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POSSIBILITIES FOR IMPROVING THE RELIABILITY OF HEAT AND ELECTRICITY GENERATING FACILITIES IN HEAT SUPPLY SYSTEMS, TAKING INTO ACCOUNT THE INSTALLATION OF RESERVE CAPACITIES

A. Mazurenko, A. Pustovit, Zh. Doroshenko, S. Gryshchenko. Можливості підвищення надійності роботи тепло та електро генеруючих установок систем тепlopостачання з урахуванням встановлення резервних потужностей. Зниження надійності тепlopостачання споживачів можливе через підвищену аварійність устаткування, як через зовнішній вплив в екстремальних умовах, так і в умовах відпрацювання розрахункового ресурсу частиною встановленого генеруючого обладнання. Характерним для енергетичних установок є циклічний режим роботи. Забезпечення високої надійності енергосистем можливе за рахунок високих показників надійності використовуваного обладнання та за рахунок належної структури та резервування систем генерації. В роботі розглянуто методи визначення величини резерву генеруючої потужності системи тепlopостачання. Величина необхідного резерву тісно пов'язана з визначенням параметрів аварійності обладнання, що використовується, а також від резерву залежить вирішенням задачі планування ремонтів. Після завершення опаловального сезону система тепlopостачання, як правило, переходить в режим зниженої потужності, необхідної для гарячого водопостачання. Проте, в деяких регіонах значна кількість систем тепlopостачання працює лише в період опаловального сезону, а це спрощує вирішення питань планування капітального ремонту устаткування системи та її резервування. Виконані необхідні розрахунки для побудови графіка визначення резерву системи тепlopостачання. Розглянуто планування капітальних ремонтів та їх періодичність. Для практичного використання в більшості випадків, розв'язання задачі резервування потужності виконано за більш простою і більш точною при невеликій кількості елементів системи методикою, побудованою на розподілі Бернуллі. При цьому був використано математичний пакет Maple. Результати отримані у вигляді графіків. При більшій загальній кількості елементів відповідно зменшується відносна доля впливу відмови окремого елемента (котла) на працездатність всієї системи (котельні) при прийнятному значенні мінімального резерву. Середня аварійність приймається досить часто постійною для однотипного енергетичного обладнання, проте необхідно мати на увазі, що навіть таке устаткування може мати показники, які значно відрізняються по надійності. Це робить доцільним проведення систематичного індивідуального обліку, збору та відповідної обробки статистичних даних по всіх елементах системи, особливо для енергетичного устаткування, яке відпрацювало значну частину свого ресурсу.

Ключові слова: система тепlopостачання, надійність енергосистем, аварійність обладнання, резервування потужностей

A. Mazurenko, A. Pustovit, Zh. Doroshenko, S. Gryshchenko. Possibilities for improving the reliability of heat and electricity generating facilities in heat supply systems, taking into account the installation of reserve capacities. The reliability of heat supply to consumers may decrease due to increased equipment failure rates, both due to external influences in extreme conditions and due to the depletion of the design life of some of the installed generating equipment. Cyclical operation is characteristic of power plants. High reliability of power systems can be ensured by high reliability indicators of the equipment used and by the proper structure and redundancy of generation systems. The paper considers methods for determining the reserve capacity of the heat supply system. The amount of the required reserve is closely related to the determination of the failure rate parameters of the equipment used, and the reserve also depends on the solution of the repair planning problem. After the end of the heating season, the heat supply system usually switches to a reduced power mode required for hot water supply. However, in some regions, a significant number of heat supply systems operate only during the heating season, which simplifies the planning of major repairs to the system's equipment and its reserve capacity. The necessary calculations have been made to construct a schedule for determining the reserve capacity of the heat supply system. The planning of major repairs and their frequency are considered. For practical use in most cases, the problem of power reserve is solved using a simpler and more accurate method for a small number of system elements, based on the Bernoulli distribution. The Maple mathematical package was used for this purpose. The results are presented in the form of graphs. With a larger total number of elements, the relative share of the impact of the failure of a single element (boiler) on the performance of the entire system (boiler room) decreases accordingly, given the accepted minimum reserve value. The average failure rate is often assumed to be constant for energy equipment of the same type, but it should be borne in mind that even such equipment may have significantly different reliability indicators. This makes it advisable to systematically record, collect and process statistical data on all elements of the system, especially for power equipment that has worked out a significant part of its resource.

Keywords: heat supply system, reliability of power systems, equipment failure rate, power reserve

Introduction

A characteristic difference between thermal power equipment, thermal and electrical power plants and manufacturing enterprises in other industries is the requirement to ensure a continuous balance between “heat and electrical energy production and consumption”. This condition must be met

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regardless of the time of day, day of the week, seasonal fluctuations in demand for the products manufactured, instability in the quality of the fuel supplied, etc.

A decrease in the reliability of heat supply to consumers is possible due to increased equipment failure rates, both due to external influences in extreme conditions [1, 2] and due to the depletion of the design life of some of the installed generating equipment.

Analysis of literature data and problem statement

The main task of power systems is to ensure uninterrupted power supply to consumers. This task can only be solved if the equipment is in good working order and operates reliably.

The reliability of heat and power generating equipment is its ability to maintain the capacity to produce electrical and thermal energy of certain parameters according to the required load schedule with a given system of maintenance and repair of equipment.

A characteristic feature of power plants is their cyclical mode of operation, shown in Fig. 1 in the form of a graph. After a certain period of operation, the plant is shut down for planned preventive maintenance (PPM), and in the event of failures during operation, unplanned repairs (UR) are carried out. In some cases, the period of plant downtime may be related to the modernisation and reconstruction of its individual elements or to external factors not related to the technical condition of the plant, for example, its decommissioning due to a reduction in electricity or heat consumption, a lack of funds to purchase fuel, or an accident in the power system.

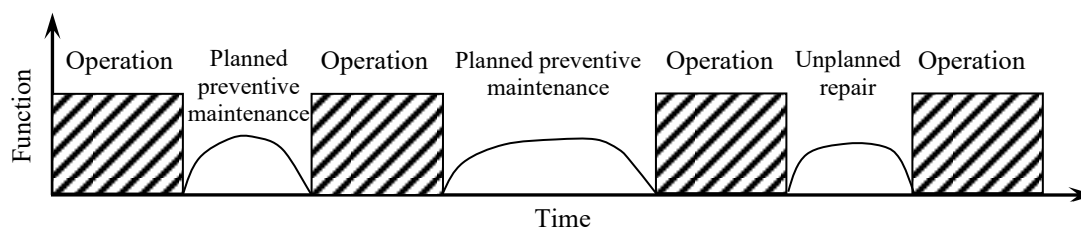


Fig. 1. Heating system operation schedule

Thus, the reliability of a power plant consists of several components: fault tolerance, durability, maintainability, and preservation.

To increase the reliability of heat and power generation systems, redundancy is used – a method of increasing the reliability of an object by introducing additional elements and functional capabilities beyond the minimum necessary for the normal performance of the object's specified functions. In this case, failure occurs only after the failure of the main element and all backup elements.

The level of reliability of energy supply to consumers in most countries is set at a fairly high level of 0.999, which corresponds to a single emergency power outage lasting one day every 2.74 years [3 – 7]. The main reasons for the extreme operating conditions of heat supply systems in Eastern Europe may be extremely low winter temperatures, strong winds, precipitation and other climatic features [8]. In the current conditions in Ukraine, additional aspects include wartime problems, including damage to infrastructure as a result of hostilities, interruptions in the supply of fuel, water and electricity, difficulties in accessing repair work in affected areas, etc. [9].

The necessary level of energy supply reliability can be achieved through passive protection, the creation of a structure of generating sources with an appropriate level of reliability [10], or, taking into account the technical characteristics of existing equipment, through an appropriate reserve of installed capacity.

In addition, high reliability of power systems can be ensured through high reliability indicators of the equipment used and through the appropriate structure and redundancy of generation systems [1].

Centralised heat supply systems are complex, spatially distributed engineering structures with a fundamental lack of statistical information about component failures and the laws governing the distribution of random variables.

The aim of this work is to determine the possibility of improving the reliability of heat and power generating units in heat supply systems, taking into account the installation of reserve capacities.

To achieve this goal, the following tasks must be solved:

- analysis of methods for determining the reserve capacity of heat supply systems;

- calculation of the power reserve of the energy system;
- construction of a graph for determining the reserve capacity of the heat supply system;
- construction of graphs showing the probability of failure of energy equipment.

Materials and methods

Let us consider methods for determining the amount of generating capacity reserve required to compensate for losses due to emergency repairs (N_{ar}), scheduled (major) repairs (N_{kr}), and possible exceedances of forecast load values (N_h) at consumers. The amount of the required reserve is closely related to the determination of the failure rate parameters of the equipment used, and the reserve also depends on the solution of the repair planning problem.

For example, let us consider a heat supply energy system consisting of n generating units with available capacity N_i , emergency shutdown intensity λ_i , and period between major repairs T_i^{kr} before the start of the heating season (e.g., in October – T_{10}).

After the end of the heating season (in this case, in April), the system usually switches to a reduced power mode, which is necessary for hot water supply. However, in some regions, a significant number of heating systems operate only during the heating season, which simplifies the planning of major repairs and maintenance of the system equipment.

The graph in Fig. 2 is presented in coordinates – power $N(t_j)$ and annual operating time T_y with monthly – ΔT_j breakdown of performance indicators, which shows the main indicators: $N^p(t_j)$ – total power that can be carried by the installed generating equipment in the j -th period of operation, J – heating system load, corresponding power reserve in the system N_j^r , and N_m^r – calculated reserve of the heating system during the period of maximum load in the current year of operation.

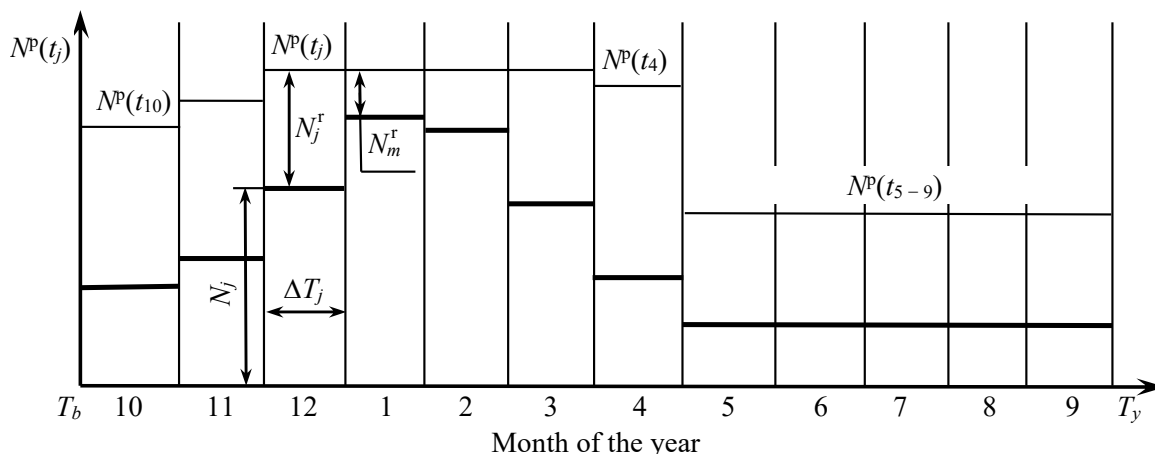


Fig. 2. Graph showing the determination of the heat supply system reserve

For a concentrated power system, its power at the beginning of period T_b is equal to:

$$N^p(t_{10}) = \sum_{i=1}^n N_i^p(t_{10}), \tag{1}$$

where: n – the number of types of generating equipment with different parameters used in the system.

It is important to note that an energy system can be considered concentrated if the throughput capacity of its energy networks (including during scheduled and emergency repairs of both main equipment and network elements) does not limit the use of the capacity of energy supply facilities at any point of consumption at all load values, i.e. the generating capacities and consumers in the calculation scheme that combines its elements through a branched system of ring or radial redundancy can be conditionally concentrated in a common node. The closest to concentrated are electrical systems with powerful electrical networks. Existing heat supply systems correspond to the concept of concentrated systems to a lesser extent. However, the existing trend of combining individual boiler rooms and their power-generating elements is a real direction for the transition to their concentration in the future. The energy load schedule N_y for the entire planned operating period T_y (as a rule, this period is the entire year for continuous operation of the heat and power supply system, or the heating season for operation exclusively for heat supply) must be specified as a piecewise constant function N_j at equal intervals

ΔT_j , period T_y , where the number of intervals j is usually equal to 12 monthly intervals for year-round operation, or 6 – 8 (depending on the characteristics of the region) for system operation only during the heating period. In this case, the monthly maximums can be considered as interval load values. It should be noted that the graph in Fig. 1 reflects a situation where, during the calculation period T_y , there is a possible change in the installed capacity in the power system with a simultaneous increase (relative to the previous calculation period) in the maximum load due to the growth in consumption, for example, when the outside temperature drops in winter for heating systems. There may be situations in which there is no increase in installed capacity, or even a decrease due to the decommissioning of emergency or obsolete equipment. In addition, the predicted change in peak loads is ambiguous and sometimes controllable. Calculating the power reserve of the power system to ensure its stability and the operation of vital consumers for such conditions is no less relevant and can be performed if there is sufficiently complete information about the technical condition of the generating equipment.

When planning major repairs, their frequency can be accepted:

$$T_i^{kr} = n_i \cdot T_y, \quad (2)$$

where: n_i – a number that characterises the frequency of major repairs in years, usually no more than three.

As a result of planning, the start and end times of major repairs of m units with a capacity of N_i^p ($i=1, m$), that are to be carried out during the period T_y (obviously, $m < n$) must be determined. The task of determining the reserve generating capacity is to determine for each interval ΔT_i^y of the period T_y such available capacity $N^p(t_j)$ that the probability of a deficit-free state of the power system q_j in any of the intervals ΔT_i^y is not lower than the required q^0 , i.e. $q_j \geq q^0, j = 1, 12$. Theoretically, it is necessary to strive for equality in the above ratio, since excessive reliability requires additional costs, but taking into account unpredictable situations and changes in equipment reliability indicators, a positive reserve value should be planned. The value of the power reserve $N^r(t_j)$ at a given moment is determined as the difference between the available installed capacity of the system and its load:

$$N^r(t_j) = N^p(t_j) - N_j. \quad (3)$$

The calculated reserve value for the period T_y is taken as the value corresponding to the annual maximum load. In our case, this refers to January, the coldest period of the heating season.

Therefore, in our case:

$$N_m^r = N^p(t_1) - N_1. \quad (4)$$

it must exceed the maximum power that can be lost in the event of an emergency shutdown of at least one generating unit in the system. The probability of system reliability q_m in the interval m , i.e. at maximum load, can be determined by the formula:

$$q_m = 1 - p_m(A|B) = 1 - \frac{p_m(A \cap B)}{p_m(B)}, \quad (5)$$

where:

$p_m(A \cap B)$ – the probability of both events A and B occurring simultaneously. An event means that the failure of k units causes the system to fail;

$p_m(B)$ – probability of event B occurring, i.e. failure of k units in the m -th interval;

$p_m(A)$ – probability of failure of the entire power system to function properly, in our example during the most stressful January period ΔT_1 .

The probability of k failures of units in the j -th interval P_j^k can be found using the formula for Poisson distribution, which describes the probability of events occurring within a set time interval ΔT_j that are independent of each other. In each test, the probability is assumed to be constant, and if the general condition is satisfied, i.e. the number of elements in the system n multiplied by the probability of failure $p \cdot n \cdot p < 10$, then the probability that failure will occur exactly k times in n tests is approximately equal to:

$$P_j^k = \frac{(\lambda_j)^k}{k!} \cdot \exp(-\lambda_j), \quad (6)$$

where:

λ_j – total failure rate in the j -th interval;

$p(N_m^r | k)$ – conditional probability that, if k units fail in the j -th interval, the system will fail when the total capacity of the power units taken out of service due to failures exceeds the capacity of the operational reserve; its value can be determined by the Bernoulli or Laplace distribution.

The Laplace distribution is a continuous probability distribution used to model data with “heavy tails” (a higher probability of extreme values) compared to the normal distribution. This means that it has a higher probability for values far from the mean, making it suitable for modelling phenomena where extreme events occur more frequently. The Laplace integral function is as follows:

$$\Phi_i = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \int_0^x e^{-\frac{s^2}{2}} \cdot dx, \quad (7)$$

where: $s = x_1 \dots x_2$, and x in turn:

$$x_i = \frac{k_i - n \cdot p}{\sqrt{n \cdot p \cdot (1 - p)}}. \quad (8)$$

In general, x_1 and x_2 are determined, respectively, at the minimum number of elements that can fail in the system – k_1 , and at the maximum number – k_2 . If the option of a possible failure from 0 to k is considered, then $k_1 = 0$.

After obtaining the values of the tabular functions Φ_1 and Φ_2 , the probability of failure of k elements is determined as the difference between these functions:

$$P = \Phi_2 - \Phi_1. \quad (9)$$

The value of the reserve N_m^r in the formula for determining the conditional probability $p(N_m^r | k)$ is the difference between the total capacity of the installed and ready-to-operate generating elements of the system and the total capacity of n operating units N_i during the period of maximum system load ($j=m$):

$$N_m^r = \sum_{i=1}^{\bar{n}_j} N_i^p - \sum_{i=1}^{n_m} N_i. \quad (10)$$

Thus, taking into account the assumptions made, the values necessary for establishing the probability of failure-free operation of the heat supply system q_j and the value of the power reserve of the power system N_m^r are determined for known general parameters of the power system and reliability indicators of its generating equipment. It should be noted that the presented method of using the tabulated Laplace distribution requires tables of local and integral functions, which somewhat complicates its practical implementation.

Research results

For practical use in most cases, the problem of power reservation can be solved using a simpler and more accurate method for a small number of system elements, based on the Bernoulli distribution, which we will use for in-depth analysis.

According to this method, the probability P_j^k of k failures of units in the j -th time interval:

$$P_j^k = \frac{n! \cdot p^k \cdot (1 - p)^{(n-k)}}{k! \cdot (n - k)!}, \quad (11)$$

where:

n – total number of installed generation facilities;

k – number of refusals considered;

p – probability of failure of a single system component.

Let us analyse the following options for reserving a boiler room with $n = 6, 8$ and 12 boilers of the same type with possible failure probabilities $p = 0.05; 0.1$ and 0.2 . Based on this initial data, we will determine the probability of emergency shutdown of one, two, three and four boilers.

To simplify the calculations, especially when there are a large number of system elements, one of the

well-known mathematical packages such as MatCad, Maple or Matlab can be used. Thus, in Maple, the program (left) and the calculation results (right) look as shown in Figure 3.

RESTART	
$q := (p, n, k) \rightarrow \frac{n! p^k (1-p)^{(n-k)}}{k!(n-k)!}$	$q := (p, n, k) \rightarrow \frac{n! p^k (1-p)^{(n-k)}}{k!(n-k)!}$
$q_1 := \text{SION}(q(0.1, 6, s), s = 0..1)$	$q_1 := 0.8857350000$
$q_2 := \text{SION}(q(0.1, 6, s), s = 0..2)$	$q_2 := 0.9841500000$
$q_3 := \text{SION}(q(0.1, 6, s), s = 0..3)$	$q_3 := 0.9987300000$
$q_4 := \text{SION}(q(0.1, 6, s), s = 0..4)$	$q_4 := 0.9999450000$

Fig. 3. Calculation using Maple

In this particular case, the calculation of the probability of failure of one, or simultaneously 2, 3, 4 boilers of the system (here s is the number of failures from 0 to k) is shown, with the probability of failure of each element $p=0.1$ and the total number of elements in the system $n=6$.

In this case, the opposite result – the probability of failure of elements in the given situation – is determined as $p_k = 1 - q_k$, and these values for all options are given in Table 1.

Table 1

Probability of failure of power supply system components

k	$n=6$			$n=8$			$n=12$		
	$p=0.05$	$p=0.1$	$p=0.2$	$p=0.05$	$p=0.1$	$p=0.2$	$p=0.05$	$p=0.1$	$p=0.2$
1	0.032774	0.186895	0.34464	0.057245	0.186895	0.496684	0.11836	0.186895	0.725122
2	0.00223	0.038092	0.09888	0.005788	0.038092	0.203082	0.019568	0.038092	0.441654
3	8.64E-05	0.005024	0.01696	0.000372	0.005024	0.056282	0.002236	0.005024	0.205431
4	1.8E-06	0.000432	0.0016	1.54E-05	0.000432	0.010406	0.000184	0.000432	0.072555

It is advisable to present the results obtained in a more visual form using appropriate graphs. It should be noted that in probabilistic calculations, qualitative assessment and identification of trends in the influence of various factors on the probability of certain events occurring are often more important than “dry” numerical values.

Analysis of the graph in Fig. 4 shows that with a small total number of generating elements in the system, the probability of failure of individual elements is quite high. Moreover, the probability of failure of one element is the highest, the probability of failure of two elements at the same time is significantly lower, and the probability of failure of three and four elements is very low.

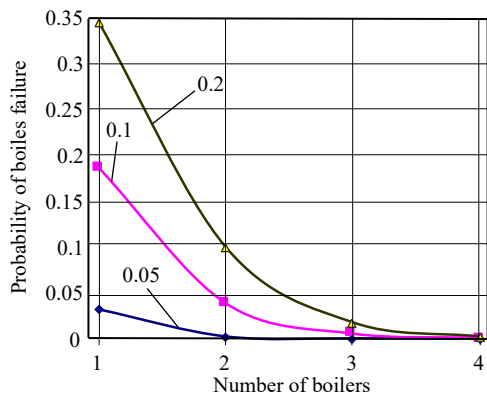


Fig. 4. Probability of failure of individual system elements when their total number is $n=6$

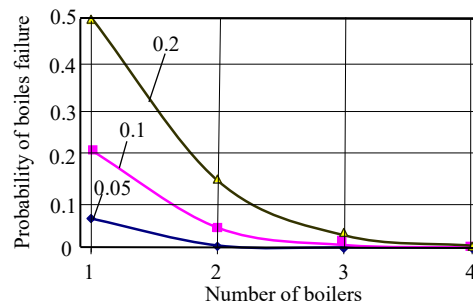


Fig. 5. Probability of failure of individual system components when their total number is $n=8$

Of course, in all cases with higher reliability indicators of elements, the probability of failure for different numbers of them is significantly lower.

When the total number of system elements is increased to $n=8$ and $n=12$ (Fig. 5, 6), there is an increase in the probability of failure of different numbers of elements k due to the increase in the sample size. However, with a larger total number of elements, the relative share of the impact of the failure of a single element (boiler) on the performance of the entire system (boiler room) decreases accordingly, given the accepted minimum reserve value.

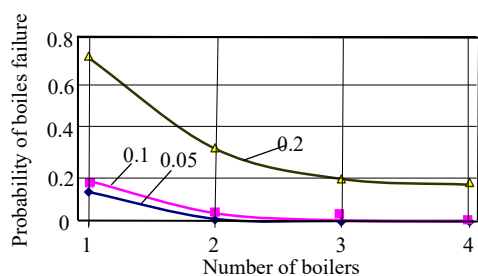


Fig. 6. Probability of failure of individual system elements when their total number is $n=12$

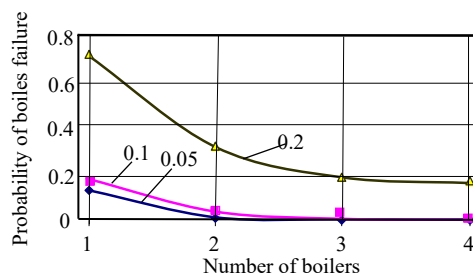


Fig. 7. Nature of change in probability of failure of individual elements with individual probability of failure $p=0.05$ when the total number of elements n changes from 6 to 12

The result of the analysis of the impact of the total number of elements, or generating boilers in the heat supply system, including concentrated with a large number of elements, can also be made on the basis of the graphs shown in Figures 7 and 8. And if, with high reliability of individual elements with $p=0.05$, the situation is obvious, then with low reliability of individual elements with $p=0.2$, a completely different nature of dependencies $p=f(k)$ is observed when one element of the system fails and four elements fail simultaneously. Additional calculations with an increase in the value of n to 16 confirmed this feature.

Obviously, this peculiarity of the influence of the total number of system elements on the probability of failure of k_{1-4} elements can be explained by the fact that when n is very large – several hundred (for example, in microelectronic elements, chips), the difference in the probability of failure of one or four elements will be insignificant.

As noted, the total reserve of the power system is determined by the sum of the load reserve – N_h , the repair reserve – N_{pr} , and the emergency reserve – N_{ar} :

$$N_y^r = N_h + N_{pr} + N_{ar} . \quad (12)$$

During periods of maximum load, the minimum value of the required reserve N_m^r is determined as the corresponding value N_{ar} , since the reliability of power supply is mainly determined by the level of emergency reserve, as the rest of the components can be fixed.

In the case of a system reserve consisting of equipment of different capacities and reliability indicators, the emergency reserve of the power system is determined as the sum of the reserves of individual types of equipment:

$$N_{ar} = \sum_{i=1}^k N_i^r , \quad (13)$$

where:

N_i^r – reserve of equipment of this type;

k – the amount of backup generating equipment of the appropriate type.

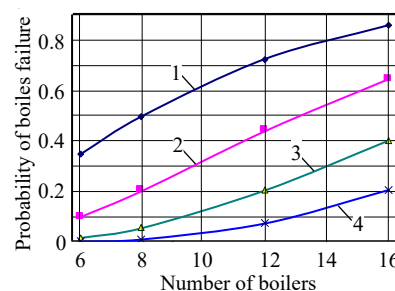


Fig. 8. Nature of change in probability of failure of individual elements with individual probability of failure $p=0.2$ when the total number of elements n changes from 6 to 16

The value of N_i^r can be determined using the formula:

$$N_i^r = N_i \cdot n_i \cdot \bar{r}_i, \quad (14)$$

where:

N_i – power of a power plant of a certain type;

n_i – number of elements in the system (in our case, boilers or autonomous electric generators) of the same type;

\bar{r}_i – specific reserve, determined by specific power:

$$\bar{N}_i = N_i / N^{pi}(t_m), \quad (15)$$

where:

p_i – average failure rate of units of type i ;

$N^{pi}(t_m)$ – total capacity that can be carried by the installed generating equipment during periods of maximum load on the heat supply power system.

The accident rate for a specific heat supply installation can be estimated using the following formula:

$$p_i = \frac{\tau_{av}}{\tau_y - \tau_{av}}, \quad (16)$$

where:

τ_y – the time during which the unit is in operation, i.e. annual or seasonal operating hours;

τ_{av} – equipment downtime due to its failure during the relevant period.

The average failure rate p_i is often assumed to be constant for energy equipment of the same type, but it should be borne in mind that even such equipment may have significantly different reliability indicators. This makes it advisable to systematically record, collect and process statistical data on all elements of the system, especially for power equipment that has worked out a significant part of its resource.

Conclusions

The paper examines the possibilities of improving the reliability of the heat supply system when installing reserve capacities. The following conclusions were made:

1. The calculated reserve value is taken to be the value corresponding to the annual maximum load; it must be greater than the maximum capacity that can be lost in the event of an emergency shut-down of at least one generating unit of the system;

2. In the course of the analysis of existing methods for calculating the reserve capacity of thermal equipment, the method based on Bernoulli distribution is simpler and more accurate for a small number of system elements;

3. The probability of failure in the heat supply system is quite high when there are a small number of generating elements of individual elements; moreover, the probability of failure of one element is significantly higher than the probability of failure of two elements at the same time, and the probability of failure of three or four elements is very low;

4. With high reliability indicators for elements, the probability of failure for different numbers of elements is significantly lower;

5. With a larger total number of elements, the relative impact of the failure of a single element (boiler) on the performance of the entire system (boiler room) decreases accordingly, given the accepted minimum reserve value.

Therefore, it is necessary to conduct appropriate systematic individual accounting, collection and appropriate processing of statistical data on all elements of the heat supply system, paying particular attention to energy equipment that has worked out a significant part of its resource.

Література

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