Mathematical model of the evolution of operating parameters of dielectrics in the marine power supply system when forcing certain factors

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Abstract. The paper addresses the issue of development of a mathematical model for the evolution of operating parameters of dielectrics in the marine power supply system when forcing certain factors. The paper addresses a comprehensive problem in comparison with the classical problem of the wear theory. With regard to the given details, factors that cause a decrease in the operating time were introduced to determine the operating time before electrical wear of the power supply unit. The study employs methods of the fuzzy (uncertain) set theory. The uncertainty of quantities in the fuzzy set theory is set by the membership function, which determines the degree of its fuzziness. In accordance with fuzzy set methods, a membership function is constructed to estimate fuzziness of the function of a shrinking time resource of operating time before wear. In Mathcad, the authors have developed a computational module for estimating the fuzzy time (due to inaccuracy of the initial data) subtracted from the total operating time before electrical wear of the berthing power supply unit. To improve the reliability of power supply to seaports and reduce accidents, new technical and organizational measures are being developed. Therefore, the task is formulated to ensure serviceability of the power supply system with due regard to its interactions with various subsystems.

1. Introduction
Long-term and stable operation of power lines has always been an urgent technical task. Requirements for ensuring high operability of power and electrical lines of seaports are determined by the increasing consumption of electrical energy associated with the increasing volume of cargo transported by sea vessels, as well as by the tendency to accidents associated with the aging of electrical equipment. To improve the reliability of power supply to seaports and reduce accidents, new technical and organizational measures are being developed. However, operational practice shows that line failures and short circuits often occur even at berths with low power demand.

When describing the processes associated with operation of berthing electrical appliances at the seaport, it is necessary to consider the factors associated with destructive interactions. Therefore, the task should be formulated to ensure serviceability of the power supply system with regard to its interactions with various subsystems that contribute to the technological process at the sea berth (terminal). In this formulation, the object of power supply of the technological process and equipment
is considered as a complex object that contains a cable line and an electrical contact column. Refer to this complex object as a berthing power supply unit.

2. Solution method

The paper considers a comprehensive problem in comparison with the classical problem of the wear theory, which aims to determine the operating time before wear $T(x_1, x_2, \ldots, x_n)$ of berthing power supply unit affected by factors $x_1, x_2, \ldots, x_n$ that include the effect of the technological regime on the electrical process.

Let us note that the operating time to failure of the contact columns (component of the electric power supply system) exceeds the operating time of the cable line, which is determined by the fact that the electric column does not contain elements with a low operating time to failure at an increased temperature [1].

When additional energy is consumed, the current value increases and exceeds the permissible values for this power supply system. During the flow of large current, a damaging factor acts. Accordingly, when developing and constructing a mathematical model describing wear in the process of power transmission in a forced mode, it is necessary to consider the damage accumulating over time.

With regard to the given details, factors that cause a decrease in the operating time were introduced to determine the operating time before electrical wear of the power supply unit. The process of forcing the technological mode lasts $t = 6$ h and is characterized by an increased current value $I = I_{\text{np}}$. Two main factors $t, I$ determine the mode of forced energy consumption of the berthing system. These factors can be measured (data collected) during the technological process.

When developing a mathematical model, use the following factors:

- the time $t$ of forcing the technological mode and increasing energy consumption;
- the current $I$ that flows in the power line of the berthing power supply unit;
- the function $F_{\text{fr}}(t, I)$ that depends on the values $t, I$, which is called the function of the shrinking time resource of the operating time before wear.

The numerical value of the function $FFR(t, I)$ characterizes the line damage and represents the time subtracted from the total operating time of the line $T_u$ due to the damaging factor.

Taking into account the introduced parameters, we construct a function with several variables for the shrinking time resource of the operating time before electrical wear of the berthing power supply unit. The term “shrinking” is used to indicate the process of object degradation due to the fact that the permissible values of currents in forced modes, as well as permissible times of their action, can be violated. As a result, the operating time before wear is reduced.

The function of the shrinking time resource includes the following components:

- impact of the time value of the forced technological process on the operating time before wear of the berthing power supply unit
  
  $$f_t(t) = \left( \frac{I}{I_{\text{bas}}} \right)^a;$$

- impact of the current value on the operating time before wear of the berthing power supply unit;

  Here $a, b, c$ are the required constants, and $I_{\text{bas}}, I_{\text{bas}}$ are the normalizing values.

Studies of electrical insulating materials show that the processes of irreversible wear develop rapidly in paper-impregnated insulation at temperatures above 135–140 °C. Long-term emergency overloads of cables are especially dangerous when the heating of the conductor and insulation significantly exceeds the long-term permissible temperature values [2,3]. It is also known that the rate of chemical reactions increases as temperature increases, and in many cases it is described by the exponential law [1]. With regard to these patterns and the fact that all considered adverse factors
simultaneously affect the insulation material of the electrical supply system, we accept the function of three variables as a new model describing the destruction of insulation:

$$\psi_1(t,I) = f_1(a,t), \quad \psi_2(t,I) = f_2(b,I),$$

where $a, b$ are parameters.

In generalized form with undefined parameters $A, a, b, c$, the resulting function is $F_{\psi\psi}(t,I)$:

$$F_{\psi\psi}(t,I) = A \cdot \prod_{i=1}^2 \psi_i(t,I) = A \cdot f_1(a,t) \cdot f_2(b,I).$$

The general view of the function of the shrinking time resource of the operating time to failure of the berthing power supply unit contains the operation time of the forced technological mode $t$ and the value of the current $I$ of the berthing power supply unit exceeding the permissible value, and is represented by the equation:

$$F_{\psi\psi}(t,I) = A \cdot \left(\frac{t}{t_{bas}}\right)^a \left(\frac{I}{I_{bas}}\right)^b, \quad t \geq 0, I \geq I_{don},$$

where $t_{bas}, I_{bas},$ are normalizing constants for variables, and variables $t \geq 0, I \geq I_{don}$ in this function take on values typical of possible damages.

Since the obtained equation is nonlinear with respect to unknown parameters $A, a, b, c$, it is necessary to linearize the function $F_{\psi\psi}(t,I)$ using the logarithm in order to apply the previously given equation $X = (M^T \cdot M)^{-1} \cdot M^T \cdot Y$ to determine these parameters from the system of equations for various values of the set of factors $t, I$,

$$\log\left[F_{\psi\psi}(t_i, I_i)\right] = \log(A) + a \cdot \log\left(\frac{t_i}{t_{bas}}\right) + b \cdot \log\left(\frac{I_i}{I_{bas}}\right),$$

where $t_{bas}, I_{bas},$ are normalizing constants for variables, and variables $t \geq 0, I \geq I_{don}$ in this function take on values typical of possible damages.

Figure 1 illustrates the algorithm for calculating the shrinking operating time of the electric supply system.
Figure 1. Algorithm for calculating the shrinking operating time to failure of the berthing power supply unit in the form of a set of actions

The order of the algorithm implementation.
In accordance with the developed mathematical model (1) and the software calculations in Mathcad, the algorithm is implemented as follows:

- variable input: \( t \) is duration of the increased load; \( I \) is current load (\( t_{bus}, I_{bus} \));
- use of the operating time recorded as a vector \( Y \);
- \( m_{i,j} = \left[1, \ln(D_{i,j})\right] \) input and taking of logarithm of matrix values \( D_{i,j} \) and matrix construction \( m_{i,j} = \left[1, \ln(D_{i,j})\right] \);
- solution of the system of equations \( \left(m^T \cdot m\right)^{-1} \cdot m^T \cdot c1 = b \);
- determination of the value \( r = b_1 + b_2 \cdot \ln\left(\frac{I}{t_{bus}}\right) + b_3 \cdot \ln\left(\frac{I}{I_{bus}}\right) \);
- calculation of time damage from the forced mode \( T_v = \exp(r) \).

3. The results of calculating the function of the shrinking operating time to failure of the berthing power supply unit
To calculate the function \( F_{\text{sh}}(t, I) \), we introduce the data matrix \( D \) that contains parameter sets \( t_i, I_i, T_i \). The data presented below in matrix \( D \) were recorded by the personnel during overloads of the electrical supply system (an overload signal appeared on the control and monitoring panel), and expert data from the personnel serving cable lines were partially used. The obtained matrix \( D \) and the given algorithm were used to determine the parameters \( A, a, b, c \) and the time of damage to the electric power supply system by constructing a computational block \( F_{\text{sh}}(t, I) \) in Mathcad.

Data matrix \( D \) (in transposed form \( D^T \)):
where \( t = D^{<1>} \) – row of matrix \( D \) – operating time of the power line under increased load;
\( I = D^{<2>} \) – row of the matrix – current flowing along the line;
\( T = D^{<4>} \) – row of the matrix – operating time of the line.

The software computational block of the function of the shrinking time resource in the forced mode
\[ F_{\text{tp}}(t,I) = F(t,I) : \]
\[ F(6,600) = (296.805 \times 10^3) \]

The decreased operating time of the berthing power supply unit is due to the forced current mode should not exceed the permissible value of 6 hours, 100 hours per year, and amounts to 293.805 hours per year. In this case, the total damage per year caused by the forced modes of the berthing power supply unit amounts to 8.904\times 10^3\) hours. Thus, the operating time of the line will be reduced by 8.904\times 10^3\) hours.

The obtained results show that the forced technological process mode causes damage of the total operating time of the electric supply system that amounts to 8.904\times 10^3\) hours. The operating time of the berth power supply unit minus this value is \( T_u = 28.97\) years. The manufacturer of cable products specifies a service life under the conditions specified in the documentation, \( T_s = 30\) years.

The software mathematical model of the shrinking operating time of the berthing power supply unit at the increased load does not contradict, in particular, operation [2,3,4]. Indeed, due to thermal oxidative processes in the part of the power line cable, the degree of cellulose polymerization decreases, and the properties necessary to ensure high electrical insulation of the power cable \( R > 10^6\) Ohm are lost. The cellulosic material breaks down and cannot be replaced. Therefore, its physical state is determined by a piece of paper soaked in oil insulation.

The actual results of the operating time of power supply systems are difficult to obtain due to the lack of data on many years of operating time in the seaport. It should be noted that the port operates 24 hours a day and there are restrictions on access to power grids and electrical equipment. The data from other nearby ports of the Black Sea show a wide scatter in the values of parameters, currents, and operating time to failures. In this case, it is impossible to use the probability theory methods due to the lack of data on the distribution laws of the random data studied.

Due to the inaccuracy and elements of uncertainty in the above data and their small volume, the use of such quantities should be justified to construct the distribution function. For this purpose, we use the methods of the fuzzy set theory. The fuzziness of quantities in the fuzzy set theory is set by the membership function, which determines the degree of the quantity fuzziness.

When using the Gaussian function as the membership function, the degree of fuzziness (blurring) will be set by the width (variance) of the membership function [6,7,8]. Note that this transition from imprecise values to fuzzy values is called fuzzification. For this purpose, the membership functions of fuzzy parameters \((t,I)\) were previously introduced:
\[ \mu_t(t) = \exp \left[ -\left( \frac{t-t_c}{\sigma_t} \right)^2 \right], \]
\[ \mu_I(I) = \exp \left[ -\left( \frac{I-I_c}{\sigma_I} \right)^2 \right], \]  
(6)

where \( \sigma_t = 0.15 \cdot t_c, \sigma_I = 0.15 \cdot I_c. \)

A fuzzy mathematical model is proposed to determine the time fuzziness, which is subtracted from the total operating time \( t_c \) of the berthing power supply unit in the forced mode.
In accordance with fuzzy set methods, the membership function is constructed, to estimate fuzziness of the shrinking time resource of the operating time before wear.

In Mathcad, the authors have developed a computational module for estimating the fuzzy time (due to inaccuracy of the initial data) subtracted from the total operating time before electrical wear of the berthing power supply unit.

Figure 2 shows graphical representation of the results of solving the membership function subtracted from the operating time before wear of the berthing power supply unit.

Figure 2. The membership function graph $\mu_{\Sigma} = FUZZY(t, I)$, which is the spread of time (in hours) subtracted from the operating time before wear of the berthing power supply unit in a fuzzy setting

4. Conclusions
The membership function presented in Figure 2 is determined using a computing program unit, and the results obtained show that the total value of the time subtracted from the total operating time of the berthing power supply unit is $T = 1.028 \cdot 10^4$ hours due to the forced mode. When using a fuzzy model (with regard to the blurring of values), the results contain the exact (clear) value of the model, which amounts to $TP = 9.196 \cdot 10^3$ hours.

As shown experimentally, a number of berth power supply units put into operation in the early 60s of the last century worked almost up to 45–50 years. At that time, the main cargo flow in the Black Sea did not pass through Russian ports. When the situation changed dramatically in 1991, especially in 2000, the load on Russian berthing power supply units increased several fold. This necessitated both forcing loading/unloading operations and increasing electrical loads on the berth power supply units. As a result, the operating time to failure of the berthing power supply unit was significantly reduced, and new methods of analysis and calculation of the time of serviceability and the operating time of the units to wear were required.

References
[1] Lobov B, Kolpakchyan P, Litskevich S 2019 Probabilistic-entropy approach to ensure the operational reliability of the seaport berth electrical contact bollards Materials Science and Engineering 680 (1) 012029
[2] Kabyshev A V 2007 Power supply of objects. Part I. Calculation of electrical loads, heating of conductors and electrical equipment (Tomsk: TPU Publishing House)
[3] RD153-34.0-20.527-98. Guidelines for the calculation of short-circuit currents and the selection of electrical equipment
[4] Kryuchkov N P 2000 *Electrical transients in electro-technical systems* (Moscow: MPEI Publishing House)

[5] Kryuchkov I P, Neklepaev B N, Starshinov V A 2008 *Calculation of short circuits and selection of electrical equipment* (Moscow: Academy)

[6] Boev M A, Kaniskin V A, Kostenko E M, Sazhin B I, Tatzhibaev A I 2001 *Diagnostics of power cables and determination of residual life in operating conditions* (St. Petersburg: St. Petersburg Power Engineering Institute for Advanced Training of Executives and Specialists of the Ministry of Energy of the Russian Federation)

[7] Dubyago M N, Poluyanovich N K 2012 Method of non-destructive testing and prediction of developing damage to the insulation of power cable lines *XI conference Automation and measurement control systems, SAUM-2012* pp. 418–422

[8] Naboka B G, Bezprozvannykh A V, Moskvitin E S, Butko M V, Butko S M, Golovan A A 2011 Diagnostics of cable lines of power systems by the tangent of the angle of dielectric losses and the time constant of self-discharge of impregnated paper insulation *Electrotechnica i Electromezhanika* 2 65–69