$$

where

$$C_1 = t_{oj}(1 - \bar{q}_{sj}), C_2 = t_{j \min} - t_{oj}\bar{q}_{sj}, C_3 = 1 - \bar{q}_{sj}, \tag{5}$$

$$\alpha_j = (1 - \delta_j)/(\delta_j - \omega_j), \tag{6}$$

$$\omega_j = q_{bj}/q_{oj}, \delta_j = q_{avj}/q_{oj}. \tag{7}$$

The full set of system states E for consumer j is divided into two subsets in relation to consequences of heating interruption: E''_j – a subset of failure states for consumer, and E'_j – a subset of other (no failure) states for consumer. Criteria for this states classification is temperature $t_{j \min}$. Taking this into account, and expressing index $\bar{\mu}_j$ from (1), (3) and using formulas (4)–(7), we obtain the following expression to determine the integral restoration rate of system components:

$$\bar{\mu}_j = \left[(\varepsilon_j + \Delta\varepsilon_j) \ln \left(\frac{C_4 C_3 - C_1}{C_4 C_3 - C_2} \right) \right]^{-1}, \tag{8}$$

where

$$C_4 = t_{sj} - (q_{oj}/\varphi_j) \left[1 - (1 - \omega_j) \left(\left(1 - K_{oj} - \sum_{s \in E'_j} p_s C_5 \right) / \sum_{s \in E''_j} p_s \right)^{1/\alpha_j} \right], \tag{9}$$

$$C_5 = 1/[(1 - \omega_j)(1 - (t_{sj} - t_{exsj})/q_{oj})]^{\alpha_j}. \tag{10}$$

Expressions (8)–(10) make it possible to determine the integral (average for all components) value of restoration rate taking into account the reliability requirements as standard level of AF and taking into account the time redundancy of prosumers. In formulas (8)–(10), we use t_{sj} , averaged for consumers, or this index corresponding to state with longest time of heating interruption. In the second variant, we have some margin on reliability, which is proportional to ratio of the maximum time of heating interruption to the its average level.

2.3. Markov model for describe of evolution of system states

Probabilities of system states are determined by solving the set of Kolmogorov equations describing a stationary Markov random process of evolution of events in system (failures and restorations of components) by [14,16,18,19]:

$$p_s \sum_{i \in I(s)} (\lambda_i + \mu_i) = \sum_{z \in E(s)} p_z \sum_{i \in I(z)} (\lambda_i + \mu_i). \tag{11}$$

Markov random processes are traditional and verified mathematical basis for solving different problems of reliability of DHS. In more detail the issues on these problems are considered in [14,16,18,19].

2.4. Modeling of flow distribution in heat network of district heating system

Calculation of flow distribution in heat network (HN) of DHS is necessary for constrained of acceptable hydraulic modes and determine the level of heat supply to each consumer in system states (in case of failures in the system components). The flow distribution is calculated using the mathematical methods developed within the theory of hydraulic circuits (THC) in [20]. The model of flow distribution in HN is represented by a matrix form by [20]:

$$\mathbf{A}_s \mathbf{x} = \mathbf{g}_s, \tag{12}$$

$$\overline{\mathbf{A}}_s^T \mathbf{p} = \mathbf{h} - \mathbf{H}, \tag{13}$$

$$\mathbf{S}\mathbf{X}\mathbf{x} = \mathbf{h}. \tag{14}$$

By solving system (12)–(14) for each of the system states s we determine heat flow rate at each consumer j , which corresponds to the level of heat supply q_{sj} .

2.5. Objective function and formalization the problem of optimal relation the time redundancy of prosumer and restoration rates of system components

The objective function for considered problem is formulated as sum of cost functions for ensuring of various levels of time redundancy of prosumer, connected with both additional capacity own HS and additional heat accumulation, and costs of ensuring different values of restoration rates of system components:

$$Z_{\text{obj}} = \sum_{j \in J} [f_j(\Delta \varepsilon_j) + f_j(q'_j)] + \sum_{i \in I} f_i(\mu_i). \tag{15}$$

Index $\overline{\mu}_j$ determined from (8)–(10) further is distributed to system components according to the following balance principles:

$$\overline{\mu}_j \sum_{s \in E''_j} p_s = \sum_{i \in I} \sum_{s \in E''_j} p_s \mu_i \text{ or } \sum_{i \in I} \mu_i = N''_j \overline{\mu}_j. \tag{16}$$

Thus, the problem of optimal relation the time redundancy of prosumer and restoration rates of components in DHS lies in the following: minimize function (15) under conditions (4)–(7), (8)–(10), (11), (12)–(14), (16) into account constrains for available values of variables of considered problem.

3. Case study

The DHS under consideration is presented in Fig. 2 and consists of one district HS with an output of 540 MW, 11 consumers (nodes 1, 4, 5, 8, 10, 11, 15–17, 19, 20) with total load equal 535 MW (heat) and a circuit HN consisting of 22 sections (branches) with main characteristics indicated in Fig. 2 (for the designed mode). The total length of HN is 7539 m. It is assumed that consumer 5 is a prosumer and has its own HS running on fossil fuel with a capacity, which completely covers a part of designed load.

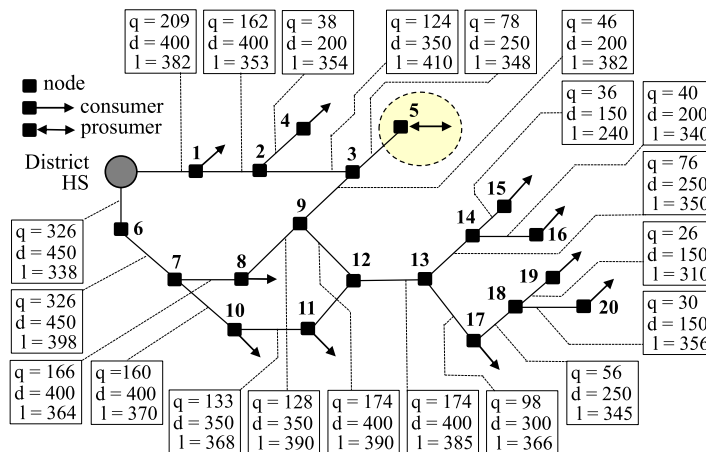


Fig. 2. Calculated scheme of DHS: in the callouts q – heat flow, MW; d – pipeline diameter, mm; l – length of network section, m.

Results of search of optimal relation the time redundancy of prosumer and restoration rates of components in DHS are shown in Fig. 3. Presented solution corresponds to the standard AF value of 0.97 and the minimal admissible inside temperature of 17.3 °C. This diagram demonstrates two curves: dashed (and orange) line represent the relationship between the integrated the time redundancy of prosumer and restoration rates of components; solid

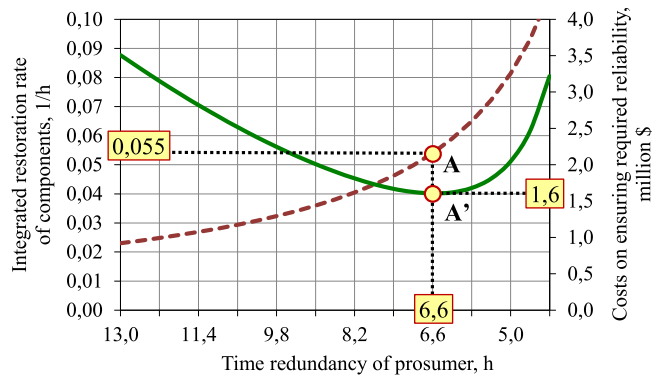


Fig. 3. Search for an optimal relation the time redundancy of prosumer and restoration rates of components in DHS.

(and green) line shows a change in the costs to ensure the required level of reliability (by AF) depending on relationship of this parameters. The solution corresponds to the reliability costs in the amount of 1.6 million \$ (point A') under the following values of variables: time redundancy of prosumer (summary both passive and active) – 6.6 h; integrated restoration rate of components – 0.055 1/h (point A).

The presented method allows to obtain more universal characteristics, which are the result of multivariate calculations depending on specified initial conditions. So, for example, if we carry out a series of similar calculations for various reliability levels of heating to prosumers (determined by minimal admissible inside temperature), then we can obtain the following results demonstrated on Fig. 4. Diagram “a” shows surface of dependence of AF on minimal admissible inside temperature and minimal costs on ensuring required reliability. Diagram “b” shows projection of this surface on the system of axes “costs-minimal temperature”.

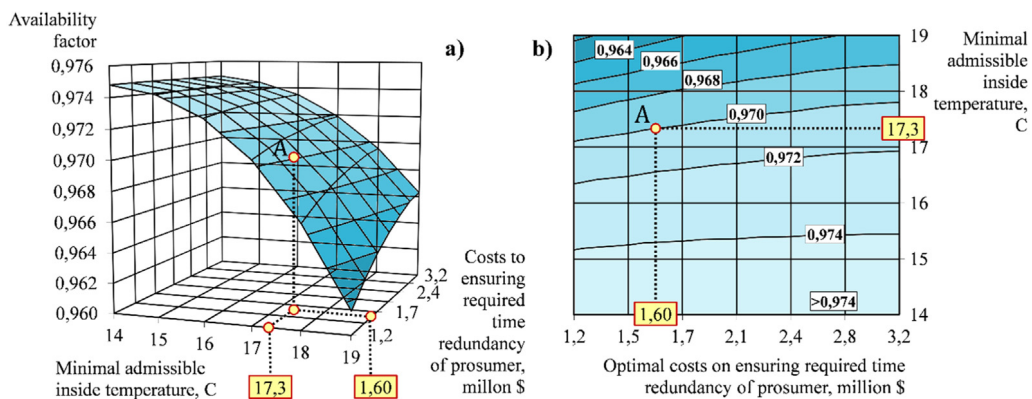


Fig. 4. Dependence of availability factor (AF) for prosumer on minimal admissible inside temperature and minimal costs on ensuring required reliability for considered DHS: (a) 3d diagram; (b) gradient of AF.

The diagram presented in Fig. 4 “b”, which is, in fact, the gradient of AF, allows determining the level of reliability (by AF), which is achieved at one or another ratio of costs and minimal admissible inside temperature. And vice versa: we can determine which costs are required to achieve the required reliability level (by AF) at an each considered values of minimal admissible inside temperature. For example, in the presented diagrams (Fig. 4), point A corresponds to solution shown earlier for the minimal admissible inside temperature of 17.3 °C and optimal costs of 1.6 million \$ under require AF of 0.97 (Fig. 3).

As can be seen from Fig. 4, for considered scheme achieve the more highest level of minimal admissible inside temperature require significantly increase the costs (for example, level of 17.8 °C require about 3.2 million \$).

4. Conclusion

Statement of the problem of optimal relation the time redundancy of prosumer and restoration rates of components in DHS under reliability requirements is formulated. Methodical approaches and models for its solution are proposed. Developed methods are based on mathematical models, which successfully use in studies of reliability of technical systems whole, and energy systems, in particular.

The developed methodological ensuring has following features and advantages:

- a joint search for time redundancy of prosumer and reliability parameters of system components (in this case, restoration rates) makes it possible to obtain optimal solutions on the ratio of system reliability and reliability of prosumer, corresponding to minimum cost on ensuring of required reliability;
- consideration of factors characteristic of actual DHS, such as the heat accumulating effect of consumers, increases the practical significance of results and applicability of developed methods for calculating actual systems;
- use of flow distribution models by the THC allows to obtain solutions within the framework of technologically admissible operating modes in HN, including emergency modes with failure sections of HN;
- nodal reliability indices make it possible to take into account the reliability of heat supply for each consumer, in contrast to approaches of aggregate reliability analysis and synthesis based on averaged indices for system whole.

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