Study of Probability Characteristics of the Reliability of Electrical Equipment in Internal Power Supply Systems

Elena Gracheva
Department of Power Supply of Industrial Enterprises
Kazan State Power Engineering University
Kazan, Russia
grachieva.i@bk.ru

Renata Maratovna Petrova
Department of Power Supply of Industrial Enterprises
Kazan State Power Engineering University
Kazan, Russia
1998renata@mail.ru

Stanimir Valtchev
UNINOVA–CTS,
Faculty of Sciences and Technology
University NOVA of Lisbon
Campus Caparica, Portugal
ssv@fct.unl.pt

Tatyana Sinyukova
Department of electric drive
Lipetsk State Technical University
Lipetsk 398055, Russian Federation
stw0411@mail.ru

2023 5th Global Power, Energy and Communication Conference (GPECOM) | 979-8-3503-0198-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/GPECOM58364.2023.10175821

***Abstract* – Industrial power supply facilities have in their composition technological cycles of varying degrees of complexity and the corresponding electrical equipment of intrashop power supply systems. The aim of the study: to determine laws of change in probabilistic reliability characteristics of low-voltage electrical equipment, namely circuit breakers, magnetic starters, contactors and power transformers on the basis of statistical data on operation. To determine the laws of changes in reliability parameters of electrical equipment of power supply systems, we conduct a study of theoretical and statistical functions of the probability of no-failure operation and the probability of failure for each type of the investigated electrical equipment. The normal law of distribution was adopted for the study. The conformity of probability characteristics of electrical equipment to the normal distribution law was checked using Kolmogorov and Pearson criteria.**

Keywords – power supply system, reliability parameters, power transformer, automatic switch, magnetic starter, contactor, probabilistic characteristics.

I. Introduction

In modern conditions of power industry development special attention is paid to improvement of reliability of intrinsic power supply systems. Below is an analysis of some [1-16] of the scientific papers by scientists conducting research in this area.

In the research E.Yu. Abdullazianov, E.I. Gracheva, A.N. Gorlov, Z.M. Shakurova, T.V. Tabachnikova, R.R. Gibadullin [1] have developed an algorithm for evaluating the efficiency of low-voltage equipment operation, which allows specifying the value of losses in low-voltage shop networks. Recommendations for increasing the reliability of calculating power losses are given.

Abramkin R.V. [2] developed a model which allows for assessing the reliability of a node operation under failure conditions of power supply system elements.

Ataev Z.A. [3] investigated the problems of reliability of power supply of some objects in the Crimea. P.V. Afanasyev, A.G. Ivakhnenko [4] proposed an algorithm for the verification of test methods in the laboratory, allowing experimental studies of the characteristics of low-voltage equipment. The tests carried out allow to adapt recommendations on verification procedure implementation for laboratories with comparable test methods.

The authors Vinogradov A.V., Bolshev V.E., Vinogradova A.V., Borodin M.V., Boukreev A.V. [6] proposed an algorithm for implementing the means of monitoring the reliability of electrical equipment of power supply systems, which allows to stimulate an increase in the operating efficiency of power supply systems as a whole.

In their work Gracheva E. I., Gizzatullina E. E. [7] used the experiment planning theory to form models to calculate the reliability indicators of shop-floor networks, taking into account operating conditions.

Gracheva E.I., Gorlov A.N., Alimova A.N. [8] investigated the main characteristics of the topology of intrashop power supply circuits and technical condition of low-voltage equipment under their operating conditions. The authors conducted a comparative analysis of the technical characteristics of circuit breakers.

The authors Gracheva E.I., Naumov O.V., Sadykov R.R., Serpionova T.A. [9] propose the development of models of the main functional parameters of the systems of intrafactory power supply, where different types of configuration of the workshop network are investigated and the law of distribution of probability characteristics of electrical equipment is revealed.

In their work, Ivshin I.V., Galyautdinova A.R. et al. [11] proposed an intelligent system for assessing the technical condition of a 35/6(10) kV transformer substation, with which real-time monitoring of the state of reliability parameters and assessment of the technical condition of equipment is possible. In the work of Kotelenko S.V. [12] presents a program of intellectualization of low-voltage equipment of distribution networks.

The scientists Lukovenko A.S., Zenkov I.V. [13] described the power supply system reliability indicators using an artificial neural network model. For the proposed development, the algorithm for calculating the reliability indicators of power supply systems, the method of power supply system failure rate and forecasting model were used.

Makasheva S.I., Pinchukov P.S. in their paper [14] considered the issues of increasing reliability of digital substations of the Russian Federation. They made a numerical estimation of the probability of failure-free operation of the main equipment, taking into account the basic provisions of the reliability theory. Nodes of the digital substation with low reliability indices were identified and recommendations for

979-8-3503-0198-4/23/$31.00 ©2023 IEEE

maintaining the required level of reliability of power supply to consumers were given.

Semenov D.A. [15] in his study proposes various ways of increasing the reliability of transformers in distribution networks, and the author also analyzed the causes of reducing their service life.

The article by Fedotov A.I., Gracheva E.I., Naumov O.V. [16] presents the basic methods of investigating the reliability of low-voltage electrical apparatuses and the results of the analysis of characteristics that determine their performance.

As experience shows, new approaches to assessment of reliability of electrical equipment elements and intra-workshop power supply systems are required at present [17-23]. In modern conditions of development of electrical complexes, when equipment breaks down, it is easier for large production enterprises to replace the equipment with new one, instead of taking it out for overhaul and prolonging its service life. On the other hand, there is an opportunity to improve the accuracy of forecast estimates of the technical condition of equipment and implementation of necessary measures to ensure the necessary efficiency of power supply systems functioning.

Scientific and practical significance of the offered article is improvement of methods of determination of reliability parameters of low-voltage electrical equipment according to statistical operational data and correlation of results of conducted researches with passport data, and also revealing of laws of distribution of probability characteristics of elements of intra-workshop power supply systems.

The difference of the presented work from the results of studies conducted by Russian and foreign scientists consists in the study of probabilistic parameters of low-voltage electrical equipment taking into account operating modes according to the operating data of enterprises.

II. MATERIALS AND METHODS

To predict the reliability of electrical equipment of low-voltage networks it is proposed to use the comparison of statistical and theoretical values of the probability distribution function of no-failure operation and the appearance of failure.

Statistical data of failures of electrical equipment installed in the systems of internal power supply of industrial facilities of a number of enterprises:

- circuit breaker 0.4 kV;
- magnetic starter 0.4 kV;
- contactor 0.4 kV;
- transformer 1600/10/0.4 kV.

Assuming that the probability characteristics of the equipment under study obey the normal distribution law, then the probabilities of no-failure operation and occurrence of failure are calculated by the formulas:

$$P(t) = \frac{F\left(\frac{T_{mean} - t}{\sigma}\right)}{F\left(\frac{T_{mean}}{\sigma}\right)} \tag{1}$$

$$Q(t) = \frac{\int_0^t e^{-\frac{(t - T_{mean})^2}{2\sigma^2}} dt}{\sqrt{2\pi} \cdot \sigma} \tag{2}$$

where t – is the observation time, year;
T_{mean} – average MTBF, year;
σ – RMS deviation of MTBF, year;
F – Laplace function.
The empirical function of the probability of no-failure operation has the form:

$$P^*(t_i) = \frac{N_0 - n_i(t)}{N_0} \tag{3}$$

where $n_i(t)$ – the total number of failed elements, pcs;
N_0 – number of considered elements, pcs.

The empirical function of the probability of failure is written in the form:

$$Q^*(t_i) = \frac{n_i(t)}{N_0} \tag{4}$$

$$Q^*(t_i) = 1 - P^*(t_i) \tag{5}$$

For a circuit breaker, the observation time is assumed to be t=15 years, the number of failed elements during this interval – 217, the number of elements in question – 283. The empirical value of the distribution function of the probability of failure-free operation and the appearance of failure in time:

$$P^*(t = 1...4) = \frac{283 - 0}{283} = 1{,}000$$

$$Q^*(t = 1...4) = \frac{0}{283} = 0{,}000$$

$$P^*(t = 5{,}6) = \frac{283 - 1}{283} = 0{,}996$$

$$Q^*(t = 5{,}6) = \frac{1}{283} = 0{,}004$$

$$P^*(t = 7) = \frac{283 - 2}{283} = 0{,}993$$

$$Q^*(t = 7) = \frac{2}{283} = 0{,}007$$

$$P^*(t = 8) = \frac{283 - 5}{283} = 0{,}982$$

$$Q^*(t = 8) = \frac{5}{283} = 0{,}018$$

$$P^*(t = 9) = \frac{283 - 10}{283} = 0{,}965$$

$$Q^*(t = 9) = \frac{10}{283} = 0{,}035$$

The calculation results are shown in Table I.

TABLE I. STATISTICAL DATA OF THE DISTRIBUTION FUNCTION OF PROBABILITIES OF NO-FAILURE OPERATION AND OCCURRENCE OF FAILURE FOR THE CIRCUIT BREAKER BY YEARS

Time of observation, t_i, year	Number of elements			Empirical value of the probability distribution function	
	failures per year, n_i	total number of failures, $n_i(t)$	serviceable, I_i	no-failure operation in time P(t)	occurrence of failure Q(t)
				$P^*(t_i)=\frac{N_0-n_i(t)}{N_0}$	$Q^*(t_i)=1-P^*(t_i)$
1	0	0	283	1,000	0,000
2	0	0	283	1,000	0,000
3	0	0	283	1,000	0,000
4	0	0	283	1,000	0,000
5	1	1	282	0,996	0,004
6	0	1	282	0,996	0,004
7	1	2	281	0,993	0,007
8	3	5	278	0,982	0,018
9	5	10	273	0,965	0,035
10	13	23	260	0,919	0,081
11	24	47	236	0,834	0,166
12	40	87	196	0,693	0,307
13	49	136	147	0,519	0,481
14	43	179	104	0,367	0,633
15	38	217	66	0,233	0,767

Based on the statistical information about the failed elements, determine the average MTBF [8]:

$$\overline{T}_{mean} = \frac{\sum_{i=1}^{N_0} t_i}{N_0} \quad (6)$$

where N_0 – is the number of elements in question, pcs.

Having information about the number of failed circuit breakers n_i at each i-th time interval $\overline{T}_{mean}$ before the first failure is defined [10-12]:

$$\overline{T}_{mean} = \frac{\sum_{i=1}^{N_0} n_i \cdot t_{mean\,i}}{N_0} \quad (7)$$

$$t_{mean_i} = \frac{t_{i-1}+t_i}{2} \quad (8)$$

where t_{i-1} – time moment of the beginning of the i-th time interval;

t_i – time moment of the end of the i-th time interval.

Excluding the first six years of testing, where the number of failed elements per year is close to 0, we determine the value of the standard deviation of the time of no-failure operation [14]:

$$\sigma = \sum_{i=1}^{n} \frac{\sqrt{(t_i - T_{mean})^2}}{t} \quad (9)$$

For the circuit breaker:

$$\overline{T}_{mean} = \frac{\sum_{i=1}^{N_0} n_i \cdot t_{mean\,i}}{N_0} =$$

$$= \frac{7\cdot 1 + 8\cdot 3 + 9\cdot 5 + 10\cdot 13 + 11\cdot 24 + 12\cdot 40 + 13\cdot 49 + 14\cdot 43 + 15\cdot 38}{217} =$$

$$= \frac{2759}{217} = 12{,}7$$

$$\sigma = \sum_{i=1}^{n} \frac{\sqrt{(t_i - T_{mean})^2}}{t} =$$

$$= \sum_{i=7}^{15} \frac{\sqrt{(7-12{,}7)^2}}{7} + \frac{\sqrt{(8-12{,}7)^2}}{8} + \frac{\sqrt{(9-12{,}7)^2}}{9} +$$

$$+ \frac{\sqrt{(10-12{,}7)^2}}{10} + \frac{\sqrt{(11-12{,}7)^2}}{11} + \frac{\sqrt{(12-12{,}7)^2}}{12} +$$

$$+ \frac{\sqrt{(13-12{,}7)^2}}{13} + \frac{\sqrt{(14-12{,}7)^2}}{14} + \frac{\sqrt{(15-12{,}7)^2}}{15} = 2{,}5$$

Thus, σ = 2.5 years; T_{mean} = 13 years.

The theoretical function of the probability of no-failure operation has the form:

$$P(t) = \frac{F\left(\frac{T_{mean} - t}{\sigma}\right)}{F\left(\frac{T_{mean}}{\sigma}\right)} \quad (10)$$

$$Q(t) = 1 - P(t) \quad (11)$$

For the circuit breaker:

$$P^*(t=1) = \frac{F(4{,}8)}{F(5{,}2)} = \frac{1{,}000}{1{,}000} = 1{,}000$$

$$Q^*(t=1) = 0{,}000$$

$$P^*(t=5) = \frac{F(3{,}2)}{F(5{,}2)} = \frac{0{,}999}{1{,}000} = 0{,}999$$

$$Q^*(t=5) = 1 - 0{,}999 = 0{,}001$$

$$P^*(t=7) = \frac{283-2}{283} = 0{,}993$$

$$Q^*(t=7) = \frac{2}{283} = 0{,}007$$

$$P^*(t=8) = \frac{283-5}{283} = 0{,}982$$

$$Q^*(t=8) = \frac{5}{283} = 0{,}018$$

$$P^*(t=9) = \frac{283-10}{283} = 0{,}965$$

$$Q^*(t=9) = \frac{10}{283} = 0{,}035$$

The results of the calculation are presented in Table II. The results of determining the reliability parameters of low-voltage electrical equipment are shown in Table III

TABLE II. THEORETICAL DATA OF THE DISTRIBUTION FUNCTION OF PROBABILITY OF NO-FAILURE OPERATION AND OCCURRENCE OF FAILURE FOR CIRCUIT BREAKERS BY YEARS

Time of observation, t_i, years	Value $\frac{T_{mean}-t}{\sigma}$	Value of the function $F(\frac{T_{mean}-t}{\sigma})$	Value of the theoretical distribution function: no-failure operation in time P(t) $P(t)=\frac{F(\frac{T_{mean}-t}{\sigma})}{F(\frac{T_{mean}}{\sigma})}$	Value of the theoretical distribution function: occurrence of failure Q(t) $Q(t)=1-P(t)$
1	4,8	1,000	1,000	0,000
2	4,4	1,000	1,000	0,000
3	4	1,000	1,000	0,000
4	3,6	1,000	1,000	0,000
5	3,2	0,999	0,999	0,001
6	2,8	0,997	0,997	0,003
7	2,4	0,992	0,992	0,008
8	2	0,977	0,977	0,023
9	1,6	0,945	0,945	0,055
10	1,2	0,885	0,885	0,115
11	0,8	0,788	0,788	0,212
12	0,4	0,655	0,655	0,345
13	0	0,500	0,500	0,500
14	-0,4	0,345	0,345	0,655
15	-0,8	0,212	0,212	0,788

Fig. 1 shows the graphs of the changes in statistical and theoretical functions of the probability of no-failure operation and the occurrence of failure over the observation period of 15 years for circuit breakers.

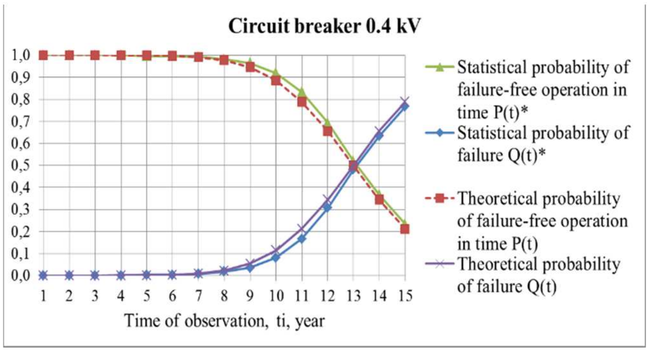

Fig.1. Statistical and theoretical probabilities of no-failure operation P and occurrence of failure Q in time t for circuit breaker by years

TABLE III. VALUES OF RELIABILITY PARAMETERS OF LOW-VOLTAGE ELECTRICAL EQUIPMENT

Name of electrical equipment	Number of failed elements n, pcs	The number of elements N_0, pcs.	Observation time t, year	Average MTBF, year	RMS deviation of MTBF, year
Circuit breaker 0.4 kV	217	283	15	13	2,5
Magnetic starter 0,4 kV	135	178	8	6	2,4
Contactor 0,4 kV	123	180	7	6	1,7
Transformer 1600/10/0,4 kV	87	129	25	22	1,5

I. RESULTS AND DISCUSSIONS

The conducted research and the data of Fig. 1 show that the probability of no-failure operation of the considered circuit-breakers remains not less than 0.8 for the time period of 11 years, which confirms the preservation of this parameter for the rated service life of the devices, equal to 10 years.

In Fig. 2-4, the graphs of probabilities of no-failure operation and occurrence of failure for the following type of electrical equipment are presented:

– magnetic starters 0.4 kV;
– contactors 0.4 kV;
– transformers 1600/10/0,4 kV.

For magnetic starters, the observation time is t=8 years, with the number of failed elements – 135, the number of observed – 178.

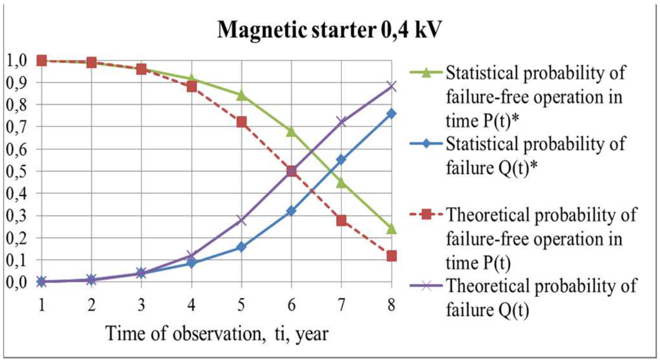

Fig.2. Statistical and theoretical probabilities of no-failure operation P and occurrence of failure Q in time t for magnetic starter by years

The results of studies of statistical data on failures of magnetic starters show that the required value of the probability of failure-free operation of the apparatus - not less than 0.85 is observed during the first 5 years of operation, and for contactors – during 4.5 years (Fig. 3), then this value decreases sharply. At the same time the certified service life of the investigated devices is equal to 15 years. The conducted research shows that under the observed actual modes of operation it is necessary to monitor the technical condition of magnetic starters, contactors and timely replacement of devices before the occurrence of failures.

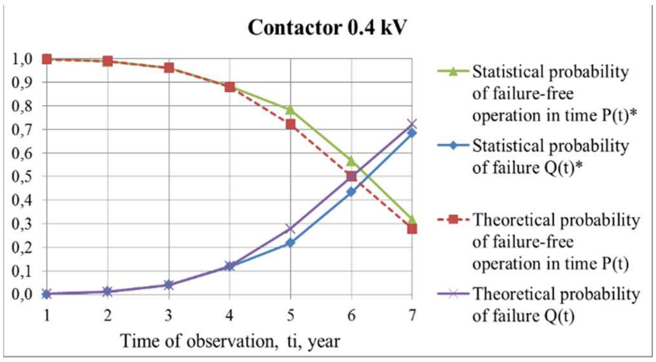

Fig.3. Statistical and theoretical probabilities of no-failure operation P and occurrence of failure Q in time t for contactor by years

For contactors the observation time is t=7 years, the number of failed apparatuses is 123, the number of monitored apparatuses is 180.

For the transformers 1600/10/0.4 kV, the observation time was t = 25 years, the number of failed – 87, the number of investigated transformers – 129.

For transformers, according to research results, the required value of probability of no-failure operation, equal to at least 0.96, is observed during the first 18 years, and the value of this parameter not lower than 0.8, is maintained during 21 years of operation at the rated service life, equal to 25 years. This type of electrical equipment, which is one of the most reliable electrical installations, is characterized, as a rule, by strict compliance with all conditions of maintenance and operation regulations.

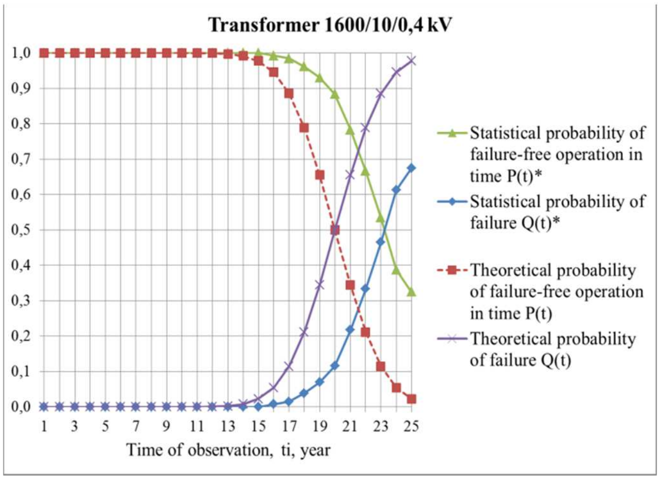

Fig.4. Statistical and theoretical probabilities of no-failure operation P and occurrence of failure Q in time t for transformer 1600/10/0,4 kV by years

II. Checking for Conformity with the Distribution Law

Checking for compliance with the chosen law of distribution will be carried out with the help of the Kolmogorov criterion [18, 20].

The Kolmogorov's criterion of agreement is designed to test the hypothesis that the sample belongs to a certain distribution law (in our case, the normal law), that is, to check that the empirical distribution corresponds to the assumed model.

The measure of difference between the theoretical and experimental values D_n is calculated as the maximum value of the modulus of difference between the statistical distribution function F*(x) and the selected theoretical distribution function F(x):

$$D_n = \max\left|F^*(x) - F(x)\right| \quad (12)$$

The value of a random variable is calculated using the formula:

$$y_n = D_n\sqrt{n} \quad (13)$$

where n – is the number of failed elements.

Table IV shows the values of the Kolmogorov criterion $P(y_n)$. Determine the probability of agreement $P(y_n)$ of the theoretical and empirical distributions from the tabulated data for the calculated y_n. From the values of the random variable y_n, determine the function $P(y_n)$ using linear interpolation. If $P(y_n) > 0.05$, the condition of agreement is satisfactory.

The divergence of the results and the random value of y for circuit breakers:

$$D_{1,2,3,4} = \max\left|0{,}000 - 0{,}000\right| = 0{,}000$$

$$y_{1,2,3} = 0{,}000 \cdot \sqrt{217} = 0{,}000$$

$$D_5 = \max\left|0{,}004 - 0{,}001\right| = 0{,}003$$

$$y_5 = 0{,}003 \cdot \sqrt{217} = 0{,}042$$

$$D_6 = \max\left|0{,}004 - 0{,}003\right| = 0{,}001$$

$$y_6 = 0{,}001 \cdot \sqrt{217} = 0{,}014$$

TABLE IV. Values of the Kolmogorov criterion

y_n	$P(y_n)$	y_n	$P(y_n)$	y_n	$P(y_n)$	y_n	$P(y_n)$
0,0	1,00000	**0,8**	05441	**1,6**	0,0120	**2,4**	0,000020
0,05	1,00000	**0,85**	0,4653	**1,65**	0,0086	**2,45**	0,000012
0,1	1,00000	**0,9**	0,3927	**1,7**	0,0062	**2,5**	0,0000075
0,15	1,00000	**0,95**	0,3275	**1,75**	0,0044	**2,55**	0,0000044
0,2	1,00000	**1,0**	0,2700	**1,8**	0,0031	**2,6**	0,0000026
0,25	1,00000	**1,05**	0,2202	**1,85**	0,0021	**2,65**	0,0000016
0,3	0,99999	**1,1**	0,1777	**1,9**	0,0015	**2,7**	0,0000010
0,35	0,9997	**1,15**	0,1420	**1,95**	0,0010	**2,75**	0,0000006
0,4	0,9972	**1,2**	0,1122	**2,0**	0,0007	**2,8**	0,0000003
0,45	0,9874	**1,25**	0,0879	**2,05**	0,0004	**2,85**	0,00000018
0,5	0,9639	**1,3**	0,0681	**2,1**	0,0003	**2,9**	0,00000010
0,55	0,9228	**1,35**	0,0522	**2,15**	0,0002	**2,95**	0,00000006
0,6	0,8643	**1,4**	0,0397	**2,2**	0,0001	**3,0**	0,00000003
0,65	0,7920	**1,45**	0,0298	**2,25**	0,0001		
0,7	0,7112	**1,5**	0,0222	**2,3**	0,0001		
0,75	0,6272	**1,55**	0,0164	**2,35**	0,000032		

Table V shows the results of testing the reliability parameters for circuit breakers by the Kolmogorov criterion.

TABLE V. Results of reliability parameter tests for circuit breakers according to Kolmogorov criterion

Time of observation, ti, year	Experimental calculation results	Theoretical calculation results	Divergence D_n	Random value $y_n = D_n\sqrt{n}$	Value of the function P(yn)
1	0,000	0,000	0,000	0,000	1,000
2	0,000	0,000	0,000	0,000	1,000
3	0,000	0,000	0,000	0,000	1,000
4	0,000	0,000	0,000	0,002	1,000
5	0,004	0,001	0,003	0,042	1,000
6	0,004	0,003	0,001	0,014	1,000
7	0,007	0,008	0,001	0,017	1,000
8	0,018	0,023	0,005	0,075	1,000
9	0,035	0,055	0,019	0,287	1,000
10	0,081	0,115	0,034	0,498	0,965
11	0,166	0,212	0,046	0,674	0,754
12	0,307	0,345	0,037	0,547	0,926
13	0,481	0,500	0,019	0,286	1,000
14	0,633	0,655	0,023	0,338	0,999
15	0,767	0,788	0,021	0,315	0,999

The data in Table IV show that the lowest value of the function $P(y_n) = P(0.674) = 0.754$. The remaining values of $P(y_n) > 0.926$, which is a satisfactory condition (> 0.8) for comparison of experimental and theoretical results. The results of calculations confirm the correctness of revealing the normal law of distribution of probability characteristics of the investigated electrical equipment of the systems of intra-workshop power supply.

Pearson's criterion (or the χ^2 criterion) is used to test the hypothesis that the theoretical and empirical distributions are consistent with a large sample size ($n \geq 100$). This method is not applicable for testing, since it is used for multivariate distributions.

CONCLUSION

As a result of the conducted research based on statistical data of operation parameters of electrical equipment reliability of intrinsic power supply systems of a number of enterprises:

1. Empirical and theoretical dependences of change in values of probability of no-failure operation P(t) and occurrence of failure Q(t) for low-voltage electrical equipment – circuit breakers, magnetic starters, contactors and power transformers have been determined. Comparison of the investigated indicators with the passport data has been carried out.

2. The normal law of distribution was chosen. Checked for compliance with the law of distribution using Kolmogorov criterion and Pearson's criterion.

ACKNOWLEDGEMENTS

The presentation of this work was partially funded by the FCT (Fundacao para a Ciencia e Tecnologia) through the program UIDB/00066/2020 and the Center of Technology and Systems (CTS/UNINOVA).

REFERENCES

[1] Abdullazyanov E.Y., Gracheva E.I., Gorlov A.N., Shakurova Z.M., Tabachnikova T.V., Shumikhina O.A., Gibadullin R.R. STUDying the Quality of Functioning of Low-Voltage Electric Apparatuses in the Structure of Electrical and Mechanical Complexes // Proceedings of Higher Education Institutions. Problems of Power Engineering. 2021. №6.

[2] Abramkin R.V. Model of Functioning of Telecommunication Node during Failures of Electric Power Supply System Elements // Proceedings of Tula State University. Technical Sciences. 2021. №12.

[3] Ataev Z.A. Reliability of Electricity Supply to Consumers in Crimea // Geopolitics and Eco-Geodynamics of Regions. 2022. №1.

[4] Afanasyev P.A., Ivakhnenko A.G. Verification of Testing Methods of Low Voltage Equipment // Proceedings of Tula State University. Technical Sciences. 2021. №12.

[5] Myshkina L.S. Reliability Factor in Distribution Grid Design // Izvestia Vuzov. Problems of power engineering. 2020. №6.

[6] Vinogradov AV, Bolshev VE, Vinogradova AV, Borodin MV, Boukreev AV Technical and economic ways to improve the efficiency of power supply systems of rural consumers // Bulletin of Agricultural Science of the Don. 2019. №47.

[7] Gracheva, E.I., Naumov, O.V., Gorlov, A.N. Modelling Characteristics of Reliability Low-Voltage Switching Devices on the Basis of Random Checks on the Example of Contactors / Proceedings of 1st International Conference on Control Systems, Mathematical Modelling, Automation and Energy Efficiency, SUMMA 2019, November 2019, No. 8947595, pp. 641-643, DOI: 10.1109/SUMMA48161.2019.8947595.

[8] Gracheva E.I., Gorlov A.N., Alimova A.N. Algorithms and Models of Power Loss on Automatic Off-Stops Settled in Industrial Networks // Vestnik MSTU. 2020. №4.

[9] Gracheva E.I., Naumov O.V., Sadykov R.R., Serpionova T.A. Modeling parameters of functional characteristics of workshop networks // Technical Sciences - from theory to practice. 2015. №12 (48).

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

[11] Ivshin I.V., Galyautdinova A.R., Vladimirov O.V., Nizamiev M.F., Karpov E.N., Melnik E.P. Intellectual System Assessment of Technical Status of Transmission Substation 35/6(10) KV // Proceedings of universities. Problems of Power Engineering. 2022. №2.

[12] Kotelenko S.V. Intellectual Solutions of Low Water Equipment of Distribution Networks // Proceedings of Tula State University. Technical Sciences. 2021. №12.

[13] Lukovenko A.S., Zenkov I.V. Reliability Calculation Methods of Electric Power Supply System // Bulletin of ISTU. 2021. №1 (156).

[14] Makasheva, S.I., Pinchukov, P.S. Calculation of the reliability indices of the digital substation // Bulletin of SUSU. Series: Power Engineering. 2019. №4.

[15] Semenov, A., Yakushev, I., Kharitonov, Y., Shevchuk, V., Gracheva, E., Ilyashenko, S. Calculation of Load Diagrams and Statistical 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

[16] Fedotov A.I., Gracheva E.I., Naumov O.V. Investigation of failure-free indicators of low-voltage switching devices of electric networks // Izvestiya vuzov. Problems of Power Engineering. 2013. №9-10.

[17] 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.

[18] S. Xiaoyan and X. Hangtian, "Analysis on influence factors of the reliability of electric power communication networks," 2016 IEEE International Conference on Electronic Information and Communication Technology (ICEICT), Harbin, China, 2016, pp. 49-52, doi: 10.1109/ICEICT.2016.7879650.

[19] 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), doi: 10.1109/ICIEAM54945.2022.9787186, 2022, pp. 321-326,

[20] Wadi, M., Elmasry, W., Kucuk, L, & Shahinzadeh, H. (2022, November). Sensitivity reliability analysis of power distribution networks using fuzzy logic. In 2022 12th International Conference on Computer and Knowledge Engineering (ICCKE) (pp. 190-195). IEEE.

[21] Ji, G., Sharma, D., Fei, W., Wu, D., & Jiang, J. N. (2019, June). A Graph-theoretic Method for Identification of Electric Power Distribution System Topology. In 2019 1st Global Power, Energy and Communication conference (GPECOM) (pp. 403-407). IEEE.

[22] Ma, Z., Broe, M., Fischer, A., Sørensen, T. B., Frederiksen, M. V., & Jøergensen, B. N. (2019, June), Ecosystem thinking: creating microgrid solutions for reliable power supply in India's power system. In 2019 1st Global Power, Energy and Communication Conference (GPECOM) (pp. 392-397). IEEE.

[23] Hosseini, S. J. A. D., Moradian, M., Shahinzadeh, H., & Ahmadi, S. (2018). Optimal placement of distributed generators with regard to reliability assessment using virus colony search algorithm. International Journal of Renewable Energy Research (IJRER), 8(2), 714-723 .