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Algorithms and Models for Evaluation of Technical Characteristics of Low-voltage Electrical Apparata

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***Abstract*—The paper reflects the problem of evaluating the efficiency of low-voltage switching devices, which are used in the systems of in-plant power supply. The technical condition of circuit breakers and contactors of different manufacturing plants has been investigated, models for determining the technical characteristics of switching devices have been developed. The dependences of active power losses in the investigated devices on the current flowing through them have been established. The result of research is approximating functions of the value of active power losses and contact resistances from the main parameters of switching devices. Developed algorithm and models for assessing the efficiency of operation of devices, which allow to specify the value of active power losses and electricity in low-voltage electrical networks.**

Keywords—low-voltage grid, electrical switching devices, circuit breakers, contactors, contact resistance, power losses, approximating functions

I. INTRODUCTION

As practice shows, due to the wide development of production of low-voltage equipment of various brands, the actual task is to identify the most efficient equipment with the lowest power and energy losses, which contributes to the implementation of optimal solutions for energy saving in the systems of shop-floor power supply [1-3].

Switchgear is one of the most widespread types of equipment of shop-floor networks. As a rule, the majority of devices of in-plant power supply operate in environmental conditions different from normal: high humidity, temperature, aggressive production environments, etc. At the same time, the load of devices varies depending on the conditions of technological processes and operating modes [4-6]. Contact systems of devices are subject to both electrical and mechanical wear due to frequent switching, external vibrations and possible mechanical effects not provided by technical conditions. These factors determine the value of transient resistance of contact connections [7-9]. Intra-shop networks are characterized by a large length and branching, and have a lot of serial and parallel nodes with contact connections. Due to the fact that the contact systems of switching devices in the process of operation are in a closed position and the level of reliability of the low-voltage network as a whole depends on their condition, - strict requirements are imposed on the contact connections [10, 11]. The reliability of low-voltage switching devices as a whole is determined by the reliability of design elements – contact system, arc suppression device and actuator.

To investigate the value of resistance of contact connections of low-voltage devices, catalog data of manufacturers of active power losses Δ*P* per pole of the device are used.

The main design features of the apparatus include the shape, materials and geometric dimensions of contacts, type of bimetallic materials and type of arc protection devices. According to the design features, the investigated low-voltage devices belong to the devices having, in addition to power contacts in the power circuit, additional elements (thermal relay sensors, coils of maximum relays).

II. MATERIALS AND METHODS

To study the technical characteristics of circuit breakers in the molded case, let us determine the type of graphical dependences of active power losses per pole in the contact systems on the rated current of devices of various manufacturers – Kursk Electrical Apparatus Plant (KEAZ), Schneider Electric, ABB, Legrand with rated current up to 250 A (Fig. 1).

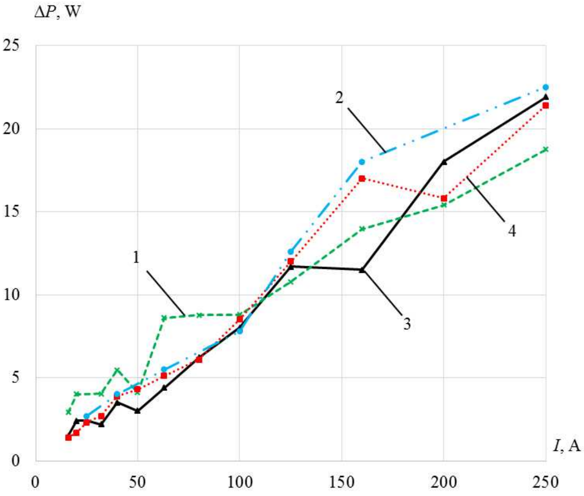

Fig. 1. Graphical dependences of active power losses on rated current of circuit breakers: 1 - ComPact NSX (Schneider Electric); 2 -DPX (Legrand); 3 - VA04 (KEAZ); 4 - Tmax XT (ABB).

The graphical dependencies obtained (Fig. 1) show that power losses per pole of circuit breakers with *I* up to 100 A have approximately the same values for devices of KEAZ, ABB and Legrand. The highest power losses are characteristic for circuit breakers manufactured by Schneider Electric - about 50% more than for devices VA04. At research of devices with *I* over 100 A it is established, that the greatest losses of active power have devices of firm Legrand - approximately on 15 % more, than VA04 It is necessary to note, that the most effective taking into account losses of

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power and cost of device are circuit breakers of manufacture KEAZ.

Graphs of dependence of power losses in the contact systems of contactors on their rated currents, plotted according to catalog data, are presented in Fig. 2.

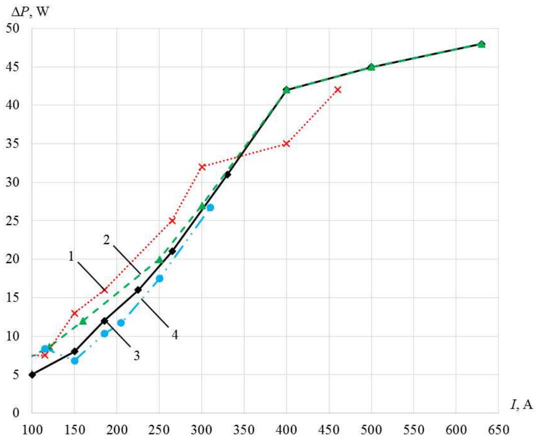

Fig. 2. Graphical dependences of active power losses on rated current for contactors: 1 - ABB A (ABB); 2 - EasyPact TVS (Schneider Electric); 3 - PML (KEAZ), KTI (IEK); 4 - CTX (Legrand)

Graphical dependence (Fig. 2) illustrate that the value of the smallest power losses in contact systems is characteristic for contactors of KEAZ and Legrand firms, approximately 27 % less than in ABB devices.

To choose a reliable approximation function, we calculate for each of them the determination coefficient R^2 and the average approximation error $\bar{A}$.

R^2 is calculated by the formula:

$$R^2 = 1 - \frac{\sum_i (y - \hat{y})^2}{\sum_i (y - \bar{y})^2} \tag{1}$$

where y_i - actual values of the variables; ŷ - calculated values of the investigated quantity; $\bar{y} = \frac{\sum_i y_i}{n}$ - the average value of the investigated value; $\sum_i(y_i - \hat{y})^2$ - sum of squared regression errors; $\sum_i(y_i - \bar{y})^2$ - sum of squared deviations of data points from the mean.

Average approximation error Ā is a value showing the average deviation of calculated values from actual values:

$$\bar{A} = \frac{1}{n}\sum_i \left| \frac{y_i - \hat{y}}{y_i} \right| \cdot 100\% \tag{2}$$

TABLE I. APPROXIMATING FUNCTIONS OF POWER LOSSES FOR CIRCUIT BREAKER VA04 (KEAZ)

Approximation function		R^2	Ā, %
exponential	$\Delta P_{VA1} = 1.9379\, e^{(0.0112 \cdot I)}$	0.762	19.65
linear	$\Delta P_{VA2} = 0.0869 \cdot I - 0.3237$	0.979	16.36
logarithmic	$\Delta P_{VA3} = 6.6325 \cdot \ln(I) - 20.065$	0.821	55.9
polynomial	$\Delta P_{VA4} = -8 \cdot 10^{(-5)} \cdot I^2 + 0.0673 \cdot I + 0.3855$	0.983	11.45
power function	$\Delta P_{VA5} = 0.1014 \cdot I^{(0.9518)}$	0.964	10.4

The results of Table I show that the most reliable approximating function for the circuit breakers under study is the polynomial one with R^2=0.9833, Ā=11.45%.

Table II presents the results of approximation of the dependence of active power losses on rated current for the studied circuit breakers and contactors. The functions were chosen on the basis of the largest determination coefficient R^2 and the smallest approximation error Ā. Optimal values of coefficients, as an indicator of reliability of approximation, correspond to polynomial dependencies.

TABLE II. APPROXIMATING POWER LOSS FUNCTIONS FOR THE STUDIED APPARATUS

Machine make and manufacturer	**Approximation function**	R^2	**Ā, %**
Circuit breakers			
VA04 (KEAZ)	$\Delta P_{VA} = -8 \cdot 10^{(-5)} \cdot I^2 + 0.0673 \cdot I + 0.3855$	0.9833	11.45
ComPact NSX (Schneider Electric)	$\Delta P_{NSX} = -6 \cdot 10^{(-5)} \cdot I^2 + 0.082 \cdot I + 1.928$	0.9724	10.17
Tmax XT (ABB)	$\Delta P_{Tmax} = -2 \cdot 10^{(-4)} \cdot I^2 + 0.1209 \cdot I - 0.9538$	0.9541	13.27
DPX (Legrand)	$\Delta P_{DPX} = -5 \cdot 10^{(-5)} \cdot I^2 + 0.1044 \cdot I + 0.0142$	0.9659	13.53
Contactors			
PML (KEAZ); KTI (IEK); EasyPact TVS (Schneider Electric)	$\Delta P_{PML} = -1 \cdot 10^{(-4)} \cdot I^2 + 0.1799 \cdot I - 15.52$	0.9725	14.8
ABB A (ABB)	$\Delta P_{ABB} = -1 \cdot 10^{(-4)} \cdot I^2 + 0.178 \cdot I - 10.411$	0.9835	4.7
CTX (Legrand)	$\Delta P_{CTX} = 5 \cdot 10^{(-4)} \cdot I^2 + 0.1204 \cdot I + 14.614$	0.9887	6.2

The data of Table II show that the approximation of power losses as a function of rated current for the investigated low-voltage devices is reliable: the coefficient of determination R^2 has a value of more than 0.95, and the error Ā does not exceed 14.8 %. With the help of the obtained dependences it is possible to determine active power losses per pole of low-voltage switching devices. This information can be recommended for use for specification of calculations on estimation of power losses in low-voltage electric networks. Fig. 3-4 show graphical dependences of the obtained approximating functions for the studied devices at loading of devices with rated current.

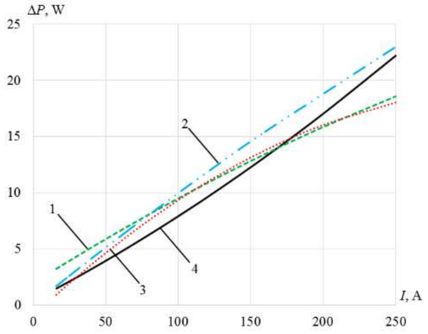

Fig. 3. Graphs of approximating functions of active power losses for circuit breakers: 1 - ComPact NSX (Schneider Electric); 2 - DPX (Legrand); 3 - Tmax XT (ABB); 4 - VA04 (KEAZ).

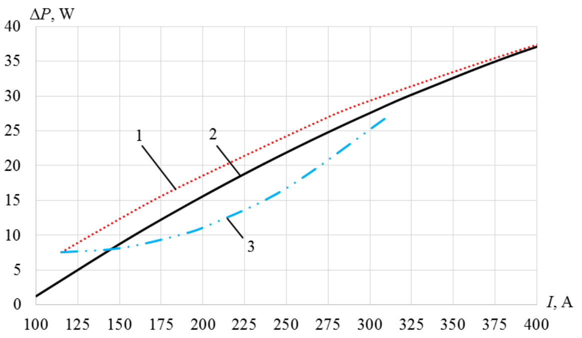

Fig. 4. Graphs of approximating functions of active power losses for contactors: 1 - ABB A (ABB); 2 - PML (KEAZ), KTI (IEK), EasyPact TVS (Schneider Electric); 3 - CTX (Legrand)

III. Results and Discussions

As a rule, not all technical characteristics of low-voltage switching devices are specified in the passport data. Resistances of most elements of low-voltage devices are not given, so, for example, there is no data on resistances of power circuits and contacts of devices.

To determine the resistance of contact connections we use the expression:

$$R' = \frac{\Delta P}{I^2} \qquad (3)$$

where ΔP - active power losses per pole of the device, W, (catalog value), I - rated current of the device, A.

The resistance of the contact connections, depending on the rated current and the load factor, is calculated as follows:

$$R'' = \frac{2\sqrt{\lambda \cdot F \cdot k \cdot S}}{I^2} \cdot \left(\theta - \frac{I^2 \cdot \rho \cdot (1 + \alpha \cdot \upsilon)}{F \cdot k \cdot S} \right) \qquad (4)$$

where λ - thermal conductivity of contact material; F - cooling surface of conductor length unit, m^2; k - heat transfer coefficient; S - cross-sectional area of contacts, m^2; I - current through contacts, A; υ - temperature of contact pads, °C; $\theta = 45$ °C - permissible temperature difference of contact relative to ambient temperature; ρ - specific electrical resistance, Ohm · m; α - temperature coefficient of resistance.

Temperature of contacts:

$$\upsilon = \frac{I^2 \cdot \rho + \upsilon_0 \cdot F \cdot k \cdot S}{F \cdot k \cdot S - I^2 \cdot \rho \cdot \alpha} \qquad (5)$$

where υ_0 - ambient temperature.

According to expression (4) for circuit breaker VA04 with $I = 100$ A, loading factor 1, resistance of contact connections:

$$R'' = \frac{2 \cdot \sqrt{390 \cdot 2 \cdot (6+6.2) \cdot 10^{-3} \cdot 16 \cdot (6 \cdot 6.2) \cdot 10^{-6})}}{100^2} \times$$

$$\times \left(45 - \frac{100^2 \cdot 1.7 \cdot 10^{-8} \cdot (1 + 0.0043 \cdot 49.3)}{2 \cdot (6+6.2) \cdot 10^{-3} \cdot 16 \cdot (6 \cdot 6.2) \cdot 10^{-6}} \right) = 0.46 \text{ mOhm}$$

where υ according to (5):

$$\upsilon = \frac{100^2 \cdot 1.7 \cdot 10^{-8} + 35 \cdot 2 \cdot (6+6.2) \cdot 10^{-3} \cdot 16 \cdot (6 \cdot 6.2) \cdot 10^{-6}}{2 \cdot (6+6.2) \cdot 10^{-3} \cdot 16 \cdot (6 \cdot 6.2) \cdot 10^{-6} - 100^2 \cdot 1.7 \cdot 10^{-8} \cdot 0.0043} = 49.3 \text{ °C}$$

The results of calculations of resistance of contact connections and temperature of contact pads for the investigated apparatus are given in Table III.

TABLE III. Results of Calculation of Technical Characteristics of Contacts of Circuit Breakers and Contactors

Type of apparatus	***I*, A**	**Contact dimensions, mm**	**Temperature of contact pads, °C**	**Resistance of contact connections, mOhm**
Circuit breaker VA	16	$a = 2.8$ $b = 2.8$	38.6	7.56
	25	$a = 2.8$ $b = 2.8$	44.1	2.68
	32	$a = 3.8$ $b = 3.8$	40.8	2.82
	40	$a = 3.8$ $b = 3.8$	44.3	1.65
	50	$a = 3.8$ $b = 3.8$	49.8	0.89
	63	$a = 4$ $b = 4$	55	0.49
	100	$a = 6$ $b = 6.2$	49.3	0.46
Contactor KTI	250	$a = 10$ $b = 20$	41.5	0.34
	400	$a = 17$ $b = 20$	43	0.18

Dependences of resistance of contact connections of low-voltage switching devices on rated current, obtained experimentally – by the method of ammeter-voltmeter are presented in Table IV. The obtained expressions for calculating the coefficients in the empirical formulas have deviations from the experimental data by ±5 %.

TABLE IV. Analytical Dependences of Switchgear Resistance on Current

Type of apparatus	**Current limits**	**Type of analytical dependence of resistance on current**
Circuit breakers and contactors	$I < 60$ A	$R = \frac{350}{I}$
	$I \geq 60$ A	$R = \frac{310}{I}$

Using the data of the conducted studies, a comparative analysis of graphical dependences of contact resistance on rated current, obtained experimentally, by power losses (catalog data), by calculation method and by reference data for circuit breakers and contactors. The results are presented in Fig. 5-8.

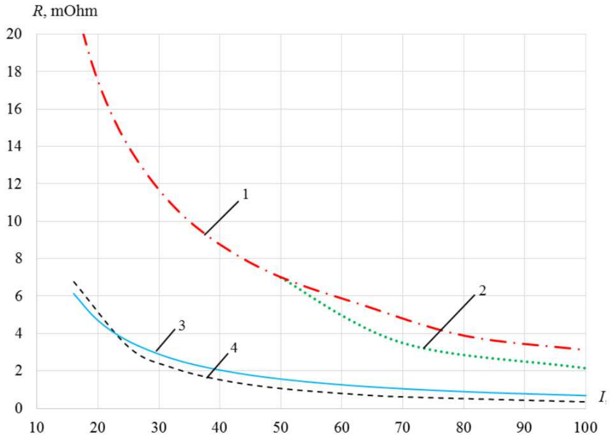

Fig. 5. Graphs of contact resistance dependences on rated current for circuit breakers (with I up to 100 A): 1 - experimental data; 2 - reference data; 3 - data on power losses; 4 - calculated values

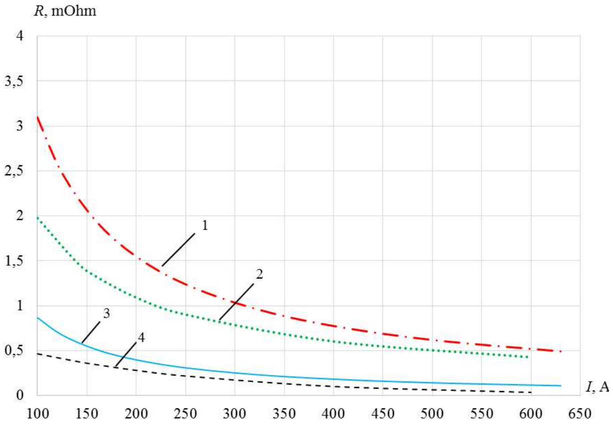

Fig. 6. Graphs of contact resistance dependences on rated current for circuit breakers (with I more than 100 A): 1 - experimental data; 2 - reference data; 3 - data on power losses; 4 - calculated values

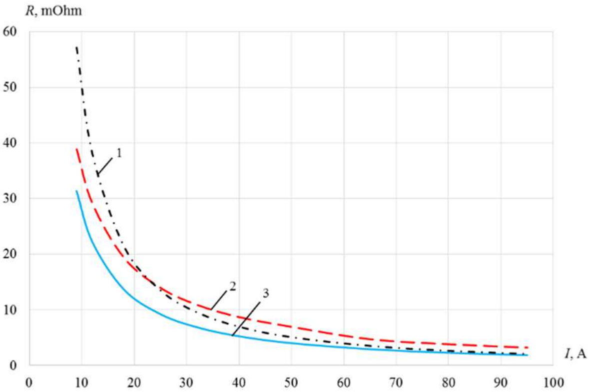

Fig. 7. Graphs of contact resistance dependences on rated current for KMI contactors: 1 - calculated values; 2 - experimental data; 3 - data on power losses

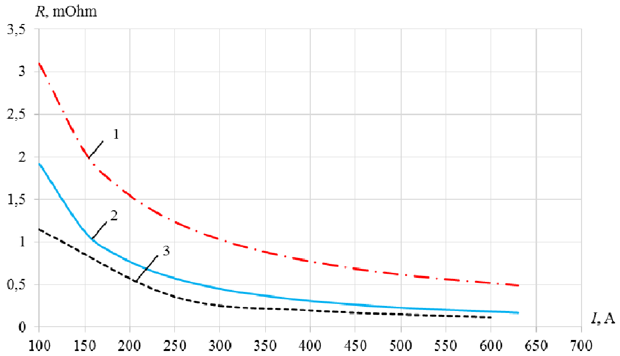

Fig. 8. Graphs of contact resistance dependences on rated current for KTI contactors: 1 - experimental data; 2 - power loss data; 3 - calculated values

The obtained dependencies show that experimental, reference, calculation and power loss data have different values. This is due to the fact that the devices have different switching cycles, differences in design features, as well as there are errors in calculations and initial data for calculations. It should also be taken into account that in the experiment we selected apparatus of the same brand, but of different manufacturing plants and, accordingly, with different level of technological equipment of apparatus production.

Fig. 9-11 show the results of calculations of errors δ, %, for approximating functions of resistance of contact connections of apparatus by different methods relative to the experimental values.

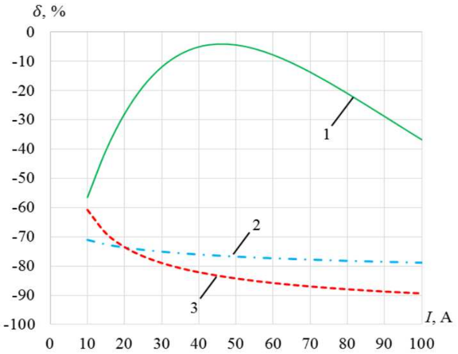

Fig. 9. Graphs of errors δ, % of contact resistance determination by different methods for circuit breakers with I less than 100 A: 1 - according to reference data; 2 - according to power losses; 3 - calculated values

The graphs presented in Fig. 9 show that the most accurate is the determination of contact resistances of circuit breakers in the range of rated currents 20 A ≤ I < 80 A by the method using reference data. The error in this case does not exceed 20%.

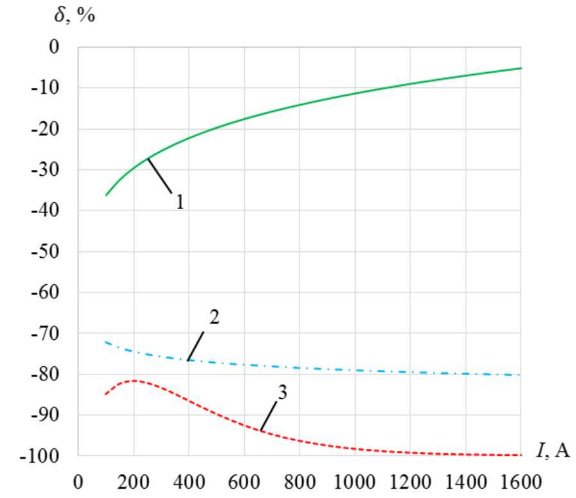

Fig. 10. Graphs of errors δ, % of determining the resistance of contact connections of circuit breakers with I more than 100 A: 1 - by reference data; 2 - by power losses; 3 - calculated values

The graphs (Fig. 10) show that the most reliable method for the given range I is the method using reference data. The error does not exceed 30%.

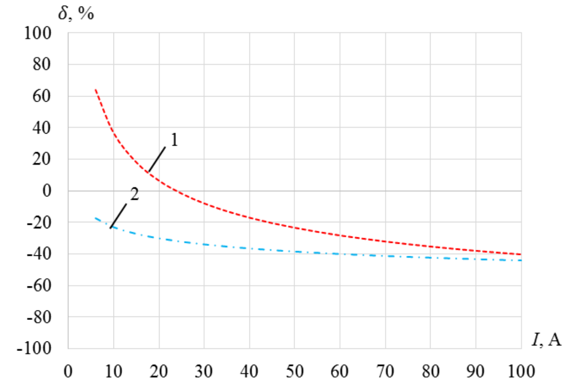

Fig. 11. Graphs of errors δ, % of determination of contact resistance of contact connections of KMI contactors: 1 - calculated values; 2 - by power losses

The graphs (Fig. 11) show that in the range of values of rated currents $10\ \text{A} \leq I < 70\ \text{A}$ can be used as the most reliable calculation data.

IV. CONCLUSION

The revealed dependencies are recommended for obtaining reliable estimates of the calculated values of equivalent resistances of low-voltage electrical networks. The obtained approximating functions of contact connection resistances have different error values depending on the initial data used. Mathematical models and analytical dependences allow to reveal the types of low-voltage devices effective in operation and rationally implement energy-saving measures in the systems of in-plant power supply. Theoretical and experimental studies show that taking into account the power losses in the contact connections of low-voltage switching devices allows specifying the value of power losses in the systems of in-plant power supply.

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