Logical-probabilistic assessment of the occurrence of destruction during intersystem interactions in the electrical system of the seaport

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Abstract. This article solves the problem of a quantitative assessment of the occurrence of destruction in the intersystem interactions of the transport system and the electrical system of the seaport, in the conditions of the technological process in the seaport, which indicates its significant impact on the electrical system, as a result of which the reliability of the berthing power line is significantly reduced. The intersystem interactions that occur during the implementation of the technological process, as experience shows, are the causes of critical situations that occur at the border of areas of different physical nature, and the consequences are recorded, in the case under consideration, in the electrical system. A mathematical model describing intersystem destruction in quantitative form is presented in this paper using a logical-probabilistic model that reflects internal and external relationships. In the object under study, the destructive cause (collision) and the consequence (accumulation of electrical damage in the insulation of the cable line) are in the same object (the mooring power supply unit), and this is limited to the effects of intersystem destruction. In such a statement, the object of power supply of the technological process and equipment is considered as a composite object containing a cable line and an electric contact column. The problem being formulated is an important and relevant scientific task, which includes not only the question of identifying the causes of increased electrical wear of the power line, but also the development of methods for obtaining quantitative results, and in practical terms also involves the diagnosis of the technical condition of electrical equipment and timely preventive maintenance.

1. Introduction
Reliability and trouble-free operation of the electrical system of the seaport is the most important condition for ensuring the successful functioning of the technological process in the seaport. A seaport, from a technical point of view, is a complex, man-made environment of interconnected technical subsystems (technogenic environment) that perform, using technological processes, various cargo handling functions. Such a technogenic environment includes not only separate technical units and subsystems, in themselves, but also contains integral intersystem relationships, both between the components of the process and each element with the entire technogenic environment as a whole [1]. Inevitable deviations and errors arising during the implementation of these processes give rise to emergencies (intersystem destruction) for the entire technogenic environment, often having different...
physical nature. Often, accidents in such an environment are the result of interactions of subsystems that are not connected but occur precisely due to the presence of integral relationships in such a complexly organized environment. Revealing such connections that arise in a dynamically interacting technogenic environment, at different stages of its existence, is an urgent task in ensuring the trouble-free operation of working processes.

The emergence of unforeseen emergencies in marine, port electrical subsystems and individual electrical devices, which at first glance occur for no apparent reason, puts forward the task of developing new approaches and methods to ensure the safety of marine technogenic processes. The primary task, in this case, is the development of a mathematical model of emergencies for electrical equipment, considering the relationship in processes, often with different physical nature, but associated with a single technological process. The complexity of the problem that arises on this path consists already in the very formulation of the original problem, since the concept of the dependence of events is introduced, and this, when applying the theory of probability, significantly complicates the mathematical analysis. Difficulties also arise in connection with the rapidly growing list of all situations leading to equipment failure.

2. Building a mathematical model

The construction of a mathematical model that adequately describes emergencies with a different physical nature requires the inclusion of such categories as causal relationships of events, as well as their logical chains, into consideration. There is also a need to consider the events taking place as a manifestation of some more general process. In the problem formulated below, it is required to construct a mathematical model that considers the connection in an emergency (collision with a quay electric pump), a hitting forklift with processes in the electrical system in the conditions of cargo movement from the ship to the place of its storage across the terminal (pier). Despite the low speed of the forklift truck (3.4 – 4) m/s, it should be borne in mind that the pier area is limited for maneuvering vehicles, and there are electric mooring columns on it, which provide electricity for both the ship and the technological process... Due to the increased intensity of unloading operations, emergencies (collisions) of autoloading equipment occur on berthing electric dispensers. As a result, the technological process is de-energized, and short circuits appear on the supply power line, and, before the circuit breakers operate (2 seconds), the current in the line increases to \( I_d \). The destructive, destructive factor is the temperature from the passing short current closures. The maximum possible temperature of the previous mode \( \theta \) is taken as the initial temperature:

\[
\theta = \theta_0 + \left( \frac{I}{I_{dd}} \right)^2 \cdot (\theta_d - \theta_r)
\]

where \( \theta_0 \) is the actual ambient temperature during a short circuit, \( ^0C \) in the ground \( \theta_0 = 20^0C \), when laid in air \( \theta_0 = 30^0C \);

\( \theta_d \) – calculated long-term permissible core temperature, \( ^0C \) (for cables with impregnated paper insulation for voltages up to 1 kV – 80°C);

\( \theta_r \) – design ambient temperature, \( ^0C \) (for earth – 15°C, for air – 25°C);

\( I \) – current value in the line up to short circuit 150 A;

\( I_{dd} \) – long-term permissible current in the line 400 A;

\( \theta_{kr} \) – core temperature at the end of a short circuit:

\[
\theta_{kr} = \theta \cdot \exp(K) + a \cdot (\exp(K) - 1)
\]
\[ K = b \cdot \frac{I_{\text{max}}^2 \cdot t_0}{S^2} \]

where \( a \) is the reciprocal of the temperature coefficient of electrical resistance at 0 °C, equal to 228 °C; 
\( b \) – coefficient for copper 19.58; 
\( S \) – cable conductor cross-section 185 mm\(^2\)
\( t_0 \) – circuit breaker response time 2 sec.

The wire temperature takes on the value \( \theta_{\text{max}} = 193^\circ C \). At this temperature, the paper "quickly collapses due to decomposition and carbonization of cellulose" [2]. With the repetition of short circuits, a destructive factor is again introduced into the line. The problem is that such situations, although they are random, during the operating time of the electric line on the pier, before wear and tear, such ramps of forklift trucks to quay columns with short circuits are repeated, and the results from them accumulate, which leads to reducing the operating time of the electric power line.

3. Logical-probabilistic assessment of intersystem destructions in the technological complex

For modeling emergencies on electrical equipment in a complex, interacting environment, the most suitable description for it is a special scenario. By a scenario, or scenario, a variant of the development of events, we mean a sequence of logically related events generated by an initiating emergency event. Accordingly, from the initial events, with the help of a set of logical operators and, according to the developed scenario, derivative events are formed leading to the resulting event. Models built on this principle are a qualitative transition to higher-level models, including processes of various origins. In this case, we are talking about the use of a scenario option for constructing a logical-probabilistic function that describes the resulting event and its probability. The peculiarity of such modeling consists in the informal justification of the scenario and the choice of cause-and-effect relationships leading to the resulting event. The construction of the scenario is carried out both from the resulting event to the initial events, and, conversely, from the initial events (causes) to the resulting event.

In the problem formulated by us, the proposed approach is based on the results presented in [3] and is represented by a scenario that consists of events \( x_1, x_2, \ldots, x_n \), connected by logical operators leading to the resulting event, namely, a forklift hitting an electric column and a short circuit by force lines.

According to the scenario, a logical-probabilistic function \( f(x_1, x_2, \ldots, x_n) \), is built, with the help of which the probability of the resulting event is calculated. We will solve the problem in 4 stages:

Stage 1. An initial set of events is formed, each of which is represented in the model as a simple (binary) event with two possible states:

- \( A_1 \) – the chosen path of the forklift is dangerous;
- \( x_1 \) – the driver made an erroneous decision on the landmarks of the forklift movement;
- \( x_2 \) – the error is not fixed and is fixed in the driver's memory;
- \( A_2 \) – the movement of the forklift is carried out in the direction of danger;
- \( x_3 \) – deviation from safe movement is not recorded by the driver;
- \( A_3 \) – a setting for an incorrect trajectory has been formed;
- \( x_4 \) – the position of the forklift truck relative to the landmarks is fixed with a large error;
- \( x_5 \) – incorrect position of the forklift is perceived as true now of orientation.
Stage 2. Logical modeling is carried out, with the help of special transformation methods, a logical function of the system's operability is built and a fault tree is formed.

Stage 3. Development of an accident (collision) tree and construction of a logical function:

\[ y(x_1, x_2, x_3, x_4, x_5) = x_1 \cdot x_2 \lor x_3 \lor x_4 \cdot x_5. \]

Figure 1. Fault tree "Assessment of the probability of a forklift hitting an electric pump"

Stage 4. In accordance with the methodology for constructing logical-probabilistic functions, the logical function is orthogonalized, the probability function is constructed and the probability of the resulting event is calculated

\[ y(x_1, x_2, x_3, x_4, x_5) = K_1 \lor K_2 \lor K_3 \]

Conjunctions of \( K_i \) of logical function \( y(x_1, x_2, x_3, x_4, x_5) = K_1 \lor K_2 \lor K_3 \)

\[ K_1 = x_1 \cdot x_2, \quad K_2 = x_3, \quad K_3 = x_4 \cdot x_5 \]

The orthogonalized logical function \( y(x_1, x_2, x_3, x_4, x_5) = x_1 \cdot x_2 \lor x_3 \lor x_4 \cdot x_5 \) (the disjunction of the conjunctions obtained because of orthogonalization) is performed in accordance with [2]:

\[ Y_{ort}(x_1, x_2, x_3, x_4, x_5) = \left( \begin{array}{c} K_1 \\ \overline{K_1} \cdot K_2 \\ \overline{K_1} \cdot \overline{K_2} \cdot K_3 \end{array} \right). \]

\( \overline{K_i} \) – the negation of the conjunction is calculated by the formula:
Result of orthogonalization of function $y(x_1, x_2, x_3, x_4, x_5) = x_1 \cdot x_2 \vee x_3 \vee x_4 \cdot x_5$ in matrix form:

$$
\begin{pmatrix}
\tilde{x}_1 \\
\tilde{x}_1 \cdot x_2 \\
x_1 \cdot x_2 \cdot \tilde{x}_3 \\
x_1 \cdot x_2 \cdot x_3 \cdot \tilde{x}_5
\end{pmatrix}.
$$

The orthogonal function ODNF has the form:

$$
Y_{\text{ort}} (x_1, x_2, x_3, x_4, x_5) = x_1 \cdot x_2 \vee \tilde{x}_1 \cdot x_3 \vee x_1 \cdot \tilde{x}_2 \cdot x_3 \vee \tilde{x}_1 \cdot x_3 \cdot x_4 \cdot x_5 \vee x_1 \cdot \tilde{x}_2 \cdot \tilde{x}_3 \cdot x_4 \cdot x_5.
$$

**Stage 4.** The probability function in accordance with the expression $Y_{\text{ort}} (x_1, x_2, x_3, x_4, x_5)$ is represented as:

$$
P((p_1, p_2, p_3, p_4, p_5)) = p_1 \cdot p_2 + (1-p_1) \cdot p_3 + p_1 \cdot (1-p_2) \cdot p_4 + (1-p_1) \cdot (1-p_3) \cdot p_5 + p_1 \cdot (1-p_2) \cdot (1-p_3) \cdot p_4 \cdot p_5.
$$

If the data is represented by intervals, then we represent them in the form of a matrix:

$$
M = \begin{pmatrix}
P_{\text{max}} & P_1 & P_2 & P_3 & P_4 & P_5 \\
P_{\text{min}} & P_1 & P_2 & P_3 & P_4 & P_5
\end{pmatrix}.
$$

To use the generated mathematical model, it is necessary to provide estimates of the probabilities (frequencies) of the occurrence of basic events. We will estimate the probabilities considering the experimentally recorded number of trips to the mooring electric pumps at the pier for mooring large-tonnage vessels over the past years. The total number of moves of a brigade of four forklift trucks with full unloading of a large-tonnage vessel is $n = 1120 \sqsupset 1160$, and the total number of moves of a crew of forklift trucks per year is estimated at $n_o = 5.6 \cdot 10^4 \sqsupset 5.8 \cdot 10^4$. Considering the observed in the experiment the average number of arrivals to the speakers per year, we get the frequency of arrivals, which is estimated by the value:

$$
p = \frac{4}{n_o} = 6.9 \cdot 10^{-5},
$$

matrix $M$:

$$
M = \begin{pmatrix}
P_{\text{min}} & 1.7 \cdot 10^{-5} & 10^{-4} & 1.7 \cdot 10^{-5} & 10^{-4} & 1.7 \cdot 10^{-5} \\
P_{\text{max}} & 6.9 \cdot 10^{-5} & 10^{-4} & 6.9 \cdot 10^{-5} & 10^{-4} & 6.9 \cdot 10^{-5}
\end{pmatrix}.
$$

After the above estimates, it should be noted that the reduced frequency of arrivals was obtained without using a logical-probabilistic model. At the same time, the given model gives a set of events that preceded the collision. Now, knowing the assessment of the final event, we can also assess those events, the result of which it was and was recorded in the matrix $M$.

The estimation of the operating time of the field line, in the considered model, associated with the number of arrivals and the short circuits generated by them, will be made using the Laplace theorem.
The theorem states that the probability that in independent tests, in each of which the probability of the occurrence of an event is \( p(0 < p < 1) \), the event occurs \( k \) times is equal to:

\[
P_x(k) = \frac{1}{\sqrt{n \cdot p \cdot (1-p)}} \cdot \varphi(x)
\]

\[
\varphi(x) = \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{x^2}{2}\right), x = \frac{k - n \cdot p}{\sqrt{n \cdot p \cdot (1-p)}}
\]

Let us find the total number of lift truck moves, at which there will be no more than 4 collisions per year:

Assessment of the total operating time of the power berthing line when it is run over by forklift trucks with a probability of \( p = 6.9 \times 10^{-5} \) when unloading large-capacity dry cargo vessels.

\[
n := 50000 \quad k := 120
\]

\[
\psi(n) := \frac{1}{\sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{k - n \left(6.9 \times 10^{-5}\right)}{\sqrt{n \left(6.9 \times 10^{-5}\right) \left(1 - 6.9 \times 10^{-5}\right)}}\right)
\]

Given

\[
\frac{1}{\sqrt{n \left(6.9 \times 10^{-5}\right) \left(1 - 6.9 \times 10^{-5}\right)}} \cdot \psi(n) = 0.95
\]

\[
w := \text{Find}(n)
\]

\[
\text{tn} := \frac{w}{5.568 \times 10^4} \quad \text{tn} = 23.517
\]

The calculations presented in accordance with the Laplace theorem show that if during the operation of the power berthing line there are more than a hundred arrivals, then the service life of this line will not exceed 24 years. The formulated problem gives an answer with a probability of \( p = 0.95 \) to the question of the operating time until the complete deterioration of the power line insulation from short circuits. The reason for the short circuits is the ramps of forklift trucks to the mooring electric pumps.

4. Conclusion

Consideration of the technological process at the berth and modeling of situations associated with arrivals made it possible to identify a destructive factor because of intersystem interactions that have a different physical nature.

The use of mathematical modeling based on the logical-probabilistic method made it possible to obtain quantitative results of the development of power electrical equipment. The maximum service life of the power line \( T_{\text{max}} = (2.8 \times 10^5 - 2.9 \times 10^5) \) hours, \((32 - 34 \text{ years})\), is typical for non-interacting electrical equipment with non-electrical factors. The actual operating time of the line under influencing, destructive factors is:

\[
T = (2.19 \times 10^5 - 2.36 \times 10^5) \text{ hours, } (25 - 27 \text{ years}).
\]

Summing up, it should be noted the advantage of logical-probabilistic modeling, which made it possible to present the analyzed system with the help of scenario design. It is also important to note that with this approach, it is possible to simulate the processes of interactions with different physical
nature. So, the process of movement of forklift trucks on the territory of the sea pier is not directly related to the electrical processes in the power lines. However, as quantitative estimates show, the limited area of the sea pier, and the location of electric columns on it, as well as the requirements for the fastest unloading of a large-tonnage ship, lead to accelerated destruction of the power electric line. Therefore, an urgent task is to build logical-probabilistic models that cover processes of different physical content. In this work, an attempt is made to implement system-structural models that allow to quantitatively solve the problems of reliability of electrical equipment for various interactions in the technosphere environment.

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