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Reliability Parameters of Low-Voltage Switchgear and Cable Lines of Workshop-Floor Network Schemes

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***Abstract*—The article analyzes the classification of the main electrical equipment of in-plant power supply schemes, namely, fuses, switches and packet switches. The laws of change of probabilistic characteristics of reliability of the studied devices, as well as cable lines on the basis of statistical data on operation are determined. To determine the laws of change of reliability parameters of electrical equipment of the systems of intra-floor power supply, the study of theoretical and statistical functions of probability of failure-free operation and probability of occurrence of failure of each type of investigated electrical equipment and cable lines has been carried out. The types of functions of change of the main reliability parameters have been determined and the corresponding graphical dependences have been presented. Comparison of the obtained results of the values of probability of failure-free operation with the requirements of GOST and passport values is carried out. The conformity of probabilistic characteristics of electrical equipment to the normal distribution law using Kolmogorov and Pearson criteria has been verified.**

Keywords—in-shop power supply system, reliability parameters of low-voltage switching devices, fuse, switch, packet switch, cable line, probabilistic characteristics, Kolmogorov criterion, Pearson criterion

I. Introduction

At present, with the development of new types of equipment [1-2, 20-21], it becomes expedient to develop and refine the existing algorithms for determining the probabilistic parameters of the equipment of on-site power supply systems. In modern conditions, as a rule, in case of failures of electrical installations, they are replaced rather than repaired [3].

At the same time, it is urgent to develop algorithms and models to increase the reliability of probabilistic estimates of reliability parameters of electrical installations and improve the quality of operation of on-site power supply [4, 13]. As it is known, the operation modes of electrical equipment also affect the reliability of shop-floor network schemes [5, 6].

The scientific novelty of the proposed article is the clarification of algorithms for assessing the reliability of operation of the equipment of in-plant power supply using operational data [7, 8, 14].

The practical significance of this article consists in the development of algorithms for the refined assessment of reliability characteristics of low-voltage electrical installations [15-17]. At the same time, the analysis of calculated and operational data of the studied information of functional parameters of operation and failure of the elements of equipment of shop networks [9-11] was carried out.

The developed classification of the main characteristics of fuses, breakers and packet switches is presented in (Fig. 1-3).

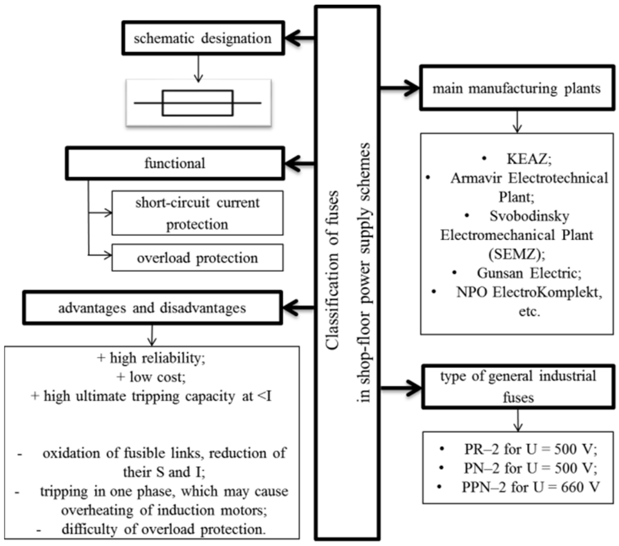

Fig 1. Classification of fuses in shop-floor power supply schemes

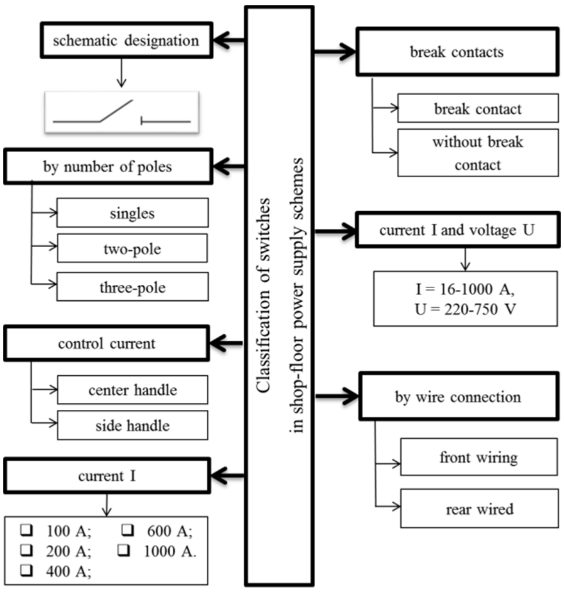

Fig 2. Classification of switches in shop-floor power supply schemes

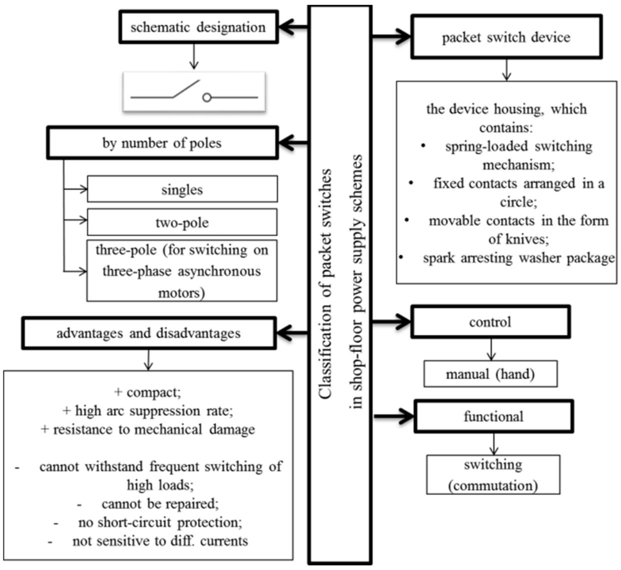

Fig 3. Classification of packet switches in shop-floor power supply schemes

Fig. 4 shows the schematic of the workshop network section with the installation of the investigated electrical equipment:

- fuses F_1-F_4;
- switches QS_1, QS_2;
- packet switches PS_1-PS_5;
- cable lines L_1-L_{11}.

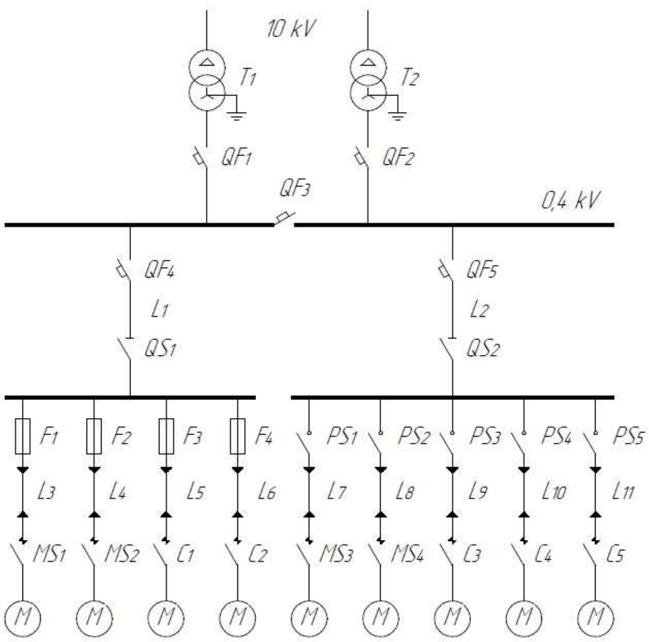

Fig 4. Schematic diagram of the workshop network section

II. Materials and Methods

For the study we will analyze the operational characteristics of low-voltage electrical installations:

- fuses PPN-33 (manufacturer "Korenevo Plant of low-voltage equipment", Kursk region, Korenevo settlement);
- switches RE19-41 ("Kursk Electrical Apparatus Plant" (KEAZ), Kursk);
- packet switches PV3-16 (EKF, Moscow);

and AVVG-0,4 kV cables (EXPERT-CABLE, Orel, Moscow, Yekaterinburg).

The value of probability of failure-free operation time – P(t) and the value of probability of failure occurrence time Q(t) [12]:

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

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

where t – the value of experimental study time, year;
T_{mean} – average MTBF, year;
σ – RMS deviation of MTBF, year;
F – Laplace function.

Experimental values of function values $P^*(t_i)$ и $Q^*(t_i)$:

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

$$Q^*(t_i) = 1 - P^*(t_i) = \frac{n_i(t)}{N_0} \tag{4}$$

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

For fuses PPN-33, I = 2-160 A, the value of the study time t = 16 years, the number of failed units of equipment – 190, the number of observed units of equipment – 281. Let's calculate $P_F^*(t_i)$ and $Q_F^*(t_i)$:

$$P_F^*(t = 1 \div 4) = \frac{281 - 0}{281} = 1{,}000$$

$$Q_F^*(t = 1 \div 4) = \frac{0}{281} = 0{,}000$$

$$P_F^*(t = 5) = \frac{281 - 1}{281} = 0{,}996$$

$$Q_F^*(t = 5) = \frac{1}{281} = 0{,}004$$

$$P_F^*(t = 6) = \frac{281 - 2}{281} = 0{,}993$$

$$Q_F^*(t = 6) = \frac{2}{281} = 0{,}007$$

$$P_F^*(t = 7) = \frac{281 - 4}{281} = 0{,}986$$

$$Q_F*(t=7)=\frac{4}{281}=0{,}014$$

$$P_F*(t=8)=\frac{281-7}{281}=0{,}975$$

$$Q_F*(t=8)=\frac{7}{281}=0{,}025$$

The calculation results are shown in Table I.

TABLE I. RESULTS OF RESEARCH OF PPN-33 FUSE PERFORMANCE FOR THE OBSERVATION INTERVAL = 16 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 $P_F*(t_i)$	occurrence of failure $Q_F*(t_i)$
				$P*(t_i)=\frac{N_0-n_i(t)}{N_0}$	$Q*(t_i)=1-P*(t_i)$
1	0	0	281	1,000	0,000
2	0	0	281	1,000	0,000
3	0	0	281	1,000	0,000
4	0	0	281	1,000	0,000
5	1	1	280	0,996	0,004
6	1	2	279	0,993	0,007
7	2	4	277	0,986	0,014
8	3	7	274	0,975	0,025
9	5	12	269	0,957	0,043
10	8	20	261	0,929	0,071
11	16	36	245	0,872	0,128
12	22	58	223	0,794	0,206
13	25	83	198	0,705	0,295
14	31	114	167	0,594	0,406
15	39	153	128	0,456	0,544
16	37	190	91	0,324	0,676

Then the mean time to failure [12]:

$$\overline{T}_{\text{mean}}=\frac{\sum_{i=1}^{N_0} t_i}{N_0}=\frac{\sum_{i=1}^{N_0} n_i\cdot t_{\text{mean}\,i}}{N_0} \qquad (6)$$

where N_0 – total number of all fuses tested, pcs;
n_i – is the number of failed fuses in the i-th interval.

$$t_{\text{mean}_i}=\frac{t_{i-1}+t_i}{2} \qquad (7)$$

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.

Without considering the first 6 years of observations (since the number of failed fuses for each year is approximately equal to zero), let us calculate the value of the standard deviation of the uptime parameter [12]:

$$\sigma=\sum_{i=1}^{n}\frac{\sqrt{(t_i-T_{\text{mean}})^2}}{t} \qquad (8)$$

For fuses PPN-33:

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

$$=\frac{7\cdot 2+8\cdot 3+9\cdot 5+10\cdot 8+11\cdot 16+12\cdot 22+13\cdot 25+14\cdot 31+15\cdot 39+16\cdot 37}{190}=$$

$$=\frac{2539}{190}=13{,}3$$

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

$$=\sum_{i=7}^{16}\frac{\sqrt{(7-13{,}3)^2}}{7}+\frac{\sqrt{(8-13{,}3)^2}}{8}+\frac{\sqrt{(9-13{,}3)^2}}{9}+$$

$$+\frac{\sqrt{(10-13{,}3)^2}}{10}+\frac{\sqrt{(11-13{,}3)^2}}{11}+\frac{\sqrt{(12-13{,}3)^2}}{12}+\frac{\sqrt{(13-13{,}3)^2}}{13}+$$

$$+\frac{\sqrt{(14-13{,}3)^2}}{14}+\frac{\sqrt{(15-13{,}3)^2}}{15}+\frac{\sqrt{(16-13{,}3)^2}}{16}=3{,}1$$

Thus, σ = 3 years; T_{mean} = 13 years.

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

$$P(t)=\frac{F(\frac{T_{\text{mean}}-t}{\sigma})}{F(\frac{T_{\text{mean}}}{\sigma})} \qquad (9)$$

$$Q(t)=1-P(t) \qquad (10)$$

Let us determine $P_F(t)$ and $Q_F(t)$ for PPN-33 fuses:

$$P_F(t=1)=\frac{F(5{,}4)}{F(5{,}769)}=\frac{1{,}000}{1{,}000}=1{,}000$$

$$Q_F(t=1)=0{,}000$$

$$P_F(t=5)=\frac{F(3{,}8)}{F(5{,}769)}=\frac{1{,}000}{1{,}000}=1{,}000$$

$$Q_F(t=5)=0{,}000$$

$$P_F(t=7)=\frac{F(3{,}1)}{F(5{,}769)}=\frac{0{,}999}{1{,}000}=0{,}999$$

$$Q_F(t=7)=1-0{,}999=0{,}001$$

$$P_F(t=8)=\frac{F(2{,}7)}{F(5{,}769)}=\frac{0{,}996}{1{,}000}=0{,}996$$

$$Q_F(t=8)=1-0{,}996=0{,}004$$

$$P_F(t=9)=\frac{F(2{,}3)}{F(5{,}769)}=\frac{0{,}989}{1{,}000}=0{,}989$$

$$Q_F(t=9)=1-0{,}989=0{,}011$$

The calculation data are shown in Table II.

TABLE II. RESULTS OF RELIABILITY CHARACTERISTIC ASSESSMENTS FOR PPN-33 FUSES

Time of observation, t_i, year	**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)	**occurrence of failure Q(t)**
			$P(t)=\frac{F(\frac{T_{mean}-t}{\sigma})}{F(\frac{T_{mean}}{\sigma})}$	$Q(t)=1-P(t)$
1	5,4	1,000	1,000	0,000
2	5,0	1,000	1,000	0,000
3	4,6	1,000	1,000	0,000
4	4,2	1,000	1,000	0,000
5	3,8	1,000	1,000	0,000
6	3,5	1,000	1,000	0,000
7	3,1	0,999	0,999	0,001
8	2,7	0,996	0,996	0,004
9	2,3	0,989	0,989	0,011
10	1,9	0,973	0,973	0,027
11	1,5	0,938	0,938	0,062
12	1,2	0,876	0,876	0,124
13	0,8	0,779	0,779	0,221
14	0,4	0,650	0,650	0,350
15	0,0	0,500	0,500	0,500
16	-0,4	0,350	0,350	0,650

Fig. 5 gives graphical dependences of change in time $P_F{*}(t_i)$, $Q_F{*}(t_i)$, $P_F(t)$ and $Q_F(t)$ for PPN-33 fuses.

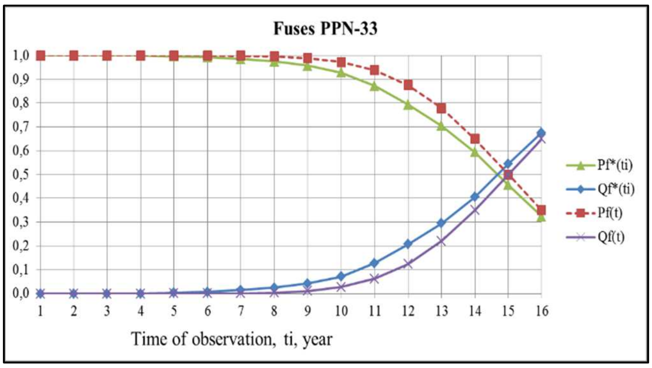

Fig 5. Graphical dependences of change in time $P_F{*}(t_i)$, $Q_F{*}(t_i)$, $P_F(t)$ and $Q_F(t)$ for PPN-33 fuses

III. RESULTS AND DISCUSSIONS

According to the data of experimental researches and GOST 17242-86, in the interval of the first eleven years of work of devices (at the passport service life equal to ten years) $P_F(t)$ of investigated fuses PPN-33 is estimated by the value, not less than 0.872, that shows preservation of standard parameters during the passport service life.

The results of the study of parameters of electrical equipment failures are presented in Table III.

TABLE III. RESULTS OF STUDIES OF ELECTRICAL EQUIPMENT FAILURE PARAMETERS

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**
Fuses PPN-33	190	281	16	13	3
Switches RE19-41	145	162	23	20	3,6
Packet switches PV3-16	117	205	21	18	2,6
Cables AVVG-0,4 kV	66	73	35	30	1,6

Figs. 6-8 shows the graphs of probabilities of uptime and failure occurrence for:

– RE19-41 circuit breakers with I up to 1000 A;
– packet switches PV3-16 with I = 16-100 A

and AVVG-0,4 kV cables with cross-section S=2,5-240 mm^2.

For RE19-41 circuit breakers the observation time interval is t=23 years, the number of inoperable devices for this interval is 145, the total number of observed devices is 162.

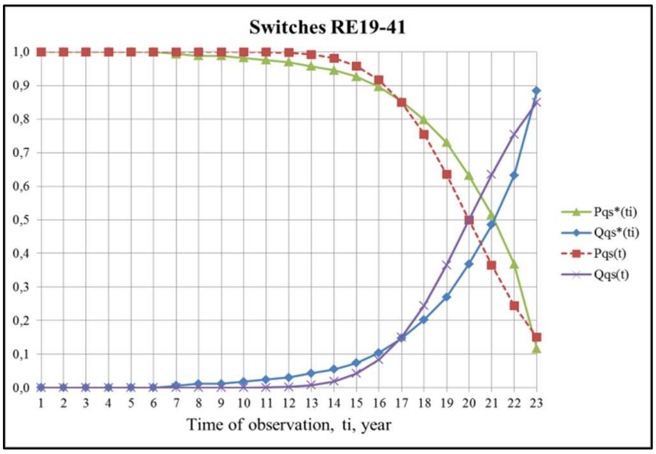

Fig 6. Graphical dependences of change in time of $P_{qs}{*}(t_i)$, $Q_{qs}{*}(t_i)$, $P_{qs}(t)$ and $Q_{qs}(t)$ for switches RE19-41

According to the data of experimental studies and GOST 12434-83 in the interval of the first fifteen years of operation (with the passport service life of devices, equal to ten years) $P_{qs}(t)$ of the studied switches RE19-41 is estimated by the value of not less than 0.975, which shows the preservation of normative parameters during the passport service life.

For packet switches PV3-16 the observation time interval amounted to t=21 years, the number of inoperable for this interval – 117, the total number of investigated – 205.

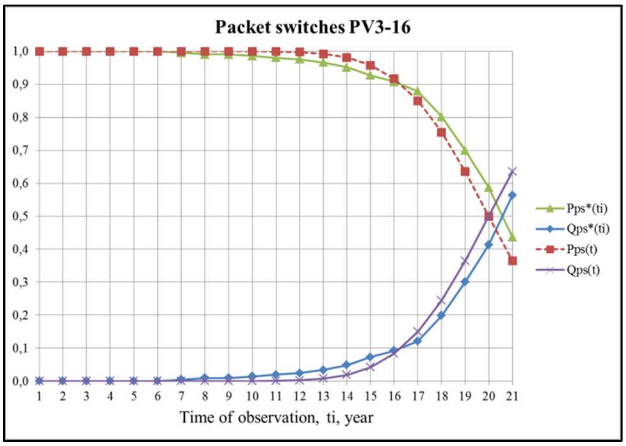

Fig 7. Graphical dependences of change in time of $P_{ps}*(t_i)$, $Q_{ps}*(t_i)$, $P_{ps}(t)$ and $Q_{ps}(t)$ for packet switches PV3-16

For packet switches, according to the results of research and according to GOST 12434-83 $P_{ps}(t)$ is estimated by the value equal to not less than 0.908, in the interval of the first sixteen years of operation (at the passport value of 0.8), which shows the preservation of this parameter to the permissible value for the passport period of operation in five years).

For cables AVVG-0,4 kV in the interval of research t=35 years the number of inoperable lines is 66 with their total number equal to 73.

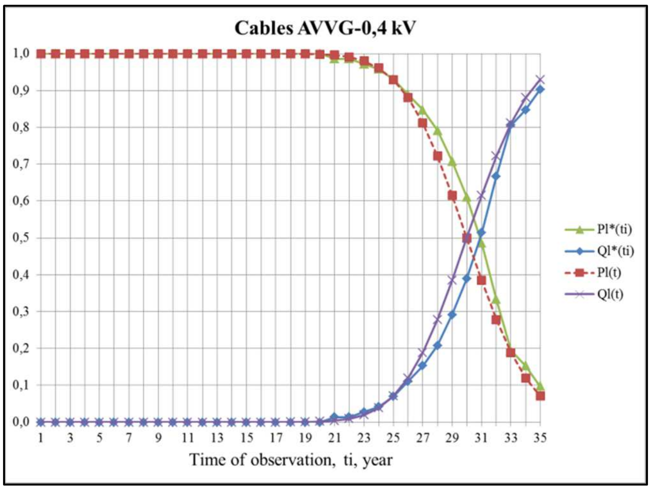

Fig 8. Graphical dependences of change in time of $P_l*(t_i)$, $Q_l*(t_i)$, $P_l(t)$ and $Q_l(t)$ for cables AVVG-0,4 kV

For cable lines AVVG-0,4 kV, according to results of researches, the required and given GOST-12434-83 $P_l(t)$ is estimated by the value, not less than 0.847 in an interval of the first 27 years of work (at the passport value of service life in 25 years), that shows conformity of the given parameter to the admissible value for a normative period of operation.

IV. Algorithms for Checking the Established Law of Distribution of the Investigated Parameters of Electrical Equipment

Using the Kolmogorov criterion, we calculate the discrepancy between theoretical and experimental data D_n:

$$D_n = \left| Q_F * (t_i) - Q_F(t) \right| \tag{11}$$

The random variable:

$$y_n = D_n \sqrt{n} = \left| Q_F * (t_i) - Q_F(t) \right| \cdot \sqrt{n} \tag{12}$$

where n – is the number of inoperable electrical installations for the period under study.

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.

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		

The discrepancy of results and random value $y_{1...16}$ for PPN-33 fuses:

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

$$y_{1,2,3,4} = 0{,}000 \cdot \sqrt{190} = 0{,}000$$

$$D_5 = \left| 0{,}004 - 0{,}000 \right| = 0{,}004$$

$$y_5 = 0{,}004 \cdot \sqrt{190} = 0{,}048$$

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

$$y_6 = 0{,}001 \cdot \sqrt{190} = 0{,}014$$

$$D_7 = \left| 0{,}007 - 0{,}000 \right| = 0{,}007$$

$$y_7 = 0{,}007 \cdot \sqrt{190} = 0{,}094$$

$$D8 = \left| 0{,}025 - 0{,}004 \right| = 0{,}021$$

$$y_8 = 0{,}021 \cdot \sqrt{190} = 0{,}294$$

Table V shows the results of verification of the probability function of time of occurrence of failures of PPN-33 fuses by the Kolmogorov criterion.

TABLE V. RESULTS OF TESTING THE PROBABILITY OF TIME OF OCCURRENCE OF FAILURES OF PPN-33 FUSES BY 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** $P(y_n)$
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	0,000	1,000
5	0,004	0,000	0,004	0,048	1,000
6	0,007	0,000	0,007	0,094	1,000
7	0,014	0,001	0,013	0,182	1,000
8	0,025	0,004	0,021	0,294	0,999
9	0,043	0,011	0,032	0,444	0,988
10	0,071	0,027	0,044	0,606	0,855
11	0,128	0,062	0,066	0,912	0,377
12	0,206	0,124	0,082	1,132	0,147
13	0,295	0,221	0,074	1,027	0,243
14	0,406	0,350	0,055	0,764	0,604
15	0,544	0,500	0,044	0,613	0,845
16	0,676	0,650	0,026	0,364	0,999

We exclude three values of the function for 11-13 years of observation, where $P(y_n)$ has minimal values, i.e., the discrepancy between experimental and theoretical calculation results >0.066. The results obtained (Table IV, Table V) show that the smallest acceptable value of the function $P(y_n) = P(0.764) = 0.604$. Other values are >0.845, which is a satisfactory condition (>0.8) in determining the type of distribution law of the studied random variables as a result of comparison of experimental and theoretical functions.

Pearson's criterion (or χ^2 criterion) [18] is used to test the hypothesis H that a random variable obeys the normal distribution law [19]. If $\chi^2 > \chi^2_{\text{table}}$, the hypothesis H is rejected, if $\chi^2 \le \chi^2_{\text{table}}$, the hypothesis is accepted.

When testing by Pearson's criterion (χ^2), we use the formula [18, 19]:

$$\chi^2 = \sum_{i=1}^{n} \frac{(Q_F{}^*(t_i) - Q_F(t))^2}{Q_F(t)} \tag{12}$$

where $Q_F{}^*(t_i)$ – experimental results of calculation;

$Q_F(t)$ – theoretical calculation results.

Excluding the first six values, where $Q_F(t) = 0$, obtain:

$$\chi^2 = \sum_{i=7}^{16} \frac{(0{,}014-0{,}001)^2}{0{,}001} + \frac{(0{,}025-0{,}004)^2}{0{,}004} + \frac{(0{,}043-0{,}011)^2}{0{,}011} + \frac{(0{,}071-0{,}027)^2}{0{,}027} + \frac{(0{,}128-0{,}062)^2}{0{,}062} + \frac{(0{,}206-0{,}124)^2}{0{,}124} + \frac{(0{,}295-0{,}221)^2}{0{,}221} + \frac{(0{,}406-0{,}350)^2}{0{,}350} + \frac{(0{,}544-0{,}500)^2}{0{,}500} + \frac{(0{,}676-0{,}650)^2}{0{,}650} = 0{,}628$$

The distribution χ^2 is determined by the number of degrees of freedom [19]:

$$s = n - z - 1 \tag{13}$$

where z – is the number of distribution parameters.

For fuses PPN-33: s = 10 – 2 – 1 = 7, where z = 2, two reliability parameters were calculated: time of failure-free operation and time of failure occurrence. Further, according to the reference table [19] we determine χ^2 table = 2.17 (for z = 2, probability 0,95).

$$\chi^2 \le \chi^2_{\text{table}}\ (0.628 \le 2.17)$$

When checked by Pearson's criterion $\chi^2 \le \chi^2_{\text{table}}$, therefore, the sample data of observations are reliable, conform to the normal law of distribution and agree with the actual data. There is no reason to reject hypothesis H about normality of distribution.

The normal law of distribution can be considered as correctly selected and optimal for calculations of probability of time of failure-free operation and probability of time of occurrence of failures of electrical equipment.

V. CONCLUSION

As a result shows the developed classification of the main low-voltage switching devices – fuses, breakers and packet switches. Regularities of change of values of:

1. $P_F{}^*(t_i)$, $Q_F{}^*(t_i)$, $P_F(t)$ and $Q_F(t)$ for fuses;
2. for switches RE19-41;
3. for packet switches PV3-16;
4. for cable lines AVVG-0,4 kV.

Thus the received data are recommended to use for adjustment of regulations of carrying out of current maintenance and capital repairs of electric installations.

It is established that reliability parameters of the investigated electrical equipment of shop networks under actual operating modes correspond to the passport service life.

The conducted check of the studied random variables has shown that theoretical and empirical functions of reliability parameters obey the normal distribution law.

According to Kolmogorov criterion: the acceptable value of the function $P(y_n) > 0.845$, which is a satisfactory condition (>0.8) when determining the type of distribution law of the studied random variables as a result of comparison of experimental and theoretical functions. According to

Pearson's criterion: $\chi^2 \leq \chi^2_{table}$ ($0.628 \leq 2.17$), therefore, there is no reason to reject the tested hypothesis of conformity to the normal law of distribution of parameters.

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