Forecasting technical state and efficiency of electrical switching devices at electric complexes in oil and gas industry

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Abstract. This work is topical, since it allows predicting the physical state of the contact joints of low-voltage switching devices and to avoid their destruction, which occurs due to mechanical and chemical effects on the contacts during operation, leading to an increase in the transition resistance and overheating of the contacts. The following criteria were adopted as serviceability criteria for the contact connections of switching devices: the maximum temperature of their heating, the maximum value of the resistance of the pole of the device and its parts, as well as the excess of the temperature of the contact heated part over the ambient temperature. The authors obtained graphs of the dependence of the resistance value of the contact connections of magnetic starters and circuit breakers on the ambient temperature and load factor. The article determines the analytical dependence of the resistance of the magnetic starter contact connections on the ambient temperature. It also features mathematical models that take into account various operating conditions of switching devices, the input values of which are refined using regression analysis.

1. Introduction

During the operation contact connections of low-voltage switching devices are exposed to mechanical and chemical influences which lead to an increase in their transient resistance, and as a result, by the action of the load current, to their overheating and subsequent destruction. The development rate of defects depends on the design of the contact connection, its location and the intensity of external influences. The time-lag between defect occurrence and the emergency failure of contact is from several months to several years. The main control of contacts is the measurement of their transient resistance to direct current. Contact resistance is measured using M-246 micrometers. The ammeter-voltmeter method measures resistance indirectly. The single bridge (Wheatstone bridge) and double bridge (Thomson bridge) methods are widely used [formula 1, 2].

Electric thermometers, thermal candles, thermal stencils, and thermal indicators were used in the energy industry to control the contact connections of conducting parts before. Nowadays, thermal imagers are being successfully used for these purposes. Now there is a possibility not only to measure the temperature of individual points but also to observe the thermal conditions of electrical installations.

The heat amount released on defective contact depends on the square, the current flowing through
it, the transient resistance, and the time. The thermal energy released when the current flows through
the contact’s transient resistance is transmitted as thermal radiation to the environment, to the
conjugated conducting parts and insulating devices. The temperature of contact connections depends
on many factors including the area of their surfaces, the heat transfer coefficients of conjugated
conducting parts, and the environmental parameters (temperature). In the formula [2] heating
temperature limit (excess of heat temperature above the ambient temperature) is adopted as the main
criterion of contact connection’s intactness at nominal current \( I_{\text{nom}} \) and in formula [3] the value limit of
phase (pole) resistance of the device and its parts. These two intactness criteria of switching devices
are equivalent since the heating of contact connections occur before mentioned in formula [2]
temperature by the flow of current load \( I_l=I_{\text{nom}} \) and energy released on the device resistance \( R_d \), a
power source of which is proportional to the resistance of conducting system.

The exceed of contact’s heated part above the ambient temperature is acceptable as a criterion for
evaluating the contact group’s state.

2. Materials and methods
The estimated temperature excess is calculated from the current load \( I_l \) and the nominal current \( I_{\text{nom}} \) of
the device:

\[
t_{\text{norm}} = t_{\text{nom}} \left( \frac{I_l}{I_{\text{nom}}} \right)^2,
\]

where \( t_{\text{norm}} \) is the normalized value of heating temperature excess for the controlled object (contact
connection).

The estimated calculated value of the contact resistance at the normal conversion temperature is
calculated using this expression:

\[
R_{\text{nom}} = R_m \frac{K + t_{\text{nom}}}{K + t_m},
\]

where \( R_m \) is the measured resistance value at \( t_m \) [°C]; \( K \) is copper coefficient equal to 235; \( t_{\text{nom}} \) is
the nominal temperature equal to 40 °C [2]; \( t_m \) is the ambient temperature at which the resistance
measurements were made \( R_m \), °C.

The electrical resistance of the contacts is calculated by the expression:

\[
R = R_{\text{nom}} + \alpha t_{\text{nom}} k_l^2,
\]

where \( \alpha \) is the temperature coefficient depending on conductor material; \( k_l \) is the load factor of the
switching device; \( R_{\text{nom}} \) is the nominal resistance of the contact groups [3].

The calculation is performed in the following order:
- calculating the contact resistance \( R_m \) at ambient temperature \( t_m=50 \) °C according to the expression
  (2):
  \[
  R_m = R_{\text{norm}} \frac{K + t_m}{K + t_{\text{norm}}} = 275 \frac{235 + 5}{235 + 40} = 259 \text{ mOm}
  \]
- contact resistances for other ambient temperature values are determined the same way;
- for study the dependence of resistances on the load we determine the contacts resistance at \( k_l=0.1 \)
  using the expression (3):
  \[
  R = R_{\text{nom}} + \alpha t_{\text{nom}} k_l^2 = 275 + 4.3 \cdot 40 \cdot 0.1^2 = 227 \text{ mOm}
  \]
- the resistance of the magnetic starter contacts at other values of the load factor is determined.
For magnetic starters having the following nominal resistances of contact groups: 82.5; 33.0; 13.1
mOhm; as well as for circuit breakers with the following nominal resistances 34.9; 27.9; 17.5 mOhm; the calculation is made the same way [2].

Dependency graphs of contact connection’s resistance value (magnetic starters and circuit breakers) on the ambient temperature and the load factor are shown in Fig. 1-4.

Predicting the development of a random process that reflects the functioning of a complex system should be preceded by statistical processing of experiment results to build a correlation field. Then, by using the correlation field we can find an empirical regression, which means to establish a quantitative relationship between the characteristics of the process.

The next step is to approximate the ultimate empirical curve of regression. The simplest way of approximation of this curve is linear regression:

\[ y = \alpha + \beta x. \]  

(4)

The change \( \gamma \) is related to some change in the parameter \( x \), but does not depend on the quantity of "parameter \( x \) has already accumulated". Using the principle of least squares it is easy to create a normal equation of linear regression [2]:

\[
\begin{align*}
\sum y_i - \sum (\alpha + \beta x_i) &= 0 \\
\sum y_i x_i - \sum (\alpha + \beta x_i) x_i &= 0
\end{align*}
\]  

(5)

Making simple transformations, we bring this system to this form

\[
\begin{align*}
m\alpha + \beta \sum x_i &= \sum y_i \\
\alpha \sum x_i + \beta \sum x_i^2 &= \sum y_i x_i
\end{align*}
\]  

(6)

\( \beta \) is a regression coefficient that can be easily calculated using determinants:

\[
\beta = \frac{m \sum x_i y_i - \sum x_i \sum y_i}{m \sum x_i^2 - (\sum x_i)^2}.
\]  

(7)

\( \alpha \) is a free regression term:

\[
\alpha = \frac{\sum y_i - \beta \sum x_i}{m}.
\]  

(8)

The resulting expressions completely determine linear regression for a given sample. Equation (5) for the free term of the regression can be rewritten in the following way:

\[
\alpha = \frac{1}{m} \sum y_i - \beta \frac{1}{m} \sum x_i = \bar{y} - \beta \bar{x}, \quad \text{when} \quad \bar{y} = \alpha + \beta \bar{x}
\]

The average point of the joint distribution of the quantities learnt always lies on the regression line [6].

For the determination of the regression line, it is enough to know only angular coefficient \( \beta \). The fact that dependence studied is assumed to be linear allows using a sample correlation coefficient \( r \) for estimating the bond strength:

\[
r = \beta \sqrt{\frac{m \sum x_i^2 - (\sum x_i)^2}{m \sum y_i^2 - (\sum y_i)^2}}.
\]  

(9)

The initial calculation is based on the dependence of the contact connections resistance of a magnetic starter from the ambient temperature (Table 1).
According to the expression (7), we calculate the regression coefficient \( \beta \):

\[
\beta = \frac{m \sum x_i y_i - \sum x_i \sum y_i}{m \sum x_i^2 - (\sum x_i)^2} = \frac{9 \cdot 60000 - 225 \cdot 2340}{9 \cdot 7125 - 225^2} = 1
\]

the coefficient \( \alpha \) is determined by the expression (8)

\[
\alpha = \frac{\sum y_i - \beta \sum x_i}{m} = \frac{2340 - 1 \cdot 225}{9} = 235
\]

- we get the correlation coefficient \( r \) according to expression (9):

\[
r = \beta \sqrt{\frac{m \sum x_i^2 - (\sum x_i)^2}{m \sum y_i^2 - (\sum y_i)^2}} = \sqrt{\frac{9 \cdot 7125 - 225^2}{9 \cdot 609900 - 2340^2}} = 0.99
\]

- the correlation coefficient is very close to 1.0 (0.99) which means that the relationship between \( x \) and \( y \) is almost linear, and the final equation must be recognized as equality.

**Table 1.** Dependence of contact connections resistance of magnetic starters on the ambient temperature (\( R_{\text{nom}} = 275\text{mOm} \))

| \( t, \degree \text{C} \) | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|--------------------------|----|----|----|----|----|----|----|----|----|
| \( R, \text{mOm} \)      | 240| 245| 250| 255| 260| 265| 270| 275| 280|

The calculation is made in the following order:

- we take \( x_i = t_i, \degree \text{C}; \ y_i = R_i, \text{mOm}; \)
- table 2 is made to simplify the calculation.

**Table 2.** The results of the intermediate calculations

| No. | \( X \) | \( Y \) | \( X^2 \) | \( Y^2 \) | \( X \cdot Y \) | \( X + Y \) | \( (X+Y)^2 \) |
|-----|--------|--------|----------|----------|--------------|----------|----------|
| 1   | 5      | 240    | 25       | 57600    | 1200         | 245      | 60025    |
| 2   | 10     | 245    | 100      | 60025    | 2450         | 255      | 65025    |
| 3   | 15     | 250    | 225      | 62500    | 3750         | 265      | 70225    |
| 4   | 20     | 255    | 400      | 65025    | 5100         | 275      | 75625    |
| 5   | 25     | 260    | 625      | 67600    | 6500         | 285      | 81225    |
| 6   | 30     | 265    | 900      | 70225    | 7950         | 295      | 87025    |
| 7   | 35     | 270    | 1225     | 72900    | 9450         | 305      | 93025    |
| 8   | 40     | 275    | 1600     | 75625    | 11000        | 315      | 99225    |
| 9   | 45     | 280    | 2025     | 78400    | 12600        | 325      | 105625   |
| \( \Sigma \) | 225   | 2340   | 7125     | 609900   | 60000        | 2565     | 737025   |
Figure 1. Dependence of contact connection resistance of magnetic starters on the ambient temperature: 1 - R_{nom}=275 \text{ mOm}; 2 - R_{nom}=82.5 \text{ mOm}; 3 - R_{nom}=33 \text{ mOm}; 4 - R_{nom}=13.1 \text{ mOm}

Figure 2. Dependence of contact connection resistance of magnetic starters on the load factor: 1 - R_{nom}=275 \text{ mOm}; 2 - R_{nom}=82.5 \text{ mOm}; 3 - R_{nom}=33 \text{ mOm}; 4 - R_{nom}=13.1 \text{ mOm}

Figure 3. Dependence of contact connection resistance of circuit breaker on the ambient temperature: 1 - R_{nom} =37.4 \text{ mOm}; 2 - R_{nom} =27.9 \text{ mOm}; 3 - R_{nom} =17.45 \text{ mOm}

Figure 4. Dependence of the contact connection resistance of circuit breaker on the load factor: 1 - R_{nom} =37.4 \text{ mOm}; 2 - R_{nom} =27.9 \text{ mOm}; 3 - R_{nom} =17.45 \text{ mOm}

3. Results

The obtained expression is consistent with the analytical dependence of contact connections resistance of magnetic starter on the ambient temperature (Figures 1 and 5).

Analytical forecasting of changes in contact resistance of switching devices during operation. The work capacity of the switching device is determined by the resistance of its contacts R_c. We consider the function R_c(T) value of which changes continuously in the time interval T_1=[t_0, t_n]. As a result, there are values of this function R_{0}, R_{1},..., R_{i}, R_{n} on the interval T_1 [2].

Figure 5. Dependence of contact connection resistance of magnetic starters on the ambient temperature
It is necessary to determine the value of the $R(t)$ function from the known $R_i$ values: $R_{n+1},\ldots, R_{n+i},\ldots, R_{i},\ldots, R_{n+m}$ at future times $t_{n+1},\ldots, t_{n+i},\ldots, t_{n+m} \in T_2$, or find out after what time the values of $R_{n+i}, t_{n+i} \in T_2$ will reach the acceptable level $R_{adm}$.

We can use the following expression to describe how the $R_c$ parameter changes in this interval

$$R_c = R_{nom} - kT,$$

(10)

Where $k = (R_{nom} - R_p)/T$; $T$ – operating time, years; $R_p$ = $5R_{nom}$ – permissible contact resistance [5].

The calculation is made in the following order [2]:
- according to expressions (10, 11), we determine the character of the $R_c(T)$ change

$$R_c = 275 + 36T$$

Where $k = (R_{nom} - R_p)/T = (275 - 1375)/30 = -36$
- we study the change in contact connections resistance during operation, i.e. $T = 1,\ldots, 30$ years:

$$R_c = 275 + 36 \cdot 1 = 311, \text{ mOm}$$

The calculation for other values of the operating time is made the same way.

The regression coefficient that characterizes the obliquity of the straight line is determined:

$$\alpha = \frac{T}{R_p - R_{nom}} = \frac{1}{1375 - 275} = 0.001$$

where $T = 1$ year, the operating time of the magnetic starter.

The calculation for other values of the operating time is made the same way.

The results of the calculations are presented in Table 3.

| $T$, year | 1  | 3  | 5  | 7  | 10 | 15 | 17 | 20 | 23 | 25 | 30 |
|-----------|----|----|----|----|----|----|----|----|----|----|----|
| $\alpha \cdot 10^{-3}$ | 1  | 3  | 5  | 6  | 9  | 14 | 15 | 18 | 21 | 23 | 27 |

Dependency graphs of the contact resistance of switching devices on service life are shown in figures 6 and 7.

**Figure 6.** Change in contact connection resistance of magnetic starters during operation: 1 – $R_{nom}$=275 mOm; 2 – $R_{nom}$=82.5 mOm; 3 – $R_{nom}$=33 mOm; 4 – $R_{nom}$=13.1 mOm.
Figure 7. Dependence of contact connection resistance of circuit breakers on service life:
1 - $R_{\text{nom}} = 34.9 \text{ mOm}$; 2 - $R_{\text{nom}} = 27.9 \text{ mOm}$; 3 - $R_{\text{nom}} = 17.45 \text{ mOm}$; 4 - $R_{\text{nom}} = 0.512 \text{ mOm}$.

4. Conclusions
During the analytical process of forecasting changes in contact groups resistance of low-voltage switching devices (magnetic starters and circuit breakers) under different operating conditions, mathematical models are obtained, the input values of which are refined using regression analysis. The change in contact connections resistance of the low-voltage devices is one of their technical condition characteristics and allows evaluating the efficiency of oil and gas industry equipment.

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