Probabilistic-entropy approach to ensure the operational reliability of the seaport berth electrical contact bollards

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Abstract. Reliability analysis of the gradual failure of high current contacts connecting the conveying units with the seaport power supply electrical network is largely based on deterministic ideas about their degradation. The use the seaport contact electrical equipment indicates the limitations and inaccuracies of such an approach. The long-term studies show that the high marine humidity, turbulent air moisture with aggressive chemical compounds play a substantial role in the wear and tear of electric contacts of seaport berth electrical bollards. The impact of these factors leads to the occasional wear of electric contacts. Thus, we need adequate mathematical apparatus of probability theory and random processes for the reliable results.

1. Introduction

The protective cover of the contact electrical bollards (CEB) is not hermetical and that is why the moisture, dust, gaseous substances and other deleterious matter can get in it. The CEB’s consists of a multicomponent mixture consists of a multicomponent mixture circulating in a turbulent air stream. Destructive factors play a substantial role in the electric contacts’ wear, fundamentally change the idea of contact wear processes and make the results make unfair the results based on the deterministic models [1-3,6]. The studies of the electrical contacts wear in seaports confirm this conclusion.

Gradual failure of high-current electrical contacts under the influence of high-entropy destabilizing factors consist of two processes. The first one characterizes the impact of internal destabilizing factors (mechanical abrasion, temperature). The second one is connected with external high-entropy destabilizing factors described above. The first process needs the use of deterministic model; the second one needs the probabilistic approach.

The probabilistic approach takes into account the time variations, the contact resistance $R_k$. When this parameter reach the limit $R_{k_{\text{max}}}$ there is a breakdown after a random timespan [5, 8]. In the initial period of the electrical contact’s operation there is a dispersion of the parameter $R_k$ regarding its mathematical expectation $R_{k_0}$. 

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As multiple measurements show, there is the noticeable change of contact resistance after a certain period of time that is random value and is connected with accumulation of damage from external highly entropic destabilizing factors [7].

The probability that the parameter $\gamma_{R_k}$ exceeds the limit $R_{kmax}$, thus the breakdown probability $F(t) = 1 - P(t)$, can be determined with the model which is calculated using the law of distribution $f(R_k, t)$ [9, 10].

The random rate of change $\gamma_{R_k}$ is the element of the model of probability. As the rate of change $\gamma_{R_k}$ of the parameter $R_k$ depends on a large number of random factors, in view of central limit theorem of probability theory, the distribution law has the following form [7, 9]:

$$f(y_{R_k}) = \frac{1}{\sigma_{R_k} \sqrt{2\pi}} \exp \left[ -\frac{(y_{R_k} - \gamma_{R_k})^2}{2\sigma_{R_k}^2} \right]. \quad (1)$$

The following expression can approximately determine the rate of change of the parameter:

$$\gamma_{R_k} = \frac{R_{k2} - R_{k1}}{t_2 - t_1},$$

where, $R_{k1}$ is the resistance at the moment $t_1$; $R_{k2}$ is the resistance at the moment $t_2$.

The average rate of change of the parameter during the whole operating time $t_{max}$ to $R_{kmax}$ is determined by the following expression:

$$\gamma_{R_{k\text{avr}}} = \frac{R_{k0} - R_{kmax}}{t_{max}}.$$ (2)

where, $R_{k0}$ is the initial value of contact resistance; $\gamma_{R_k}$ is the contact resistance change rate.

Assuming that the resistance parameters of heavy-current contacts have the normal distribution, the expression for time $T = t$, determines the average contact resistance:

$$R_{k\text{avr}} = R_{k0} + \gamma_{R_{k\text{avr}}} \cdot T,$$ (3)

and the standard deviation of the contact resistance is [9,10]:

$$\sigma_{R_k} = \sqrt{\sigma_{R_{k0}}^2 + \sigma_{\gamma_{R_k}}^2 \cdot T^2},$$ (4)

where, $\sigma_{R_k}$ is the standard deviation of $R_k$; $\sigma_{R_{k0}}$ is standard deviation of initial value of $R_{k0}$; $\sigma_{\gamma_{R_k}}$ is the standard deviation of average rate of change of $R_{k}$.

Under these conditions, the odds that $R_k$ will not exceed the value $R_{kmax}$ during the period of time $t = T$ will be represented as $P(T) = \text{BEP}(R_k \leq R_{kmax}) \ [9,10]$. When external and internal destabilizing factors act together, the degradation becomes nonlinear (the contact heats up at high current, and the air moisture further contributes to the formation of the nonconducting film on the contacts). The rate of contact resistance change $\gamma_{R_k}(t)$ and the standard deviation $\sigma_{\gamma_{R_k}}(t)$ of the rate of change $R_k$ become a function of time. In this case, we obtain a generalized function of the probability of no-failure operation [9, 10]:

$$P(t) = 0.5 + F \left[ \frac{R_{k0} \gamma_{R_k max}}{\sigma_{R_{k0}}^2 + \sigma_{\gamma_{R_k}}^2 \cdot t^2} \right],$$ (5)

where $F(x) = \frac{1}{\sqrt{2\pi}} \int_0^x \exp \left[ -\frac{u^2}{2} \right] \, du$ is the normalized Laplace function.

Figure 1 shows the contact resistance change rates versus time curve based on the experimental data $y_{R_k}(t)$. 


Figure 1. Contact resistance change rates-vs-time curve

The approximation function for the standard deviation of the contact resistance change rate over time is 
\[ \sigma_{\gamma_{R_k}} = A \cdot [1 - \exp(-B \cdot t^C)]. \]
We use the least-squares procedure and receive the expressions for parameters 
\[ A = 0.037, B = -2.393 \cdot 10^{-3}, C = 0.52. \]

The approximated function for the standard deviation of the contact resistance change rate over time is:
\[ \sigma_{\gamma_{R_k}}(t) = 0.037 \cdot [1 - \exp(-2.393 \cdot 10^{-3} \cdot t^{0.52})]. \]

The probability of bollard’s one contact no-failure operation versus time curve is based on the statistical material, which is assembled on the large pier of the Novorossiysk seaport. Figure 2 shows the probability of bollard’s one contact no-failure operation dependence on time \( P(t) \), taking into account received approximations \( \gamma_{R_k}(t), \sigma_{\gamma_{R_k}} \) and the formula above.

\[
P(t)_{\text{result}} = 0.5 + F \left\{ \frac{400 - 20 - 5.183 \cdot 10^{-3} \cdot \exp(6.802 \cdot 10^{-5} \cdot t^2)}{\sqrt{0.037 \cdot [1 - \exp(-2.393 \cdot 10^{-3} \cdot t^{0.52})]^2 \cdot t^2 + 0.02^2}} \right\}^3
\]

Figure 2. The probability of one contact no-failure operation versus time curve when the resistance limit is \( R_k = 400 \mu\text{Ohm} \)

The expression for the probability of three-phase contact no-failure operation versus time is
\[ P(t) \cdot P(t) \cdot P(t) = P(t)^3, \]
(since the operation of the three-phase disconnecting device is ensured only when three contacts are closed), and taking into account the obtained approximations \( \gamma_{R_k}(t) \) and \( \sigma_{\gamma_{R_k}}(t) \), is:
\[
P(t)_{\text{result}} = 0.5 + F \left\{ \frac{R_{k0} Y_{R_{k\text{max}} \gamma}}{\sigma^2_{R_{k0}} + \sigma^2_{\gamma_{R_k}} t^2} \right\}^3
\]

Substituting into (7) the approximated values obtained above we get the expression for the probability of non-failure operation.
Figure 3 shows the $P(t)_{result}$ versus time curve:

$$P(t)_{result} = \left\{ 0.5 + F \left[ \frac{400 - 20 - 5183 \times 10^{-3} \exp(6.802 \times 10^{-5} \cdot t) \cdot t \cdot F}{\sqrt{0.037 \cdot 1 - \exp(-2.393 \times 10^{-5} \cdot t^{0.55})}} \cdot t^{0.5} + 0.02^2 \right] \right\}^3.$$ 

Figure 3 shows the $P(t)_{result}$ versus time curve:

The initial time of service is the time when the entropy is maximum (figure 4):

$$H(t) = -\int_0^t \left\{ 0.5 + F \left[ \frac{Rk_{\max}}{\sigma_{Rk}^2 + \sigma_{Rk}^2 (u)^2 \cdot u^2} \right] \right\}^3 \times \log \left( \frac{0.5 + F \left[ \frac{Rk_{\max}}{\sigma_{Rk}^2 + \sigma_{Rk}^2 (u)^2 \cdot u^2} \right] \right) \, dt.$$  

Figure 4. Probability of non-failure operation-vs-time curve of three-phase disconnecting device for three contacts of the circuit.

The initial time of service is the time when the entropy is maximum (figure 4):

$$H(t) = -\int_0^t \left\{ 0.5 + F \left[ \frac{Rk_{\max}}{\sigma_{Rk}^2 + \sigma_{Rk}^2 (u)^2 \cdot u^2} \right] \right\}^3 \times \log \left( \frac{0.5 + F \left[ \frac{Rk_{\max}}{\sigma_{Rk}^2 + \sigma_{Rk}^2 (u)^2 \cdot u^2} \right] \right) \, dt.$$  

Figure 4. Entropy change of non-failure operation probability

The figure 4 shows that the entropy function is maximum when the operational time is $t = 24930$ hours. Figure 5 shows that the maximum entropy growth rate $\left( \frac{dH}{dt} = \frac{H(t+h) - H(t)}{h} \right)$, $h = 0.01$ hour is observed at an instant of $t = 16830$ hour.
Thus, the entropy characteristics values of probability model \( \max H(t) \) and \( \max \frac{dH}{dt} \) can be used as criteria of critical operation of electrical contact bollards and determine the timescales of equipment maintenance or replacement.

Conclusion.
Expression that was suggested for the non-failure operation probability allow us to calculate the reliability of certain contacts, mechanisms, bollards and electricity distribution systems in its entirety for any point in time.

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