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Modeling of Power Losses in Contact Systems of Low Voltage Switching Devices

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***Abstract* — The article studies the dependence of active power losses in contacts and contact systems of circuit breakers, contactors, and magnetic starters from the main parameters of electrical equipment. Models of functional dependencies of active power losses on nominal current for low voltage switching devices of some manufacturers were developed. Approximation functions of these characteristics have been compiled and the value of determination coefficient of the obtained functions of active losses and approximation error have been calculated. Graphical presentations of the investigated parameters of low-voltage equipment are shown in relation to the commutated variables.**

***Keywords* — low-voltage switching devices, contact connections, power losses, approximating functions, design features.**

I. Introduction

At present, the low voltage apparata are been intensively developing all over the world. New materials and designs of devices are being applied, and the functions they perform are becoming more complex. There are more stringent requirements for low voltage switching devices, they must have a sufficient level of reliability and function effectiveness throughout the entire period of operation [1; 2]. At the same time, low voltage switching devices are one of the main elements of control systems for electric drives and control systems for electric machines [3]. For the correct choice of the type and nominal parameters of the low voltage switching devices, it is necessary to have reliable information about the magnitude of the calculated loading of the consumed power from the commutated objects [4; 5].

In general, the lines of intra-workshop power supply networks contain many contacts and contact connections of devices. To analyze and evaluate power and electricity losses in low voltage electrical networks, the magnitude of the losses in the contact connections of the switching devices are required [6; 7].

The main factors determining active power losses in switching devices are: the value of the rated current; geometric shape and contact area; device switching frequency; contact material: their shape and uniformity of structure; sections of the conductive parts of the apparatus and the operating environment of electrical equipment.

At this stage of development of the electric power industry, the requirements for the power and electricity losses in intra-workshop power supply systems are changing. At the same time, obtaining reliable information is associated with the complexity of determining the parameters and the regime data of power supply systems. The trustworthiness of the information about the parameters of electrical equipment significantly increases the possibility of making correct decisions for increasing the energy efficiency of the operation of power supply systems [8].

For modern conditions of development of the electrical industry, an increase in the range of low-voltage devices produced is characteristic. Developments are being actively carried out to create both domestic and foreign devices. New designs of devices with additional functionality are being studied [2]. So, for example, modern molded case circuit breakers can perform switching operations without the intervention of operating personnel, that is work in combination with a program logic controller [9].

Most of the devices are designed to operate with a long-term closed state of contacts, so it is necessary that the devices function with a stable value of the contact resistance of the contact groups.

As a rule, the technical literature does not provide information about the power losses of most devices, in connection with this, it becomes necessary to study the laws of change in power losses in contacts and contact connections of various groups of devices.

II. Materials and Methods

We will analyze and study the technical parameters of automatic switches, magnetic starters, and contactors, which are most common in national industrial enterprises. The devices of the Kursk Electrical Apparatus Plant (KEAZ) and of some foreign manufacturers (Schneider Electric, ABB, Legrand) were selected for the study.

Depending on the rated current of the device, its power loss will be different. According to the catalog data of low voltage switching devices, we study the dependences of power losses ΔP on the rated current I_n for automatic switches (Fig. 1), magnetic starters (Fig. 2) and contactors (Fig. 3) of various manufacturers.

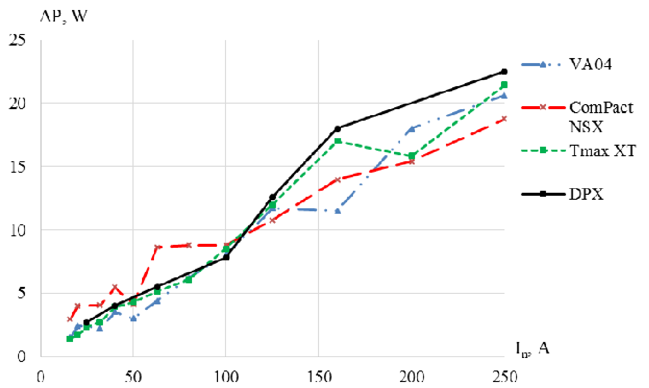

Fig.1. Graphical dependences of active power losses on the rated current of circuit breakers from various manufacturers

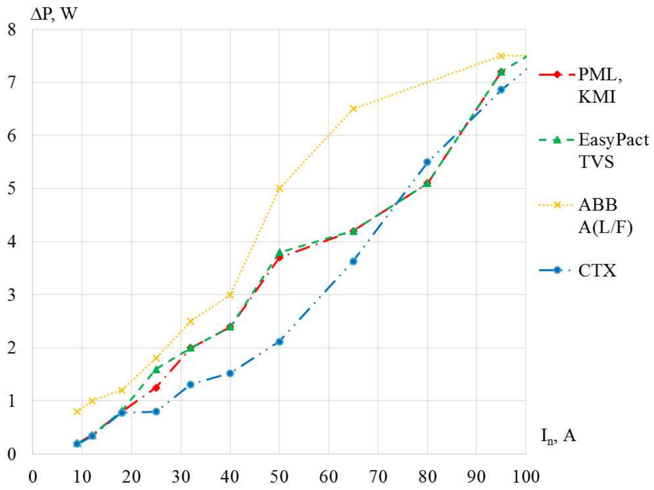

Fig.2. Graphical dependences of active power losses on the rated current for magnetic starters

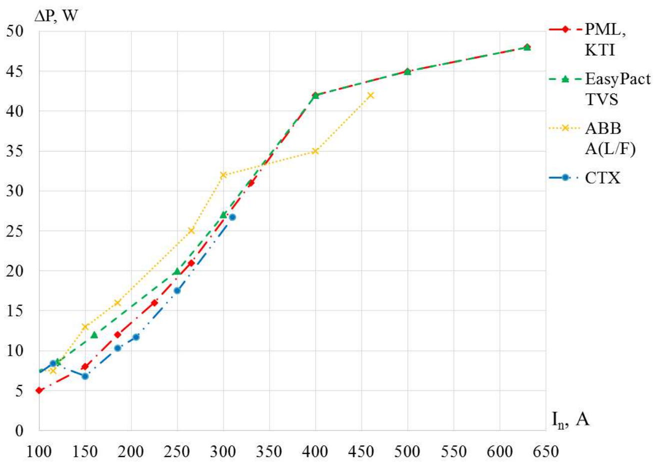

Fig.3. Graphical dependences of active power losses on the rated current for contactors

Data analysis shows that the main technical parameters of automatic circuit breakers manufactured by KEAZ, Schneider Electric, ABB and Legrand have similar values, however, there are differences in the values of active power losses per pole.

Based on the statistical data of failures of magnetic starters, it was revealed that the weakest element is its power contacts [10]. When comparing the characteristics of domestic and foreign magnetic starters, similarities in technical parameters were established - for example, starters of the PML (KEAZ), KMI (IEK) and EasyPact TVS (Schneider Electric) brands are characterized by the same values of active power losses in power contacts.

An approximation of the constructed functions to find the dependences of power losses on the rated current [11; 12]. For the functions under study, we determine the coefficient of determination R^2 and the average approximation error $\bar{A}$.

Approximation is the replacement of some mathematical objects with others that are close to the original ones [13]:

$$\Delta P = F(I_n) \quad (1)$$

where $F(I_n)$ – functional dependences of active power loss values on the rated current value; I_n – is the rated current.

The coefficient of determination R^2 is a statistical measure of agreement, with which you can determine how the regression model fits the data on which it is built. The coefficient R^2 corresponds to the values in the range from 0 to 1 [14; 15].

R^2 is calculated by the formula:

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

where y_i - actual values of the variables;

$\hat{y}$ - 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 [16].

III. Results and Discussions

The parameters of VA04 (KEAZ) are examined. In this case, approximating functions are obtained, which are represented by the following expressions:

- exponential

$$\Delta P_{VA1} = 1.9379 e^{(0.0112 \cdot I_n)} \quad (3)$$

- linear

$$\Delta P_{VA2} = 0.0869 \cdot I_n - 0.3237 \quad (4)$$

- logarithmic

$$\Delta P_{VA3} = 6.6325 \cdot \ln(I_n) - 20.065 \quad (5)$$

- polynomial

$$\Delta P_{VA4} = -8 \cdot 10^{(-5)} \cdot I_n^2 + 0.0673 \cdot I_n + 0.3855 \quad (6)$$

- power function

$$\Delta P_{VA5} = 0.1014 \cdot I_n^{(0.9518)} \quad (7)$$

Here is calculated the coefficient of determination by expression (2) for the polynomial function:

$$R^2 = 1 - \frac{(1.5-1.48)^2 + ... + (21.9-22.21)^2}{(1.5-7.438)^2 + ... + (21.9-7.438)^2} = 1 - \frac{8.59}{515.11} = 0{,}9833$$

The closer the value of the coefficient to 1, the more significant the dependence and the more accurate the approximation function.

Next, we calculate the average approximation error:

$$\bar{A} = \frac{1}{n} \sum_i \left| \frac{y_i - \hat{y}}{y_i} \right| \cdot 100\% \quad (8)$$

$$\bar{A} = \frac{1}{13} \cdot \left| \left(\frac{1.5-1.48}{1.5} \right) + ... + \left(\frac{21.9-22.21}{21.9} \right) \right| \cdot 100\% = 11.45\%$$

The error was less than 15%, which indicates a fairly high approximation accuracy. The calculation results are shown in Table I.

TABLE I. THE RESULTS OF CALCULATING THE COEFFICIENT OF DETERMINATION FOR A POLYNOMIAL FUNCTION

y_i	$\hat{y}$	$\bar{y}$	$(y_i-\hat{y})^2$	$(y_i-\bar{y})^2$	$\sum_i(y_i-\hat{y})^2$	$\sum_i(y_i-\bar{y})^2$	R^2	Ā, %
1.5	1.48		0.0003	35.265				
2.4	1.76		0.4051	25.381				
2.4	2.13		0.0795	25.381				
2.2	2.62		0.1773	27.437				
3.5	3.2		0.0867	15.508				
3	3.95		0.9035	19.696				
4.4	4.94	7.44	0.2948	9.229	8.59	515.1	0.983	11.45
6.2	6.28		0.0066	1.533				
8	7.92		0.0071	0.316				
11.7	10.05		2.7291	18.165				
11.5	13.2		2.8951	16.500				
18	17.04		0.9111	111.55				
21.9	22.21		0.0964	209.15				

Table II shows the approximating functions for the circuit breakers under study, their coefficient of determination and the approximation error.

Through the data that are presented in Table II it will be seen that the highest accuracy of the approximating expressions for the parameters of the circuit breakers under this study, have most of all, the polynomial functions, describing the dependence $\Delta P = F(I_n)$. It is seen also that the least accurately studied parameters, are described by exponential functions.

Thus, the functional dependences of the changes of power losses per pole, on the rated current are determined by approximating functions. Those functions have the largest values of the determination coefficients and the smallest values of approximation errors. For circuit breakers operating at a loading factor of 1, the dependences under study have the form shown in Fig. 4.

TABLE II. APPROXIMATION FUNCTIONS OF POWER LOSSES FOR THE STUDIED CIRCUIT BREAKERS

Approximation function		R^2	Ā, %
VA04 (KEAZ)			
exponential	$\Delta P_{VA1} = 1.9379e^{(0.0112 \cdot I_n)}$	0.762	19.65
linear	$\Delta P_{VA2} = 0.0869 \cdot I_n - 0.3237$	0.979	16.36
logarithmic	$\Delta P_{VA3} = 6.6325 \cdot \ln(I_n) - 20.065$	0.821	55.9
polynomial	$\Delta P_{VA4} = -8 \cdot 10^{(-5)} \cdot I_n^2 + 0.0673 \cdot I_n + 0.3855$	0.983	11.45
power function	$\Delta P_{VA5} = 0.1014 \cdot I_n^{(0.9518)}$	0.964	10.4
ComPact NSX (Schneider Electric)			
exponential	$\Delta P_{NSX1} = 3.6152e^{(0.0076 \cdot I_n)}$	0.828	18.3
linear	$\Delta P_{NSX2} = 0.0668 \cdot I_n + 2.4667$	0.969	10.71
logarithmic	$\Delta P_{NSX3} = 5.3394 \ln(I_n) - 13.71$	0.891	22.73
polynomial	$\Delta P_{NSX4} = -6 \cdot 10^{(-5)} \cdot I_n^2 + 0.082 I_n + 1.928$	0.972	10.17
power function	$\Delta P_{NSX5} = 0.4648 \cdot I_n^{(0.6584)}$	0.967	10.4
Tmax XT (ABB)			
exponential	$\Delta P_{Tmax1} = 2.0861e^{(0.0107 \cdot I_n)}$	0.464	32.27
linear	$\Delta P_{Tmax2} = 0.0761 \cdot I_n + 0.6608$	0.931	13.89
logarithmic	$\Delta P_{Tmax3} = 6.1907 \cdot \ln(I_n) - 18.209$	0.885	39.42
polynomial	$\Delta P_{Tmax4} = -2 \cdot 10^{(-4)} \cdot I_n^2 + 0.1209 \cdot I_n - 0.9538$	0.954	13.27
power function	$\Delta P_{Tmax5} = 0.0999 \cdot I_n^{(0.9625)}$	0.931	8.45
DPX (Legrand)			
exponential	$\Delta P_{DPX1} = 2.692e^{(0.0099 \cdot I_n)}$	0.664	19.54
linear	$\Delta P_{DPX2} = 0.0924 \cdot I_n + 0.4753$	0,964	12.34
logarithmic	$\Delta P_{DPX3} = 7.16 \cdot \ln(I_n) - 20.82$	0.826	43.70
polynomial	$\Delta P_{DPX4} = -5 \cdot 10^{(-5)} \cdot I_n^2 + 0.1044 \cdot I_n + 0.0142$	0.966	13.53
power function	$\Delta P_{DPX5} = 0.1949 \cdot I_n^{(0.8492)}$	0.948	15.37

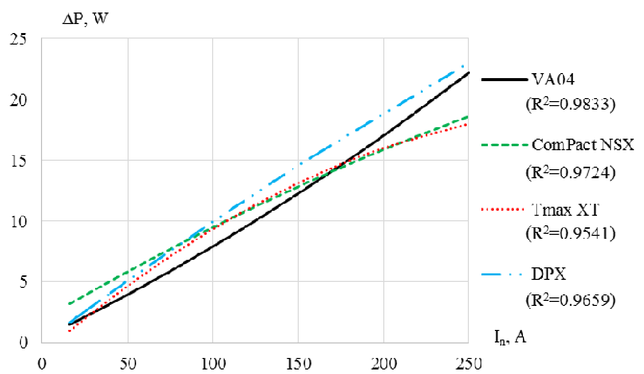

Fig.4. Graphs of approximating functions of active power losses for circuit breakers

The next step was to study the technical characteristics of the magnetic starters of the PML (KEAZ), KMI (IEK), EasyPact TVS (Schneider Electric), ABB A (ABB), CTX (Legrand) brands, the results are presented in Table III.

TABLE III. APPROXIMATION FUNCTIONS OF POWER LOSSES FOR MAGNETIC STARTERS OF VARIOUS MANUFACTURERS

Approximation function		**R^2**	**Ā, %**
PML (KEAZ); KMI (IEK); EasyPact TVS (Schneider Electric)			
exponential	$\Delta P_{PML1} = 0.3607e^{(0.0363 \cdot I_n)}$	0.504	46.08
linear	$\Delta P_{PML2} = 0.0773 \cdot I_n - 0.5701$	0.984	9.26
logarithmic	$\Delta P_{PML3} = 2.697 \cdot \ln(I_n) - 6.7099$	0.881	78.93
polynomial	$\Delta P_{PML4} = 9 \cdot 10^{(-5)} \cdot I_n^2 + 0.068 I_n - 0.412$	0.985	7.23
power function	$\Delta P_{PML5} = 0.0101 \cdot I_n^{(1.4646)}$	0.948	13.87
ABB A (ABB)			
exponential	$\Delta P_{ABB1} = 0.853e^{(0.0272 \cdot I_n)}$	0.67	22.58
linear	$\Delta P_{ABB2} = 0.0877 \cdot I_n - 0.1078$	0.964	11.94
logarithmic	$\Delta P_{ABB3} = 3.1114 \cdot \ln(I_n) - 7.2501$	0.89	41.45
polynomial	$\Delta P_{ABB4} = -3 \cdot 10^{(-4)} \cdot I_n^2 + 0.121 I_n - 0.666$	0.972	17.5
power function	$\Delta P_{ABB5} = 0.0703 \cdot I_n^{(1.0452)}$	0.962	11
CTX (Legrand)			
exponential	$\Delta P_{CTX1} = 0.2751e^{(0.0377 \cdot I_n)}$	0.794	29.36
linear	$\Delta P_{CTX2} = 0.0762 \cdot I_n - 0.9405$	0.957	52
logarithmic	$\Delta P_{CTX3} = 2.5181 \cdot \ln(I_n) - 6.5$	0.768	114
polynomial	$\Delta P_{CTX4} = 6 \cdot 10^{(-4)} \cdot I_n^2 + 0.013 \cdot I_n + 0.12$	0.992	12.48
power function	$\Delta P_{CTX5} = 0.0088 \cdot I_n^{(1.4428)}$	0.98	11.45

TABLE IV. APPROXIMATION FUNCTIONS OF POWER LOSSES FOR CONTACTORS OF VARIOUS MANUFACTURERS

Approximation function		**R^2**	**Ā, %**
PML (KEAZ); KTI (IEK); EasyPact TVS (Schneider Electric)			
exponential	$\Delta P_{PML6} = 5.5e^{(0.0042 I_n)}$	0.406	28.03
linear	$\Delta P_{PML7} = 0.0922 \cdot I_n - 2.9528$	0.929	15.05
logarithmic	$\Delta P_{PML8} = 27.167 \cdot \ln(I_n) - 126.6$	0.939	25
polynomial	$\Delta P_{PML9} = -1 \cdot 10^{(-4)} \cdot I_n^2 + 0.1799 I_n - 15.52$	0.972	14.8
power function	$\Delta P_{PML10} = 0.0105 \cdot I_n^{(1.3517)}$	0.843	11.1
ABB A (ABB)			
exponential	$\Delta P_{ABB6} = 6.2703e^{(0.0045 \cdot I_n)}$	0.828	17.82
linear	$\Delta P_{ABB7} = 0.0969 \cdot I_n - 1.604$	0.967	8.02
logarithmic	$\Delta P_{ABB8} = 24.528 \cdot \ln(I_n) - 110.13$	0.979	7.66
polynomial	$\Delta P_{ABB9} = -1 \cdot 10^{(-4)} \cdot I_n^2 + 0.178 \cdot I_n - 10.411$	0.984	4.7
power function	$\Delta P_{ABB10} = 0.0304 \cdot I_n^{(1.1926)}$	0.946	9.54
CTX (Legrand)			
exponential	$\Delta P_{CTX6} = 3.0389e^{(0.0068 \cdot I_n)}$	0.968	10.7
linear	$\Delta P_{CTX7} = 0.1003 \cdot I_n - 6.7492$	0.898	18.5
logarithmic	$\Delta P_{CTX8} = 18.56 \cdot \ln(I_n) - 84.04$	0.787	25.92
polynomial	$\Delta P_{CTX9} = 5 \cdot 10^{(-4)} \cdot I_n^2 + 0.1204 I_n + 14.614$	0.988	6.2
power function	$\Delta P_{CTX10} = 0.0137 \cdot I_n^{(1.2911)}$	0.889	16.34

The approximating functions of the studied magnetic starters with the highest determination coefficients are shown in Fig. 5.

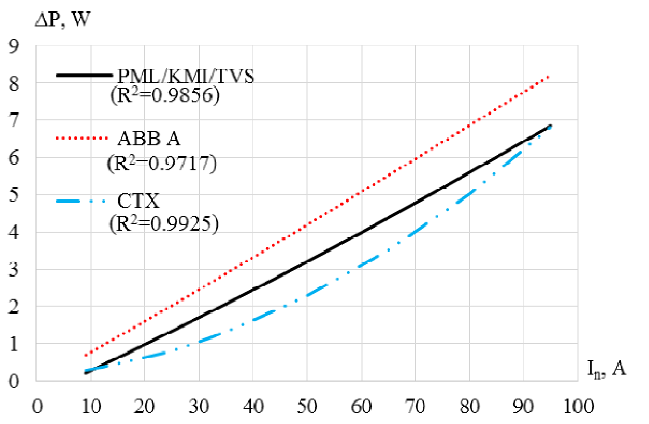

Fig.5. Graphs of approximating functions of active power losses for magnetic starters

Table IV shows the approximating power loss functions for the studied contactors of the brands PML (KEAZ), KTI (IEK), EasyPact TVS (Schneider Electric), ABB A (ABB), CTX (Legrand).

The research results (Tables III and IV) show that the dependences of power losses on the rated current of magnetic starters and contactors are most accurately described by polynomial expressions, and the least reliable are exponential and logarithmic functions. The approximating functions of the investigated contactors with the highest determination coefficients are shown in Fig. 6.

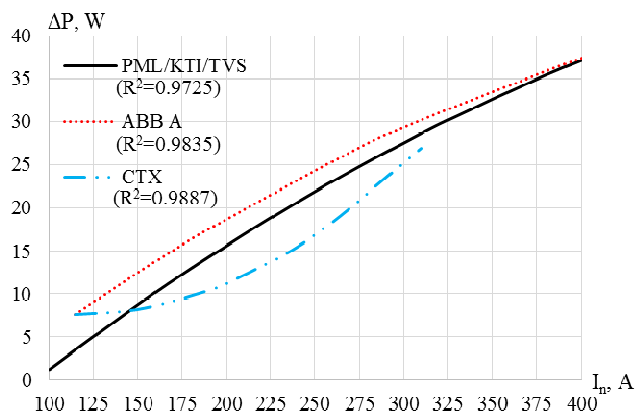

Fig.6. Graphs of approximating functions of active power losses for contactors

IV. CONCLUSION

In the presented article, a study was made of the dependences of the value of active power losses in automatic switches, magnetic starters, and contactors on the main parameters of the equipment. Comparative analysis of the technical characteristics of circuit breakers VA04, ComPact NSX, DPX, Tmax XT showed that there are differences in the values of active power losses per device pole. Active power losses in contact systems of magnetic starters and contactors of PML, KMI/KTI and EasyPact TVS brands are the same.

For the investigated circuit breakers of low-voltage equipment manufacturers - KEAZ, Schneider Electric, Legrand and ABB, in accordance with the catalog data, functional dependences of active losses in the contact systems of devices on the rated current have been developed. Similar dependencies have been developed for magnetic starters and contactors from KEAZ, IEK, Schneider Electric, Legrand and ABB. Dependences of power losses change in contacts and contact systems of automatic switches, magnetic starters and contactors on the rated current are modeled - approximating functions with the largest determination coefficients and the smallest approximation errors. The developed models can be recommended to clarify the magnitude of electricity losses in intra-workshop power supply systems.

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References

[1] E.I. Gracheva, O.V. Naumov, A.N. Gorlov, Modelling Characteristics of Reliability Low-Voltage Switching Devices on the Basis of Random Checks on the Example of Contactors, Proceedings – 2019 1st International Conference on Control Systems, Mathematical Modelling, Automation and Energy Efficiency, SUMMA 2019, 8947595, 641- 643 (2019).

[2] E. I. Gracheva, O. V. Naumov and A. N. Gorlov, "Simulation of Laws Change in Technical Characteristics of Circuit Breakers of Various Manufacturers," 2021 International Conference on Electrotechnical Complexes and Systems (ICOECS), 2021, pp. 404-406, doi: 10.1109/ICOECS52783.2021.9657222.

[3] Petrov, T.I. Theoretical aspects of optimization synchronous machine rotors / T.I. Petrov, A.R. Safin // E3S Web of Conferences. – 2020. – Vol. 178. – paper No 01049.

[4] Y.I. Soluyanov, A.I. Fedotov, A.R. Akhmetshin and V.I. Soluyanov, Application of intelligent electricity metering systems for timely adjustment of standard values for electrical loads calculation, in 3rd 2021 International Youth Conference on Radio Electronics, Electrical and Power Engineering, 2021, art. no. 9388018, doi: 10.1109/REEPE51337.2021.9388018.

[5] Y.I. Soluyanov, A.I. Fedotov, D.Y. Soluyanov and A.R. Akhmetshin, Experimental research of electrical loads in residential and public buildings, IOP Conference Series: Materials Science and Engineering, vol. 860, art. no. 012026, 2020, DOI: 10.1088/1757-899X/860/1/012026.

[6] Gibadullin, R.F., Lekomtsev, D.V. & Perukhin, M.Y. Analysis of Industrial Network Parameters Using Neural Network Processing. Sci. Tech. Inf. Proc. 48, 446–451 (2021). https://doi.org/10.3103/S0147688221060046

[7] Z. Gizatullin and M. Nuriev, "Modeling the Electromagnetic Compatibility of Electronic Means under the Influence of Interference Through the Power Supply Network," 2022 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), 2022, pp. 321-326, doi: 10.1109/ICIEAM54945.2022.9787186.

[8] Semenov, A., Yakushev, I., Kharitonov, Y., Shevchuk, V., Gracheva, E., Ilyashenko, S. Calculation of Load Diagrams and Static Characteristics of Multimotor Electric Drive Systems using the Methods of Equivalent Forces and Reduced Moments International Journal of Technology Volume 11, Issue 8, 2020, Pages 1537-1546, DOI: 10.14716/ijtech.v11i8.4541

[9] B. Hnatiuc, M. Borta and M. Hnatiuc, "Switching Transient Regime of Shunts Release from a Low Voltage Circuit Breaker Commanded by a PLC," 2019 International Conference on Electromechanical and Energy Systems (SIELMEN), 2019, pp. 1-6, doi: 10.1109/SIELMEN.2019.8905865.

[10] Gracheva, E.I., Naumov, O.V. Evaluation criteria of contact group technical state concerning electrical appliances(Article) / International Journal of Pharmacy and Technology, Volume 8, Issue 4, December 2016, Pages 26763-26770, DOI: 10.1051/e3sconf/201912402013

[11] Feizifar B., Usta Ö. A new failure protection algorithm for circuit breakers using the power loss of switching arc incidents // Turkish Journal of Electrical Engineering and Computer Sciences. 2019. 27(3), P. 1982–1997. DOI: 10.3906/elk-1805-84.

[12] Lei C., Tian W., Zhang Y., Fu R. [et al.]. Probability-based circuit breaker modeling for power system fault analysis // IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 2017. P. 979–984. DOI: 10.1109/apec.2017.7930815.

[13] E.I. Gracheva, O.V. Naumov, A.N. Gorlov, 2019. Influence of Value Resistance Contact Units of Switching Devices on Losses of the Electric Power in Shop Networks of Low Tension. IOP Conference Series: Materials Science and Engineering, Volume 643(1), pp. 1–6

[14] Z.M. Gizatullin, R.M. Gizatullin, M.G. Nuriev Methodology and Models for Physical Simulation of Electromagnetic Interference on the Example of the Interference-Resistance Analysis of Vehicle Electronic Devices // Journal of Communications Technology and Electronics. – 2021. – Vol. 66. – No 6. – P. 722-726. DOI 10.1134/S1064226921060103.

[15] S.A. Nazarychev, A.R. Akhmetshin and S.O. Gaponenko “Full compensation of reactive power in electric networks 0.4-10kV,” Journal of Physics: Conference Series, 2019 vol. 1588, iss. 117, art.no. 012036 doi: 10.1088/1742-6596/1588/1/012036.

[16] G. Li, W. Chai, P. Lv and H. Dong, "Research on start criterion of automatic reclosing of low voltage circuit breaker based on wavelet packet and neural network," 2021 IEEE 4th International Electrical and Energy Conference (CIEEC), 2021, pp. 1-6, doi: 10.1109/CIEEC50170.2021.9510300