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Models for predicting damage due to accidents at energy objects and in energy systems of enterprises

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Abstract. Achieving energy security by preventing and timely eliminating the consequences of accidents at energy facilities and in energy supply systems of enterprises is one of the important tasks of energy management. The basis for planning appropriate energy security measures is the prediction of damage from these accidents. The purpose of forecasting is to assess the possibility of an accident occurring at some point in time and leading to a particular damage, and to assess the magnitude of this damage. The article proposed methodological approaches to the construction of mathematical models of such prediction. In this case, as an indicator of damage, the economic losses caused by these accidents are taken. The simulation is based on the representation of this indicator in the form of a step change function of the magnitude of losses in the event of an accident. Depending on the amount of information available in the period prior to forecasting, the mathematical representation of the forecasting problem is reduced to the construction of conditionally determined or stochastic models. Conditionally determined models allow obtaining acceptable damage estimates with a short period of retrospection and small amounts of information, and stochastic models with significantly large amounts. At the same time, the principle of "maximum uncertainty" formalized in the form of maximum entropy is the basis for removing uncertainty in the construction of both conditionally determined and stochastic models. Its use has allowed increasing the objectivity of forecasts by minimizing the subjective information used in modeling. The proposed approaches to the construction of mathematical models for predicting accidents at energy facilities and power supply systems of enterprises are the basis for creating specific techniques for solving relevant energy management tasks both at the micro level at the scale of individual enterprises and at the macro level at the scale of industries, regions and the state as a whole.

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1 Introduction

The development of the economy is characterized by the involvement in economic circulation of an increasing number of natural resources, the growth of the production base, the use of more and more complex technological systems, their concentration, and the increase in the amount of energy consumed by mankind. All this leads to a sharp increase in the number and potential danger of accidents at energy facilities in general and the systems of energy supply of enterprises, in particular. So, according to the Ministry of Energy of the Russian Federation, published on its official website, only in January 2019, 214 accidents occurred at the facilities of the generating companies of the unified power grid (UPG) of Russia. In electrical grids 110 kV and above of UPG of Russia, 571 accidents occurred. There were 24 cases of power outages of consumers with a capacity of 10 MW or more. At the same time, an increase in the concentration of production and an increase in population density leads to the fact that certain small-scale accidents can provoke and strengthen each other and cause synergistic effects that cause enormous economic damage. For example, a study of 5 thousand of the largest accidents of the last decades showed that 90-95% of them occurred in the industrialized countries of the world [1, 2].

This necessitates the formation in the process of energy management of measures to counter industrial accidents at power facilities and energy supply systems, as well as measures to eliminate the consequences of these accidents. The high cost of such measures determines the need for their adequate comparison with the degree of danger of man-made accidents at various facilities. The reliability of the hazard assessment of these accidents can be ensured by using appropriate mathematical models. Development in the interests of energy management of methodological approaches to building models for predicting damage due to accidents at power facilities and in power supply systems of enterprises is the goal of this article.

2 Research Method

The danger of accidents at energy facilities and in the systems of energy supply of enterprises can be assessed by the possibility of an event occurring at time t leading to a given economic damage and the magnitude x of this damage.

For damage assessment it is proposed to use indicators characterizing the economic losses caused by these accidents.

The simulation is based on the representation of these indicators in the form of a discontinuous function of the magnitude of losses in the event of an accident. Depending on the amount of information available in the previous forecasting period, either a conditionally deterministic or stochastic approach to the construction of forecasting models is chosen [3, 4]. Conventionally determined models allow obtaining acceptable damage estimates with a short period of retrospection and small amounts of information, and stochastic models with significantly large amounts. In order to increase the objectivity of forecasts due to minimization of subjective information used in modeling, uncertainty relief in building both conditionally determined and stochastic models is based on the “maximum uncertainty” principle formalized in the form of maximum entropy [5-7].

3 Results of the study

3.1 Methodical approach to the construction of conditionally deterministic models

Within the framework of the conditionally deterministic approach, the modeling of step processes characterizing the dynamics of the risk of accidents at the respective power facilities and in the systems of energy supply of enterprises relies on the use of functions of the form

$$x(t)=\sum_{j=1}^{n} a_j n(t-t_j) \quad (1)$$

where $x(t)$ is the expected value of economic damage by the time t;

a_j is the expected magnitude of the jump in the measure of economic damage associated with the occurrence of the j-th (j=1,2,…,n) event;

t_j is the expected time of occurrence of the j-th (j=1,2,…,n) event;

$n(t-t_j)$ - function of type

$$n(t-t_j)=\begin{cases}1, & (t-t_j)>0 \\ 0, & (t-t_j)\le 0\end{cases}, \quad j=1,2,\ldots,n \quad (2)$$

For the constructive representation of the function (1) it is necessary to construct functions

$$a_j=f_1(j), \quad (3)$$

$$t_j=f_2(j). \quad (4)$$

Since the moments of occurrence of events leading to economic damages and the magnitudes of these damages are of a stochastic nature, within the framework of the conditionally deterministic approach, the values a_j и t_j, defined by relations (3), (4), should be interpreted as the mathematical expectations of the considered value.

The initial information for the construction of functions (3), (4) is the totality

$$w=\{x_j,\, t_j\}, \quad j=1,2,\ldots,n. \quad (5)$$

It contains the values x_j, t_j determined during the period preceding the forecast, as well as a priori data on the possible nature of the predicted processes, obtained on the basis of the safety management experience of similar objects or expert opinions [8 - 10]. Set (5), as a rule, has a small volume. This imposes significant restrictions on the possibility of using the classical methods of mathematical statistics and probability theory for the construction of functions (3), (4). One of the most common approaches to overcoming the difficulties of determining the specific type of functions (3), (4) associated with the lack of a priori information is the application of an additional extreme condition based on the principle of "maximum uncertainty". It postulates that the least questionable representation of functions (3), (4) will be a representation that maximizes uncertainty while taking into account all given information. The application of the maximum uncertainty principle to determine the type of functions (3), (4) allows minimizing subjective information introduced into the forecasting process and sufficiently taking into account the available objective information about the characteristics and conditions of implementation of the process being studied [11-15].

The experience of energy management shows that a wide range of energy facilities and power supply systems of enterprises as they develop and become larger are characterized by an increase in economic damage during accidents, that is,

$$a_n > a_{n-1} > ... > a_1 \tag{6}$$

In part of the function (4), it is natural to assume that it is a decreasing function of the integer argument *j*, that is,

$$t_1 > t_2 > ... > t_n \, . \tag{7}$$

Ratio (7) reflects the fact that an increase in the number and scale of the technosphere objects and an increase in their energy needs leads to a reduction in the time intervals between accidents at energy facilities and in energy supply systems of enterprises, leading to economic damage.

We will assume that:

the average jump in the measure of economic damage for the previous period is a_0;

the average time between jumps during this period was t0;

performing the ratio (6) and (7);

the values aj and tj are independent.

Then, taking into account the principle of "maximum uncertainty", ratio (3) can be represented as

$$a_j = a_0 F_1(j), \quad j = 1,2,...,n \, , \tag{8}$$

where $F_1(j)$ - assessment of probability for the elements of the variation row (7).

The ratio (4) can be represented as

$$t_j = t_0 F_2(j), \quad j = 1,2,...,n , \tag{9}$$

where $F_2(j)$ assessment of probability for the elements of the variation row (6).

To estimate the values $F_1(j)$, $F_2(j)$, in the information situation described by ratio (6), (7) it is advisable to use the second kind of entropy

$$H_2(F_2) = \prod_{j=1}^{n} F_2^{n-j+1}(j) \, . \tag{10}$$

The expediency of its use is due to the fact that, unlike the first-kind entropy (Shannon's entropy), it is more sensitive when solving extremal tasks with constraints in the form of inequalities.

When it is used as a measure of the uncertainty of entropy (10) of the functions $F_2(j)$ included in ratio (9) are the solution to the conditional extremum of the task [16].

$$H_2(F_2) = \prod_{j=1}^{n} F_2^{n-j+1}(j) \xrightarrow[F_2)j)]{} \max \, , \tag{11}$$

$$\sum_{j=1}^{n} F_2(j) = 1 . \tag{12}$$

They are:

$$F_2(j) = \frac{n - j + 2}{n2^j}, \quad j = 1,2,\ldots,n. \tag{13}$$

The functions $F_1(j)$ included in (8) are determined by the ratio

$$F_1(j) = 1 - F_2(j), \quad j = 1,2,\ldots,n \tag{14}$$

With the weakening of the assumption that the magnitude of the jumps in the damage indicator in case of accidents at power facilities and in the power supply systems of enterprises increases, the ratio (6) takes the form

$$a_n \geq a_{n-1} \geq \ldots \geq a_1 . \tag{15}$$

Then the assessment of probability for the elements of the variation row in (8) are determined by the relation

$$F_1(j) = 1 - \frac{2n - j + 1}{n(n+1)}, \quad j = 1,2,\ldots,n . \tag{16}$$

When weakening the assumption of a decrease in the time intervals between jumps, ratio (7) takes the form

$$t_1 \geq t_2 \geq \ldots \geq t_n . \tag{17}$$

Then $F_2(j)$ are determined by the ratio

$$F_2(j) = \frac{2n - j + 1}{n(n+1)}, \quad j = 1,2,\ldots,n . \tag{18}$$

In general, the presented ratios (1) - (4), (8), (9), (13), (14) are a conditionally determined model for forecasting in the interests of the energy management of economic damage during technological accidents at energy facilities and in power supply systems enterprises under assumptions (6), (7).

Ratios (1) - (4), (8), (9), (16), (17) are a conditionally deterministic model for predicting these jumps under assumptions (6), (15).

Ratios (1) - (4), (16), (18) are a conditionally deterministic model for predicting jumps under the assumptions (15), (17).

It should be noted that the considered models that implement the conditionally deterministic approach do not fully take into account random factors inherent in the economic damage caused by accidents at power facilities and in power supply systems of enterprises. Therefore, along with these models, it is advisable to use stochastic models, which allow estimating not only the expected values of damages, but also their probability characteristics.

3.2 Stochastic models

When building stochastic models, the totality of values $x_j, t_j,$ determined during the period preceding the forecast can be viewed as a sample of the general set subject to the two-dimensional distribution law $Q(x,t)$ of random values of jumps X of economic damage as a result of accidents at energy facilities and in energy supply systems of enterprises, as well as the periodicity T of their appearance. The size of this sample determines the possibility of forming one or another stochastic model. We will assume that the sample size allows us to determine not only the average time t_0 between jumps and the average value x_0 of a jump in the measure of economic damage, but also the correlation coefficient r_{xt}. In such an informational situation, based on the principle of "maximum uncertainty" and first-kind entropy, the model for predicting jumps of value of the economic damage rate as a result of accidents is E. Gumbel's two-dimensional exponential distribution [17]. The density function for this distribution in the previously adopted notation is

$$q(x,t)=\frac{1}{x_0 t_0}\exp\left(\frac{xt}{x_0 t_0}\right)\left[1+\rho\left(2e^{-\frac{x}{x_0}}-1\right)\left(2e^{-\frac{t}{t_0}}-1\right)\right]. \tag{19}$$

The parameter ρ of the distribution law (18) is determined by the ratio

$$\rho=4r_{xt}. \tag{20}$$

Using the integral function

$$Q(x,t)=\int_0^t\int_0^x q(x,t)dxdt, \tag{21}$$

you can determine the probability of economic damage x for time t.

Ratios (19) - (21) are a stochastic model that allows estimating not only the expected values of economic losses due to accidents at power facilities and energy supply systems of enterprises, but also their probabilistic characteristics.

If the sample size allows us to determine the private (marginal) laws Q1(x) and Q2(t) of the random variables X and T, then the stochastic model (18) - (20) can be refined. The construction of variants of a stochastic model for various marginal laws of the distribution of random variables X and T is the task of further research.

Stochastic models can also be used to assess extreme economic losses as a result of accidents at power facilities and in power supply systems of enterprises. The initial information for their evaluation is a sample of volume n

$$R=\{x_1,x_2,...,x_n\} \tag{22}$$

from the general set, determined by a random variable X damage.

We assume that the values x_j (j=1,2,…,n) in the sample (22) are numbered in such a way that the ratio is fulfilled

$$x_1\le x_2\le...\le x_n . \tag{23}$$

In this case, the distribution of extreme economic losses as a result of accidents is determined by the distribution $G(x)$ of the rightmost member x_n of the variation row (23).

If all the components of the sample (22) are independent random variables with the distribution function $F(x)$, then the ratio takes place

$$G(x)=P(x_1<x,\ x_2<x,...x_n<x)=F^n(x)=\left[\int_0^x f(x)dx\right]^n, \qquad (24)$$

where $P(x_1<x,\ x_2<x,...x_n<x)$ is the probability that all sample values of economic damage will not exceed the value of x;

$f(x)$ - the distribution density function of a random variable X of economic damage.

In fact, the form of the distribution function *F (x)* is, as a rule, not known, and the sample size is small.

Suppose that the sample size (22) allows us to calculate the estimate m of the mathematical expectation of the random variable X and the estimate σ^2 of its variance. Then, as shown in [18], based on the principle of maximum uncertainty, the function *G (x)* of the distribution of extreme economic damage is a solution of a differential equation

$$n\sigma^2\left[G(x)\right]^{\frac{n-1}{n}}\frac{d^2G(x)}{dx^2}+(x-m)\frac{dG(x)}{dx}=0 \qquad (25)$$

with natural boundary conditions

$$G(-\infty)=0, \qquad (26)$$

$$G(\infty)=1. \qquad (27)$$

It is completely determined by the obtained estimates of the expectation m and the variance σ^2 of the random variable X damage and the sample size (22).

In general, ratio (22) - (27) represent a stochastic model for estimating extreme economic damages resulting from industrial accidents at power facilities and in energy supply systems of enterprises.

4 Discussion

A characteristic feature of the modern stage of economic development of states is the steady expansion of the technosphere. Its expansion leads to an increase in energy consumption and an increase in the threat of accidents at energy facilities and in the energy supply systems of enterprises. Such accidents cause significant economic damage. This makes it necessary to take measures to prevent these accidents. Their adoption is based on the prediction of the possibility of these accidents and the assessment of the economic damage they cause. The tool for such prediction, in particular, is the corresponding models, including mathematical ones. Methodical approaches to the construction of these models are proposed in this article. They are based on the current informational situation. In this case, the removal of the inherent uncertainty of the information situation is ensured by applying the principle of "maximum entropy" of the first and second kinds. For the formation of conditionally deterministic models, the entropy was used, defined by the ratio (10). For the formation of stochastic models, Shannon entropy was used. This allowed us to take into account the characteristic features of these types of models, due to the limited and heterogeneous information available for their construction.

5 Conclusion

The proposed approaches to the construction of mathematical models for predicting accidents at energy facilities and power supply systems of enterprises are the basis for creating specific methods for solving relevant energy management tasks both at the micro level at the scale of individual enterprises and at the macro level at the scale of industries, regions and the state as a whole

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