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Abstract. Forecasting and ensuring the required high reliability level of heat power plants (thermal power plants) at a stage of their creation and operation is an important problem of economic value. For the solution of this problem in the present article the task is to develop such mathematical models of forecasting of reliability at all stages of life cycle of a thermal power plant from designing before removal from operation. It would be possible to reduce costs of realization of concrete actions. Parametrical mathematical models of growth of reliability have been developed for the solution of an objective. In particular two-parametrical, three-parametrical and multiple parameter models of growth of reliability have been developed and presented. For calculation of estimates of parameters of distribution standard programs are offered. All developed mathematical models of forecasting of reliability level are based on use of the statistical data obtained in the course of tests or operation of products analogs. Change of reliability level on five stages of life cycle of the power equipment of a thermal power plant is graphically shown in the article.

Keywords. Heat power equipment, reliability level, methods, parametrical mathematical models, laws of distribution.

1. Introduction

Mathematical models of growth of reliability allow to predict change of reliability of the power equipment of a thermal power plant in the course of its creation and operation and also to give an assessment to reliability at any moment of prototypes' tests and in use at the moments of carrying out completions [1-4]. It is known that in the course of carrying out tests or operation there are refusals which reason can be not always unambiguously established [5-7]. Owing to this fact the carried-out completions also ambiguously influence change of reliability, nevertheless the tendency of growth of reliability from one completion to another is observed. Thus, process of change of reliability due to completions has a casual reason. Graphically it is shown in figure 1.

From the schedule is visible that at a design stage thanks to introduction of new constructive decisions and other actions reliability increases to the required value.

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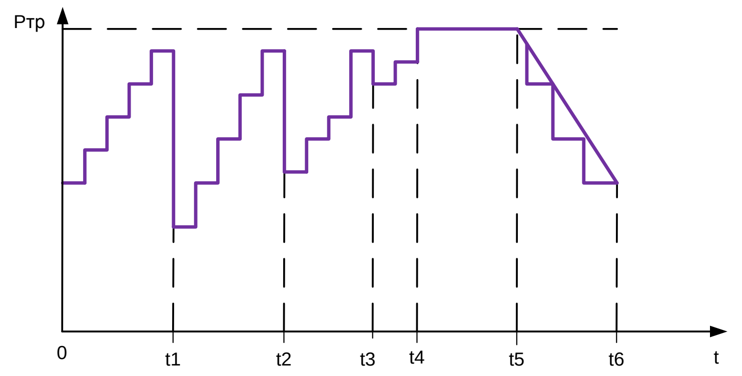

Figure 1. Change of reliability level of the power equipment of a thermal power plant in the course of creation and operation

2. Results

Upon transition to prototypes' tests there is a sharp falling of function of reliability at the moment t_1. It is caused by the fact that at a design stage it is almost impossible to consider all features of the created prototype and therefore the high design reliability coinciding with the required reliability, as a rule, isn't maintained.

At a stage of prototypes' tests ($t_1 - t_2$) at the expense of the carried-out completions there is an increase in a reliability level to the size close to the required value. On an initial stage of operation ($t_2 - t_3$) at the beginning there is some falling of reliability level due to constructive and technological refusals. On the site of operation ($t_4 - t_5$) within a warranty period at the expense of the held events reliability to the required level increases. Outside a warranty period of operation, the site ($t_5 - t_6$), there is a sharp falling of reliability level because of material aging and wear of the rubbing surfaces.

Thus, for quality control and reliability of the power equipment of a thermal power plant is necessary to find analytical model of change of reliability at all stages of its creation and operation. The function of reliability presented in fig. 1 includes sites on which reliability passes with jump from one stage to another, remains to a constant or grows at the expense of the carried-out completions. Therefore, for the description of all function of reliability is necessary to receive such models which would reflect three characteristic manifestations of reliability.

Creation of the model of reliability's change by results of tests is carried out at rather large number of tests and a large number of completions. In the case under consideration carrying out completions only after establishment of causes of refusals is provided in mathematical model and provided that these completions don't reduce reliability level. In the course of creation of model results of tests are presented in the form of separate series with a certain number of completions in each of them. For the description of an increment of reliability of a product from one series of tests to another the linear dependence can be as a first approximation used (1):

$$\Delta P_i = a_i (P_r - P_{i-1}), \qquad (1)$$

where a_i – the coefficient characterizing efficiency of i-oh completion which is in an interval $(0{,}5 \le a_i \le 1{,}0)$;

P_r– the required value of probability of no-refusal operation;

P_{i-1} – probability of successful test after $(i$-1) - completions.

As in the course of tests completion is carried out in case of obvious clarification of a cause of refusal, reliability of a product changes only after completion performance.

Change of function of reliability in the course of working off has spasmodic character (figure 2).

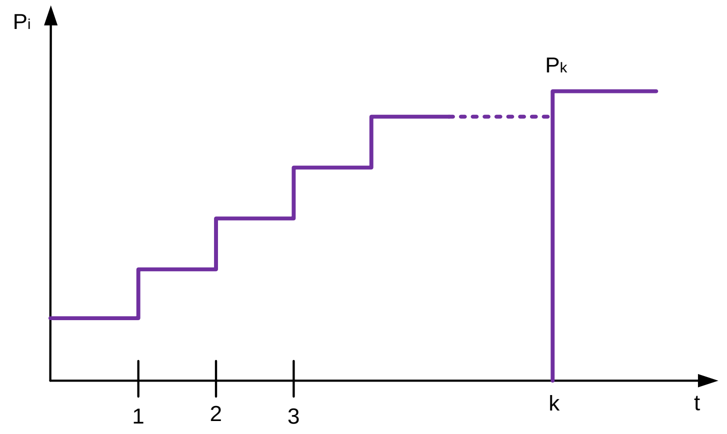

Figure 2. Change of Function of Reliability (probability of no-refusal operation) at working off of a product

Function P_i has jumps only in those points of i after which completions have been carried out, and these jumps depend on the reached reliability $P_{i\text{-}1}$ and also the coefficient a_i characterizing success of elimination of a cause of refusal i.e. it is possible to write down (2):

$$P_i = P_{i-1} + a_i(P_r - P_{i-1}). \tag{2}$$

Then required function of reliability (probability of no-refusal operation) describing all process of working off has an appearance (3):

$$P_i = P_0 + \sum_{i=1}^{k} a_i(P_r - P_{i-1}), \tag{3}$$

where P_0 – initial reliability (probability of no-refusal operation) of a product received before carrying out the first completion;

k – number of the carried-out completions.

Thus, the probability of no-refusal operation depends on two parameters – P_0 and a_i, so-called two-parametrical model. If these parameters are determined by results of tests, then it is possible to calculate values of function of reliability in points of carrying out completions and to predict change of reliability level and costs of carrying out completions [8-12].

The similar formula can be written down for function of reliability expressed as average value of a time between refusals (4):

$$T_i = T_0 + \sum_{i=1}^{k} a_i(T_r - T_{i-1}) \tag{4}$$

where T_0 – the average value of a time between refusals received before carrying out the first completion;

ΔT_i – an increment of average value of a time between refusals from (i-1) - oh before i-oh completion, $\Delta T_i = T_i - T_{i-1}$.

On the basis of the assumptions accepted above for working off of products the three-parametrical model is received (5) [13]:

$$P_i = P_r - (P_r - P_0)\left(1 - \frac{a_i}{P_r}\right)^i \tag{5}$$

For finding of parameters of distribution P_0, P_r also a_i use a method of maximum likelihood for what it is necessary to make function of credibility (6):

$$L = \prod_{i=0}^{k} \frac{n_i!}{m_i!(n_i - m_i)!} P_i^{n_i - m_i} (1 - P_i)^{m_i} \tag{6}$$

where n_i – number of tests between i-oh and (i+1) - oh completions;
m_i – number of refusals in n_i tests after which completion was carried out.

Substituting in a formula (6) instead P_i of its value from a formula (5), we will receive the required function of credibility (7) depending on three parameters – P, P_r and a_i:

$$L = \prod_{i=0}^{k} C_{n_i}^{m_i} \left[P_r - (P_r - P_0)\left(1 - \frac{a_i}{P_r}\right)^i \right]^{n_i - m_i} \times \left[P_r - (P_r - P_0)\left(1 - \frac{a_i}{P_r}\right)^i \right]^{m_i} \tag{7}$$

The equation (7) includes the known skilled data m_i and n_i also unknown parameters P_o, P_r and a_i. Estimates of maximum likelihood are estimates P_o, P_r and a_i at which function of credibility (7) addresses in a maximum. For the solution of this task standard programs of a minimum of linear function are used.

For the description of change of function of reliability P_i the method based on representation P_i in the form of function of casual arguments which values can be determined by results of tests of this type of products or products analogs can be used. Such approach allows to establish an analytical form of dependence which is function of reliability [14-19].

In a general view the function (7) can be written down as follows (8):

$$P_i = P(\alpha_1, \alpha_2, \ldots, \alpha_s, t) \tag{8}$$

where α_i – unknown parameters.

Having chosen several various forms of function P_i, it is possible to estimate which of them in the best way describes an experimental curve.

We will consider hyperbolic model of growth of function of reliability and other mathematical models.

The hyperbolic model of change of reliability is based on the assumption that all program of tests is presented in the form of k-stages, on each of which make a certain number of tests, build a curve of growth of reliability which has an type of a hyperbole and is expressed by dependence (9):

$$P_i = P_r - \frac{\alpha}{i} \tag{9}$$

where α – the parameter characterizing reliability growth rate;
i = 1, 2, 3, … – stages of tests.

The described model depends on two parameters α and P_r.
Then for i-oh of a stage of working off we will have (10):

$$L_i = P_i^{n_i - m_i}(1 - P_i)^{m_i} \tag{10}$$

Believing that the results of all stages are statistically independent, we will receive (11):

$$L = \prod_{i=1}^{k} L_i = \prod_{i=1}^{k} P_i^{n_i - m_i}(1 - P_i)^{m_i} \tag{11}$$

or after logarithming:

$$\ln L = \sum_{i=1}^{k}(n_i - m_i)\ln\left(P_r - \frac{\alpha}{i}\right) + \sum_{i=1}^{k} m_i \ln\left(1 - P_r + \frac{\alpha}{i}\right)$$

The equations of credibility can be written down in the form of (12):

$$\frac{d\ln L}{dP_r} = \sum_{i=1}^{k}\frac{n_i - m_i}{P_r - \frac{\alpha}{i}} + \sum_{i=1}^{k}\frac{m_i}{1 - P_r + \frac{\alpha}{i}} = 0;$$

$$\frac{\mathrm{d}\ln L}{\mathrm{d}\alpha} = -\sum_{i=1}^{k}\frac{(n_i - m_i)/i}{P_r - \frac{\alpha}{i}} + \sum_{i=1}^{k}\frac{m_i / i}{1 - P_r + \frac{\alpha}{i}} = 0. \tag{12}$$

As a result of the solution of the equation (12) we will receive estimates of parameters (13), (14):

$$\hat{\alpha} = \frac{\sum_{i=1}^{k} n_i \left[\sum_{i=1}^{k} i(n_i - m_i) - \frac{k+1}{2}\sum_{i=1}^{k}(n_i - m_i)\right]}{\frac{k+1}{2}C - k}, \tag{13}$$

$$\hat{P}_r = \frac{\sum_{i=1}^{k} n_i \left[\frac{C}{k}\sum_{i=1}^{k} i(n_i - m_i) - \frac{k+1}{2}\sum_{i=1}^{k}(n_i - m_i)\right]}{\frac{k+1}{2}C - k}, \tag{14}$$

$$\mathrm{C} = \sum_{i=1}^{\mathrm{k}}\frac{1}{\mathrm{i}} \approx \ln\left(\mathrm{k} + \frac{1}{2}\right) + \mathrm{E}$$

where E = 0,57721– constant.
As the approximating dependences it is possible to use models of a look (15):

$$P_i = 1 - (1 - P_0)\exp(-\alpha_i) \tag{15}$$

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Or model (16):

$$P_i = \frac{P_0}{P_0 + (1 - P_0)\exp(-\alpha_i)}. \quad (16)$$

The most widespread is the model described by the indicative law (17):

$$P_i = 1 - A\exp\left[-c(i-1)\right], \quad (17)$$

where $A = \beta \cdot P$; $c = ln\frac{1}{1-\alpha \cdot P} > 0$.

This function depends on three parameters *β*, *P* and *α* which can be determined by method of maximum likelihood or method of the smallest squares by standard programs. More general model of growth of reliability [20-22] has a type of (18):

$$P_i = P_r - \alpha \cdot f(i) \quad (18)$$

where $f(i)$– the positive monotonously decreasing function.

For finding of estimates of parameters α and P_r method of the smallest squares calculate the sums:

$$C_1 = \sum_{i=1}^{k} f(i),\ C_2 = \sum_{i=1}^{k} f^2(i).$$

For some types of the $f(i)$ functions approximate formulas for calculations of C_1 and C_2 (table 1) are given.

Table 1. Approximate formulas for calculations of C_1 and и C_2

f (i)	C_1	C_2	Note
$i^{-\frac{1}{2}}$		$\ln\left(k+\frac{1}{2}\right)+0{,}577$	
i^{-1}	$\ln\left(k+\frac{1}{2}\right)+0{,}577$	$\frac{\pi^2}{6}-\left(k+\frac{1}{2}\right)^{-1}$	$\frac{\pi^2}{6}=1{,}645$
i^{-2}	$\frac{\pi^2}{6}-\left(k+\frac{1}{2}\right)^{-1}$	$\frac{\pi^4}{90}-\frac{1}{3}\left(k+\frac{1}{2}\right)^{-3}$	$\frac{\pi^4}{90}=1{,}082$
i^{-3}	$1{,}2-\frac{1}{2\left(k+\frac{1}{2}\right)^{-2}}$	$\frac{\pi^6}{945}-\frac{1}{5}\left(k+\frac{1}{2}\right)^{-5}$	$\frac{\pi^6}{945}=1{,}017$

Assessment of parameter of distribution is found, solving the equations (19) and (20):

$$Q = \sum_{i=1}^{k}\left[\frac{n_i - m_i}{n_i} - P_r + \alpha \cdot f(i)\right]^2;$$

$$\frac{\mathrm{d}Q}{\mathrm{d}P_r} = -2\sum_{i=1}^{k}\left[\frac{n_i - m_i}{n_i} - P_r + \alpha\cdot f(i)\right] = 0\,; \tag{19}$$

$$\frac{\mathrm{d}Q}{\mathrm{d}\alpha} = 2\sum_{i=1}^{k}\left[\frac{n_i - m_i}{n_i} - P_r + \alpha\cdot f(i)\right]\cdot f(i). \tag{20}$$

As a result of the solution of the equations (19) and (20) we will receive estimates of parameters (21) and (22):

$$\hat{P}_r = \frac{C_2\sum_{i=1}^{k}\left(\frac{n_i - m_i}{n_i}\right) - C_1\sum_{i=1}^{k}\left(\frac{n_i - m_i}{n_i}\right)\cdot f(i)}{k\cdot C_2 - C_1^2} \tag{21}$$

$$\hat{\alpha} = \frac{C_1\sum_{i=1}^{k}\left(\frac{n_i - m_i}{n_i}\right) - k\sum_{i=1}^{k}\left(\frac{n_i - m_i}{n_i}\right)\cdot f(i)}{k\cdot C_2 - C_1^2} \tag{22}$$

Change of reliability of a product at its stage-by-stage test can also be estimated statistically. Reliability assessment after i-oh series of tests is determined by dependence of a type (23):

$$\hat{P}_i = \alpha\cdot \hat{P}_i^{'} + (1-\alpha)\hat{P}_{i-1} \tag{23}$$

where $\hat{P}_i^{'}$ and $\hat{P}_{i-1}$ – reliability estimates by results of respectively only i-oh series of the tests and all tests which are carried out to i-oh series;
α – the coefficient characterizing the weight of each assessment.

Let's say that reliability of the tested samples in each series is identical. Features of this model are that that at α =1 in its all tests to *i*-oh series aren't considered, and at α=0 – results of the last series. The value of assessment $\hat{P}_i^{'}$ is defined by results of tests on a formula (24):

$$\hat{P}_i^{'} = 1 - \frac{m_i}{n_i} \tag{24}$$

It is possible to be set by value of parameter, proceeding from practical reasons that it reduces efficiency of use of this model.

The obtained results can be used in the development of new turbines.

The developed parametric models of reliability forecasting were used at the stage of creation of complex technical systems such as mobile units for special purposes and found practical confirmation in published scientific publications [23-25].

3. Conclusions

1. For the purpose of a solution of the problem of providing the power equipment of a thermal power plant required the reliability level in the present article methods and mathematical models of forecasting of reliability with use of estimates of parameters of distribution of function of reliability are developed.

2. The method of maximum likelihood and a method of the smallest squares are applied to finding of estimates of parameters of distribution.

3. Mathematical models of forecasting are developed and presented in the form of function of reliability with two, three and large number of parameters.

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