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DETERMINATION OF THE PROBABILITY OF FAILURES IN THE OPERATION OF ELEMENTS OF URBAN HEAT SUPPLY SYSTEMS IN EXTREME OPERATING CONDITIONS

А. Мазуренко, А. Пустовіт, П. Шилов, Д. Шилов, В. Станіславов. **Визначення ймовірності відмов в роботі елементів систем міського теплопостачання в екстремальних умовах експлуатації.** Сучасні централізовані міські чи районні системи опалення багатоквартирних житлових будинків, а також адміністративних та промислових будівель мають доволі складну інфраструктуру. Основними елементами є системи генерації тепла, системи транспорту, а також відповідно абонентські вводи споживачів. Вказана складність системи, яка визначається необхідною життєдіяльністю багатьох елементів впливає на надійність роботи інфраструктури теплопостачання в цілому. В роботі визначено основні причини екстремальних умов експлуатації систем теплопостачання в східній Європі та в теперішніх України. Наведено основні проблеми експлуатації систем під час військового стану, що включають в себе: пошкодження інфраструктури через бойові дії, перебої з постачанням палива, води та електрики, складнощі доступу до ремонтних робіт у зонах враження. Обґрунтовано застосування теорії ризиків для складних систем в яких широко використовується побудова дерева відмов чи дерева подій. Перевагою вказаних методів є можливість визначення ймовірності відмови чи справної роботи системи в цілому при відомій величині ймовірності відмови окремих елементів в екстремальних умовах. В роботі розглянуто метод збору та обробки статистичн6их даних, а також доволі перспективний універсальний метод експертних оцінок. На прикладі, ймовірності відмови в підключені резервного електрогенератора, в разі відключення чи руйнування основної системи електроживлення для аналізу використано метод експертних оцінок. В результаті дослідження отримано: напрацювання енергоустаткування в годинах з роками від введення в експлуатацію; зміну аварійних зупинок енергоблоку з роками. Аналіз наведених даних свідчить про наявність періоду підвищення надійності енергоустаткування по мірі його освоєння після введення в експлуатацію, далі наступає, після деякої стабілізації, інтенсивне зменшення надійності, особливо після відпрацювання розрахункового ресурсу. Отримана закономірність є характерною для більшості технічних систем.
Ключові слова: надійність енергетичного обладнання, стабільність системи, системи централізованого теплопостачання, когенераційні установки

A. Mazurenko, A. Pustovit, P. Shylov, D. Shylov, V. Stanislavov. **Determination of the probability of failures in the operation of elements of urban heat supply systems in extreme operating conditions.** Modern centralized city or district heating systems of multi-apartment residential buildings, as well as administrative and industrial buildings, have a rather complex infrastructure. The main elements are heat generation systems, transport systems, and, accordingly, consumer subscriber inputs. The complexity of the system, which is determined by the necessary vital activity of many elements, affects the reliability of the heat supply infrastructure as a whole. The paper identifies the main reasons for the extreme operating conditions of heat supply systems in Eastern Europe and in present-day Ukraine. The main problems of operating systems during martial law are presented, including: damage to infrastructure due to hostilities, interruptions in the supply of fuel, water and electricity, difficulties in accessing repair work in the affected areas. The application of risk theory for complex systems in which the construction of a fault tree or event tree is widely used is justified. The advantage of the specified methods is the ability to determine the probability of failure or proper operation of the system as a whole with a known probability of failure of individual elements in extreme conditions. The paper considers the method of collecting and processing statistical data, as well as a rather promising universal method of expert assessments. For example, the probability of failure to connect a backup generator in the event of a shutdown or destruction of the main power supply system, the method of expert assessments was used for analysis. As a result of the study, the following were obtained: operating hours of power equipment in hours over years from commissioning; change in emergency shutdowns of the power unit over years. Analysis of the data provided indicates the presence of a period of increasing the reliability of power equipment as it is developed after commissioning, then, after some stabilization, an intensive decrease in reliability occurs, especially after the estimated resource is exhausted. The obtained pattern is characteristic of most technical systems.
Keywords: energy equipment reliability, system stability, district heating systems, cogeneration plants

1. Introduction

The main reasons for extreme operating conditions of heat supply systems in Eastern Europe may be extremely low winter temperatures, strong winds, precipitation, and other climatic features [1]. In the current conditions of Ukraine, additional aspects include wartime problems, which include: damage to infrastructure due to hostilities, interruptions in the supply of fuel, water, and electricity, difficulties in accessing repair work in affected areas, and so on [2].

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Individual heating systems, which are widespread in rural areas or suburban zones, are quite resistant to extreme conditions due to the possibility of using various types of fuel, a closed coolant system, and, in many cases, the absence of the need for stable electricity supply.

Modern centralized city or district heating systems for multi-apartment residential buildings, as well as administrative and industrial buildings, are significantly more complex [3]. Their main elements are heat generation systems (boiler houses or combined heat and power plants), heat transport systems from the source to consumers, and, accordingly, consumers, who, in turn, also consist of a significant number of elements that can fail under external influence.

2. Analysis of literary data and formulation of the problem

In risk theory for complex systems, the construction of a fault tree or event tree is widely used. The advantage of an event tree is the ability to determine the probability of failure or proper operation of the system as a whole with a known probability of failure of individual elements in extreme conditions [4].

Obviously, the objective determination of the probabilities of failure of various system elements – P_i – is the most difficult problem in constructing an event tree [5].

There are various methods for such quantitative assessments [6]:

– These are calculation methods for the strength of the main equipment elements based on operating conditions (temperature, pressure, radiation level, and similar factors), operating life (considering the influence of the long-term strength limit, stress relaxation at high temperatures), properties of the materials used, and so on.

– The next quite effective and widely used method for assessing the reliability indicators of individual elements or systems as a whole is the collection of statistical data on failure frequency over a long period of operation. With appropriate mathematical processing of the obtained data, the reliability of the obtained parameters can be quite high.

– In cases of insufficient accumulated statistical data due to short-term operation of relevant equipment, its uniqueness, or when using fundamentally new systems with no experience of their use, the method of expert assessments seems useful [7]. In this regard, it is important to select a sufficient number of experts with relevant specialized education, work experience, and analytical thinking.

Each of these methods is based on its own features, approaches, and tools and has its own advantages and disadvantages [8]. In this paper, we will consider the method of collecting and processing statistical data, as well as a quite promising and, to some extent, the most universal method of expert assessments.

3. The purpose and objectives of the research

The main goal of the study is to analyze the probabilities of failures of the main elements of the heat supply system under extreme operating conditions. To achieve this goal, the following tasks had to be solved:

– To analyze existing methods for quantitative assessments of failures of the main elements of heat supply systems.

– Based on the conducted analysis, to select methods for collecting and processing statistical data on the operation of the heat supply system.

– To conduct a study of the probability of failure of power equipment under extreme operating conditions using the selected methods.

4. Methods of conducting research and processing experimental data

For example, the determination of the probability of failure to connect a backup power generator $(K_{\mathrm{g}}^{\mathrm{p}})$ in the event of a shutdown or destruction of the main power supply system was taken using the expert assessment method. Nine specialists and postgraduate students with specialized training in heat power engineering and electrical power engineering, who have experience in both practical and scientific activities, were invited as experts. Based on the results of an anonymous survey of the selected specialists, the following expert assessments of the probability of power supply failure of the boiler house from the backup generator were obtained, which are presented in Table 1.

Using the expert assessment method, it is necessary to:

– evaluate the consistency of the experts' actions;

– determine the total expert assessment of the probability of power supply failure of the boiler house from the backup generator.

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Table 1

Expert assessments of the probability of boiler house power supply failure

Experts	Probability of failure				
	0.5	0.4	0.3	0.2	0.1
1	5	4	3	1	2
2	4	5	2	1	3
3	5	3	4	2	1
4	5	3	4	2	1
5	5	4	3	2	1
6	3	5	4	1	2
7	5	4	3	2	1
8	5	4	3	1	2
9	4	5	3	2	1

In the table, the expert assessment is assigned based on the expert giving *1* point to the probability value that they consider most realistic, and the maximum score of *5* to the probability that is least realistic.

The consistency of experts' actions is assessed by calculating the concordance coefficient. The total rank of probability based on the actual expert assessments of all experts from Table 1 of the initial data is presented in Table 2.

Table 2

Total probability rank

Experts	Probability of failure				
	0.5	0.4	0.3	0.2	0.1
Total probability rank	41	37	29	14	14

Next, the priority is calculated – the number of experts who rated the corresponding share with a rank of 1, and the results are presented in Table 3.

Table 3

Priority

Probabilities of failure	Number of expert responses
0.5	0
0.4	0
0.3	0
0.2	4
0.1	5

The total rank of the probability of failure in the case of complete agreement of experts' opinions is determined as the product of the priority (highest) expert assessment and the number of experts who participated in the survey (Table 4).

Table 4

Total probability rank

Expert assessment	Probability of failure				
	0.5	0.4	0.3	0.2	0.1
Priority	0	0	0	4	5
Total coincidence rank – $x_{i\phi}$	0	0	0	36	45

The calculation of variance (deviation of a random variable from the center of distribution) of actual estimates is performed using the formula:

$$\sigma_{\phi}^{2} = \frac{1}{m}\sum_{1}^{m}(x_{i\phi} - \bar{x})^{2} = 518,$$

where: $x_{i\phi}$ are the actual expert assessments (by total coincidence rank); $\overline{x}$ is the average value of the expert assessment; m is the number of assessment options.

The calculation of the average value of the total assessment is performed using the formula:

$$\overline{x} = \frac{n \cdot (m+1)}{2} = 27,$$

where: n is the number of experts.

To assess the consistency of experts' actions, Kendall's rank correlation coefficient (concordance coefficient) is determined. The value of the concordance coefficient (W) ranges from 0 to 1: when $W = 0$, it is considered that there is no consistency in actions, and when $W = 1$, there is complete agreement of opinions. In other cases, a normative value for the concordance coefficient is established, with which its actual value is compared. Most often, the normative value of the concordance coefficient is $W = 0.5$. If $W > 0.5$, it is considered that the experts' opinions are largely consistent, and vice versa. In our case:

$$W = \frac{12 \cdot \sigma_{\phi}^2}{n^2 (m^3 - m)} = \frac{12 \cdot 518}{9^2 \cdot (5^3 - 5)} = 0.64.$$

Thus, the concordance coefficient is $W = 0.64$, which is slightly more than 0.5 and indicates a good level of consistency in the experts' opinions.

The calculation of the total expert assessment is performed using the weighted average formula:

$$\overline{P} = \frac{\sum_{1}^{m} p_i \cdot h_i}{\sum_{1}^{m} h_i} = 0.14,$$

where: p_i is the option for the probability of failure of the backup generator; h_i is the priority of failure.

Thus, the average probability of failure of the boiler house's backup power generator startup was determined to be 0.14. The probability of successful startup of the backup generator, in this case, is *0.86*.

Of course, the considered example of an approach to assessing the reliability of a district heating system under extreme conditions requires solving a rather complex problem of determining the probability coefficients of an event tree, taking into account the peculiarities of each individual system, its components, operating conditions, and probable destruction scenarios. At the same time, different elements of the system can be evaluated in terms of reliability using different methods that allow obtaining quantitative indicators of the risks of their failure.

5. Results of experimental bench research

Let's consider the possibilities of assessing the probability of power equipment failures using the method of collecting and analyzing statistical data during its long-term operation. For example, let's analyze the data on emergency shutdowns of one of the heat and power supply units (2nd unit of MGRES) during 23 years of its operation. Table 5 shows the data on the number of forced (emergency) shutdowns by year, and the corresponding operating time in hours.

Table 5

Data on the number of forced (emergency) shutdowns by year

Year	1	2	3	4	5	6	7	8	9	10	11
Hours of operation	5100	10716	16574	24079	30565	38006	43635	51289	58993	65954	74004
Number, emerg. stop	7	2	7	3	7	1	2	3	4	9	5

Year	12	13	14	15	16	17	18	19	20	21	22	23
Hours of operation	81328	89152	95341	103300	111192	117643	124473	132249	140080	147493	153659	161930
Number, emerg. stop	12	4	4	7	7	10	12	13	11	14	15	15

A graphical representation of this data was performed in a software package and is shown in Fig. 1 and Fig. 2.

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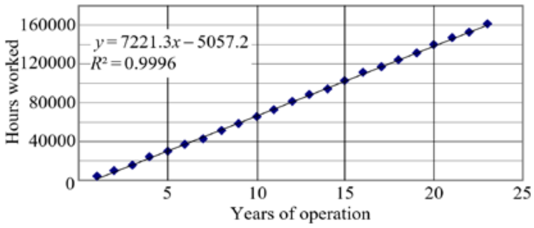

Fig. 1. Operating hours of power equipment in hours over years from commissioning

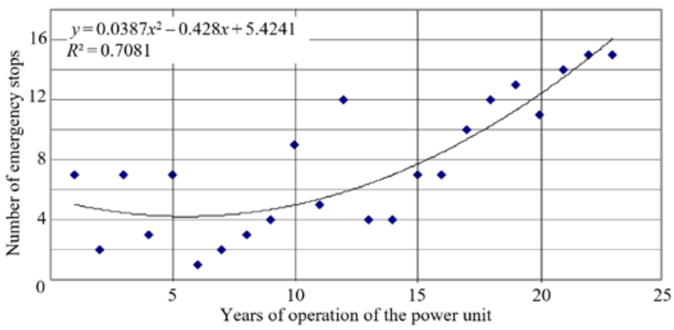

Fig. 2. Change in emergency shutdowns of the power unit over the years

As can be seen (Fig. 1), during the period under consideration, the dependence of equipment operating hours on the year of operation is purely linear, meaning its operation was quite stable. This makes it possible to consider the failure intensity per year in the analysis.

When choosing a polynomial trend line, an equation was obtained that describes the pattern of equipment reliability change over the years with a reliability of $R^2 = 0.708$, which allows estimating the probability of system or its element failure in a given operating period. For example, if we use the obtained regression equation, then during the 15th year of the power unit's operation, approximately 7.71, or about 8, emergency shutdowns may occur, which gives a daily shutdown probability $P_{\text{day}} = 7.71/365 = 0.0211$. The probability of reliable operation, in this case, is approximately 0.98.

The analysis of the presented data indicates the presence of a period of increasing the reliability of power equipment as it is developed after commissioning, then, after some stabilization, an intensive decrease in reliability occurs, especially after the estimated resource of 100 thousand hours is worked out. This pattern is characteristic of most technical systems.

Conclusions

In the work, in accordance with the tasks of the study, an analysis of existing methods for quantitative assessments of failures of the main elements of heat supply systems was carried out. To assess the reliability of heat supply systems based on the analysis, a method of collecting and processing statistical data was selected, as well as a rather promising and, to some extent, the most universal method of expert assessments.

Using the selected methods, data on emergency shutdowns of one of the heat and power supply power units during 23 years of its operation were analyzed using the example of the 2nd unit of the MGRES. Dependences of changes in emergency shutdowns of the power unit during the specified period were obtained.

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