ABSTRACT

The third part of the article is a continuation of the previous part and examines the data of Soviet scientists on the dependence of the electrical strength of insulation of power transformers on time in historical development. Where possible, the scatter values of breakdown voltage and/or partial discharge initiation voltage have been extracted from the publications under consideration for data collection to optimize insulation design and possible future statistical coordination of the internal insulation of transformers. The article is intended for young transformer engineers and for teaching transformers to undergraduate and postgraduate students in universities.

KEYWORDS:

breakdown voltage, GOST, failure, EHV, insulation coordination, insulation testing, internal insulation, PD, power transformer, probability distribution, transformer oil, UHV, volt-time curve

Volt-time curves of oil-filled power transformer insulation

Survey of 100 years of research – Part III

7. Other works by Morozova's team

Of the dozens of papers by Morozova's team, we singled out only those that contained information of interest to us about the VTC and the scatter of experimental data.

7.1. Scatter of breakdown voltage gradients for different oil gap sizes

In [8], Morozova (Panov died three years before the article was published) gives two figures with experimental data on the effect on the dielectric strength of the width of the oil gap closest to the winding S. The experiments were carried out on models similar to Figs. 2 and 7a. The gap was formed using a piercing rail or gaskets resting on the cylinder. The gaskets were of three types. For each gap size and each type of formation, 9 to 14 experiments were carried out.

Fig. 14 shows curves with plotted experimental points of the dependence of the breakdown field intensity of 50 Hz on the gap width.

By extracting and processing the data from Fig. 14, we obtained the statistics shown in Table 2.

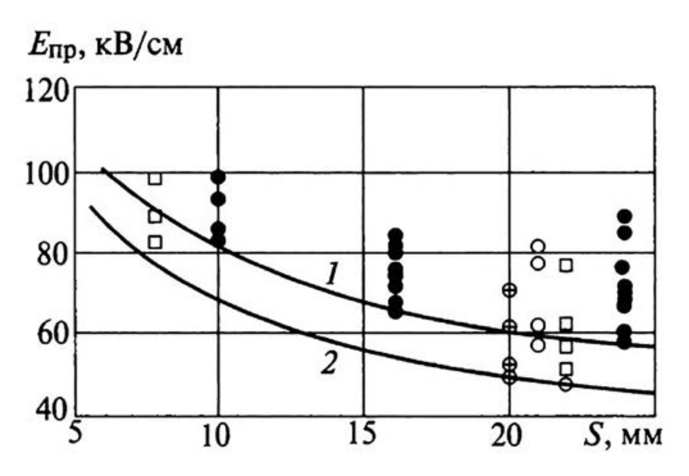


Figure 14. Dependence of the breakdown voltage gradient of the oil duct adjacent to the winding on its width (middle of winding). Alternating voltage, one-minute-long application

Table 2. The coefficients of variation of the breakdown gradient of the oil duct adjacent to the winding of 50 Hz

Oil duct width, mm	Number of points, N	Mean/kV	CV%
6	3	89.7	8.9
10	4	89.8	8.8
16	8	74.6	9.3
20	4	59.5	15.0
22	4	69.8	15.4
24	5	55.8	14.1
28	8	71.8	16.0

CV% is in the range of 3 - 10.4 and has a noticeable but weaker tendency to increase the scatter with an increasing channel compared to a voltage of 50 Hz

As follows from this table, CV% is in the range of 8.8 - 9.3 for 6-16 mm gaps and almost twice as much for large gaps (CV% = 15 - 16 for 20-28 mm gaps).

Fig. 15 shows curves with plotted experimental points of the dependence of the breakdown field intensity of impulse 1.5/40 µs on the gap width.

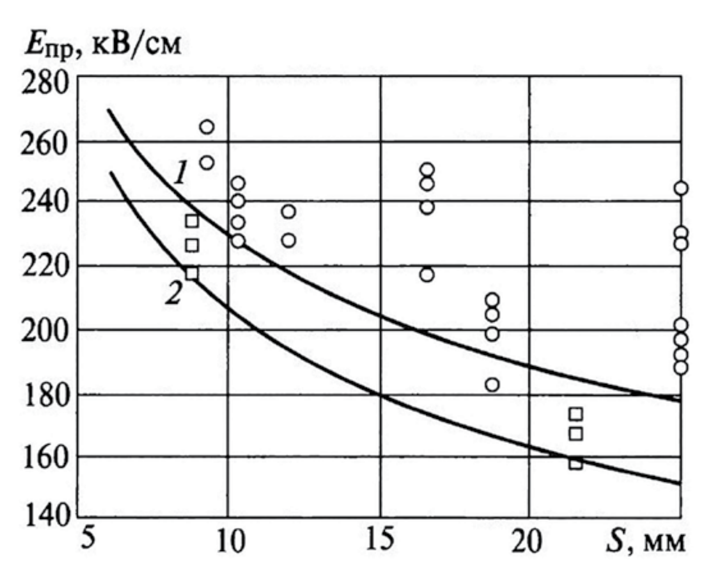


Figure 15. Dependence of the breakdown voltage gradient of the oil duct adjacent to the winding on its width (middle of winding). Impulse 1.5/40 µs

By extracting and processing the data from Fig. 15, we obtained the statistics shown in Table 3.

As follows from this table, CV% is in the range of 3 - 10.4 and has a noticeable but weaker tendency to increase the scatter with an increasing channel compared to a voltage of 50 Hz. However, the trends indicated in Tables 2 and 3 may be unreliable due to the very small number of points.

7.2. The volt-second characteristic of the insulating structure “lead – plane” acc. to Danishina & Morozova

The volt-second characteristics of individual parts of the insulation are influenced by the degree of field uniformity, and therefore, the gaps between taps and grounded parts, between the input screen and the tank wall, etc. they, may not be the same as for the main insulation of transformers. In the work of Danishina and Morozova, the volt-second characteristic of the insulating structure lead-plane was studied in the time range from a lightning impulse to a one-minute power frequency voltage [9]. The work is pleasantly different from previous publications by VEI employees in that it contains statistics on the scatter of breakdown voltage (number of experimental points, average values, coefficients of variation) and gives the average (not minimum) breakdown voltage values.

The volt-second characteristics of individual parts of the insulation are influenced by the degree of field uniformity

Table 3. The coefficients of variation of breakdown voltage gradient of the oil duct adjacent to the winding on its width (middle of winding). Impulse 1.5/40 µs

Oil duct width, mm	Number of points, N	Mean/kV	CV%
6	3	226	3.8
10	4	236	3.0
16	4	238	6.2
18	4	199	6.1
24	3	167	5.1
30	7	245	10.4

> **The test results show that with impulses of all types, the breakdown of the insulation of models occurs without its preparation by partial discharges**

The studies were carried out on models of leads with a circular cross-section with a diameter of 20 mm. The lead was insulated with a varnished cloth, cable, or crepe paper 18 mm thick per side. The distance between the tap and the grounded plane was assumed to be 40 mm. Experiments were done with and without a gap fixed with wooden planks. The models reflect a certain group of possible real designs of taps in transformers. The models underwent technological processing corresponding to the processing of transformers filled with oil under vacuum.

The models were tested with a lightning impulse of 1.2/50 μs, switching impulses of various durations: 170/1200, 400/3300, 800/14000 μs and at one-minute power frequency voltage. The voltage of spark discharges in the oil gap between the insulated lead and the plane, which sometimes left traces in the form of branched shoots on the surface of the lead insulation, resulting from the evaporation of oil impregnating the insulating material, was taken as a criterion that determines the electrical strength of the model under all types of impact.

The test results show that with impulses of all types, the breakdown of the insulation of models occurs without its preparation by partial discharges. However, when tested with an industrial frequency voltage, the breakdown begins with the appearance of a high-intensity PD ($\geq 5 \cdot 10^{-7}$ C). These PDs, which are an oil gap breakdown, damage one or two layers of cable (crepe) paper or varnished fabric. The voltage at which these PDs occurred was noted as damaging. The interval between damaging and breakdown voltage was 15%.

Table 4 shows the results of testing the models.

As follows from Table 4, the coefficients of variation are in the range of (5.6-20.3)%. The switching impulse of 170/1200 μs has the greatest scatter: CV% = (15.5-20.3).

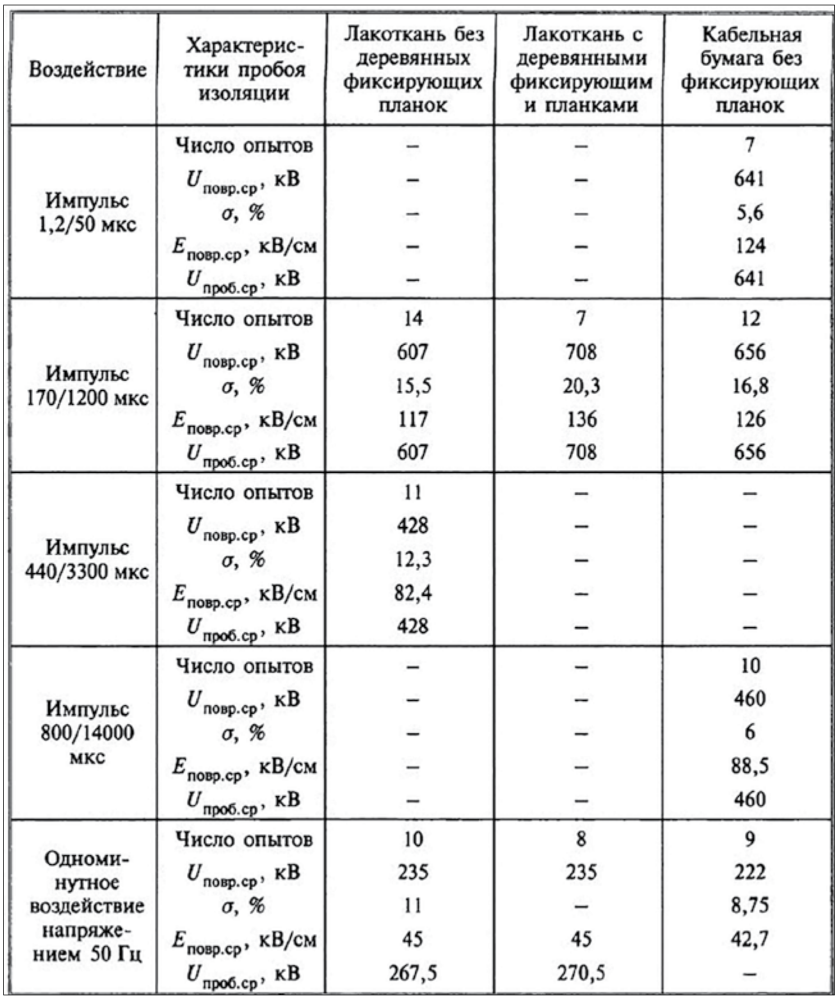
When constructing the volt-second characteristic, the authors combined the results for models with and without fixing wooden planks into one group because statistical processing showed that the difference was random in nature. Also, on this basis, the results for leads insulated with paper and varnished cloth are combined into one group.

Fig. 16 shows the dependence of the impulse ratio on the duration of exposure in the range of 50 μs - 1 min. The curve is plotted from the average values of voltage and impulse ratio.

The analysis of Fig. 16 shows that the volt-second characteristic of the lead-plane differs from that of the main insulation, with a smaller time dependence in the region from 10 to 100 μs and a much larger one in the region from 100 to 10000 μs. This characteristic can be

> **When constructing the volt-second characteristic, the authors combined the results for models with and without fixing wooden planks into one group**

Table 4. Test results of insulation models acc. to Danishina & Morozova



Воздействие	Характеристики пробоя изоляции	Лакоткань без деревянных фиксирующих планок	Лакоткань с деревянными фиксирующим и планками	Кабельная бумага без фиксирующих планок
Импульс 1,2/50 мкс	Число опытов	–	–	7
	$U_{\text{повр.ср}}$, кВ	–	–	641
	σ, %	–	–	5,6
	$E_{\text{повр.ср}}$, кВ/см	–	–	124
	$U_{\text{проб.ср}}$, кВ	–	–	641
Импульс 170/1200 мкс	Число опытов	14	7	12
	$U_{\text{повр.ср}}$, кВ	607	708	656
	σ, %	15,5	20,3	16,8
	$E_{\text{повр.ср}}$, кВ/см	117	136	126
	$U_{\text{проб.ср}}$, кВ	607	708	656
Импульс 440/3300 мкс	Число опытов	11	–	–
	$U_{\text{повр.ср}}$, кВ	428	–	–
	σ, %	12,3	–	–
	$E_{\text{повр.ср}}$, кВ/см	82,4	–	–
	$U_{\text{проб.ср}}$, кВ	428	–	–
Импульс 800/14000 мкс	Число опытов	–	–	10
	$U_{\text{повр.ср}}$, кВ	–	–	460
	σ, %	–	–	6
	$E_{\text{повр.ср}}$, кВ/см	–	–	88,5
	$U_{\text{проб.ср}}$, кВ	–	–	460
Одноминутное воздействие напряжением 50 Гц	Число опытов	10	8	9
	$U_{\text{повр.ср}}$, кВ	235	235	222
	σ, %	11	–	8,75
	$E_{\text{повр.ср}}$, кВ/см	45	45	42,7
	$U_{\text{проб.ср}}$, кВ	267,5	270,5	–

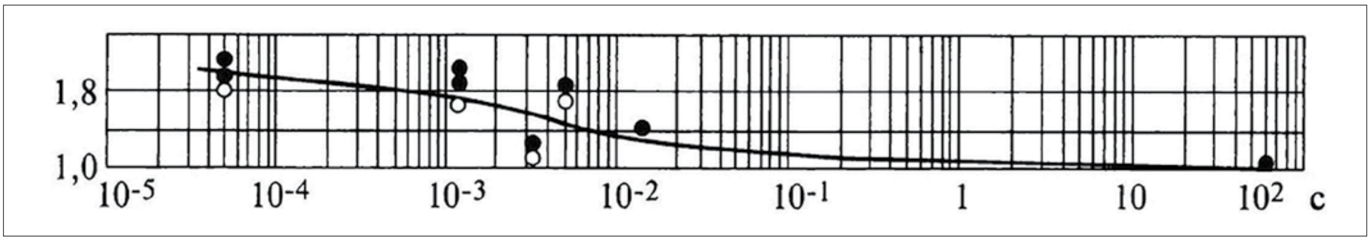


Figure 16. Volt-second characteristic of the lead-plane acc. to Danishina & Morozova
● - are the values of the momentum coefficients calculated from the damaging voltage;
○ - the same for breakdown voltage

> **Danishina & Morozova's important numerical information on the scatter of the breakdown voltage and the fact that this scatter is the largest in the region of switching impulses**

divided into three areas: 10 - 100, 100 - 10000 µs and 10000 µs - 1 min.

The first area (10–100 µs) is characterized by a relatively small (about 6%) breakdown voltage drop and scatter (CV%= 6). Breakdown voltage drop, apparently, is explained by a purely statistical increase in the breakdown probability with increasing time.

In the second region (100–10000 µs), a more significant (about 30%) decrease in electrical strength and a significant increase in the scatter (CV% = 12–20) are noted. The latter can be explained by the fact that, in inhomogeneous fields with switching impulses, breakdown can develop according to two different mechanisms.

In the third section (10,000 µs—1 min), the breakdown voltage decrease somewhat slows down, which is again associated with the probabilistic nature of insulation breakdown. Scatter in this area also decreases (CV% = 8–11).

Let us note Danishina & Morozova's important numerical information on the scatter of the breakdown voltage (Table 4) and the fact that this scatter is the largest in the region of switching impulses.

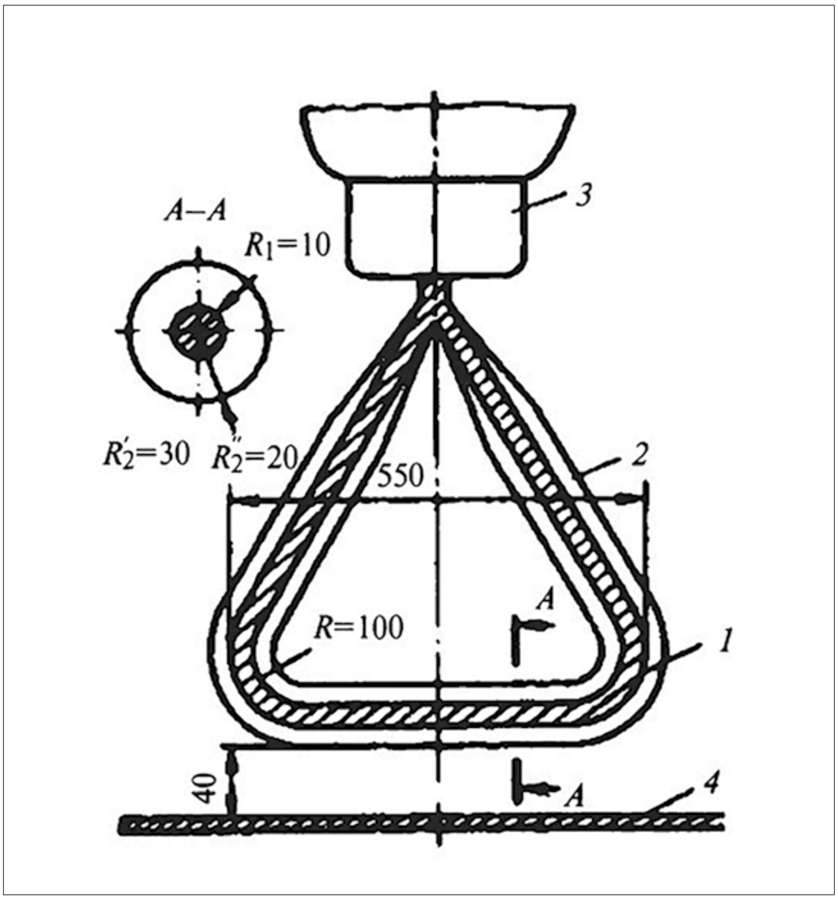


Figure 17. The design of the lead model acc. to Marushchenko & Danishina

7.3. The volt-second characteristic "lead - plane" acc. to Marushchenko & Danishina [10]

To obtain the volt-second characteristic, the models are presented in Fig. 17. The lead insulation was crepe paper.

Two types of models were studied: in one case, the branch insulation was 20 mm thick on each side (25 models), while in the other case, it was 10 mm thick (15 models). After insulation, the models were subjected to thermal vacuum treatment according to standard

> **Two types of models were studied: in one case, the branch insulation was 20 mm thick on each side (25 models), while in the other case, it was 10 mm thick (15 models)**

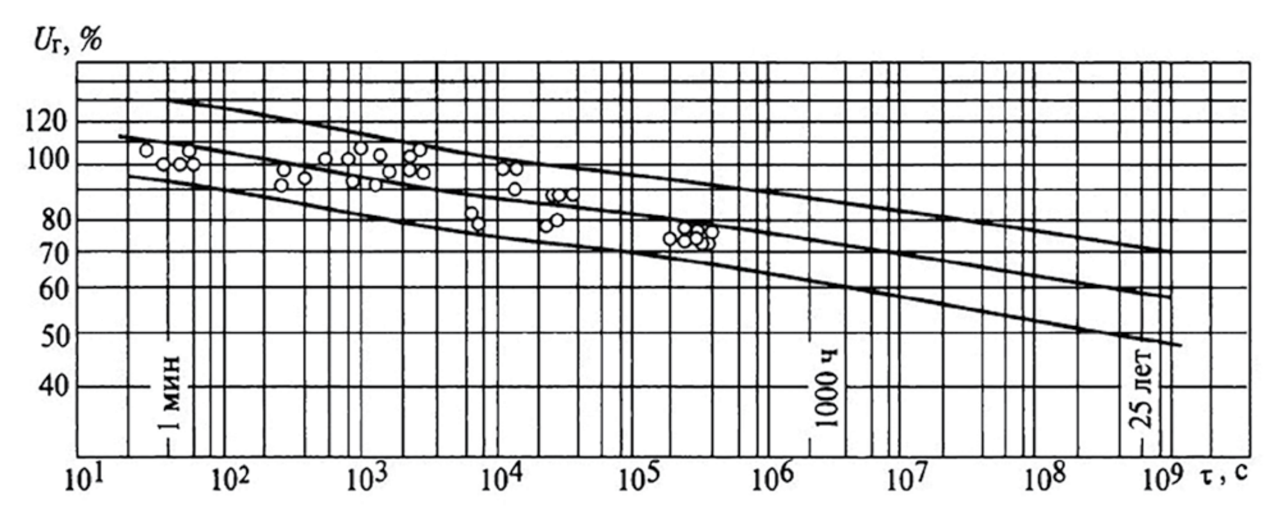


Figure 18. Volt-second characteristic of the lead - plane acc. to Marushchenko & Danishina

technological processes used by manufacturers of >220 kV transformers. The models were tested on a special stand for long-term testing in the mode of simultaneous exposure to electric and thermal alternating fields, causing gas and moisture exchange processes in the paper-oil insulation of the leads. That is, the test conditions were close to the conditions of real operation.

The 40 models were tested at AS test voltage for 1 min - 100 h. The voltage of the occurrence of a high-intensity PD (about 10^{-7} C), leading to damage to the solid insulation or to a complete breakdown of the model, was selected as a criterion. An analysis of the results showed that, in the entire time range, PDs 10^{-7} C appear without preliminary weak PDs. The breakdown mechanism is most likely associated with the formation of compositions (bridges) in the oil gap from impurities present in the oil and is of a statistical nature. Therefore, to construct a generalized volt-second characteristic, all data for the two types of models were combined into one common sample. For this, the voltage of the occurrence of a PD (or breakdown) was presented in relative units.

Fig. 18 shows the volt-second characteristic with confidence limits 0,1. The lower limit of the interval with a 90% probability describes the minimum damaging stresses of the investigated insulating structure lead-plane.

VTC in Fig. 18 extrapolated to 25 years. The validity of this extrapolation is confirmed by extending the tests, first up to 1000 h, and then even further so that the resulting total (practically continuous) duration of testing of the models was 7500 h. The authors consider it proven that up to 25 years, the electrical strength of the models is determined by the formation of bridges from impurities in oil, and there are no processes of gas formation under the action of an electric field, as well as a PD of more than 100 pC. We emphasize this important statement by Marushchenko & Danishina.

> **Up to 25 years, the electrical strength of the models is determined by the formation of bridges from impurities in oil, and there are no processes of gas formation under the action of an electric field**

7.4. Distribution laws and coefficients of variation of breakdown voltages of oil gaps greater than 100 - 150 mm [11]

Antonov, the author [11], studied large oil gaps (more than 100–150 mm) without barriers (or with a small number of them) in order to test the effect of a “stressed” volume on their dielectric strength. “Stressed” volume is that part of the volume of oil in the gap in which the tension is greater than or equal to 90% of the maximum intensity on the electrodes. The volume of the gap of 2.4 mm, formed by standard electrodes and equal to 0.05 cm^3, was taken as a unit. For larger gaps, flat electrodes with a diameter of 50 mm (volume of 5 cm^3) and 250 mm (volume of 70 cm^3) with a distance between them of 2.5 and 3.5 mm were used.

The rounding of the edges of the electrodes was carried out in such a way as to avoid breakdown at the edge. When examining the electrodes after the experiments, it was established that traces of breakdowns were scattered over their entire surface. Moreover, they were practically absent on the rounded edge. The tests were carried out in a transparent organic glass tank with a capacity of 40 litres. The oil was purified from mechanical impurities and water and subjected to vacuum drying, its moisture content was 15–25 g/t, and the content of mechanical impurities was no more than 10 g/t.

The studies were carried out at one-minute power frequency voltage, lightning (1,2/50 μs) and switching (150/800 μs) impulses. Table 5 shows the test results. As follows from the table, the change in the coefficients of variation of the breakdown voltage with an increase in the volume of oil between the electrodes is practically not established, and they lie in the range of 3–9%.

When calculating the breakdown voltage distribution function, Antonov test-

The studies were carried out at one-minute power frequency voltage, lightning (1,2/50 µs) and switching (150/800 µs) impulses

ed two hypotheses: the distribution of experimental data corresponds to the normal law or the Weibull law. It turned out that for all examined intervals with "tense" volumes (0.05, 5 and 170 cm^3) under the influence of lightning and switching impulses, the Weibull distribution is preferred. For power frequency voltage, the Weibull distribution turned out to be preferable only for a volume of 0.05 cm^3 and for volumes of 5 and 170 cm^3 - the normal law.

7.5. The coefficients of variation of breakdown intensity of transformer oil: Decreased scatter with increasing oil volume

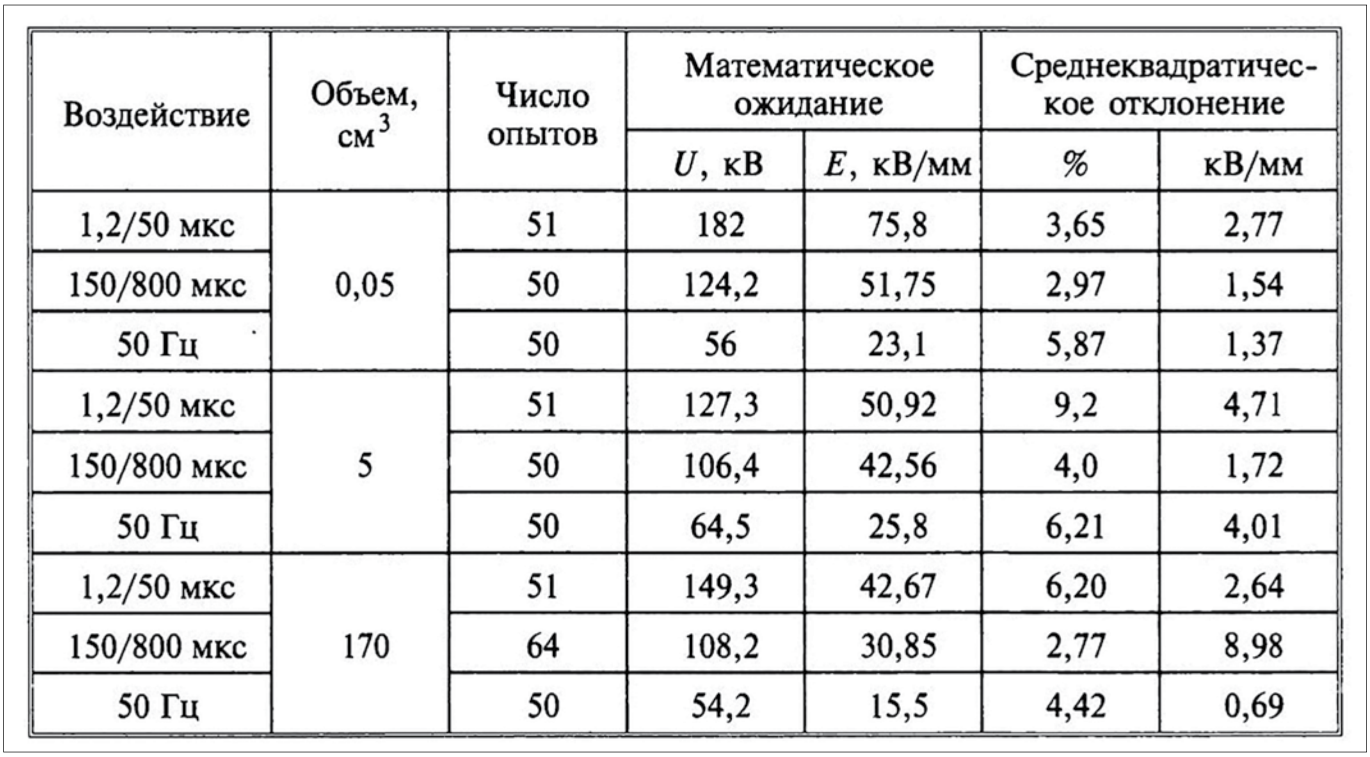
Morozova & Antonov, the authors [12], studied the effect of oil volume on the dielectric strength of gaps with different electrodes. This publication is one of the rare cases where the authors have provided detailed statistics of their experiments. Tables 6 and 7 show the geometric characteristics of the electrode devices that were used in the study and the results of the experiments. Two types of oils were used in the experiments (I and II).

The 26 coefficients of variation from Tables 6 and 7 are within (1.38 - 11.4)%. In this case, no dependence on the type of electrode devices and the distance between the electrodes is visible. Only one coefficient value equal to 18% (fourth line of Table 7) inexplicably falls outside these limits.

Further research by the authors is of interest to verify the accuracy of the selected value of the stressed oil volume. Previously, many researchers accepted the volume of oil limited by the electrode and the equigradient surface, the intensity of which was 90% of the maximum intensity on the electrode surface. Morozova & Antonov investigated the area of dispersion of traces of discharges on electrodes "ball-plane" with a ball diameter of 62.5, 25 and 5 mm. The balls were previously carefully polished. Up to 50 experiments were carried out on each device. After tests were conducted on the surface of the electrodes, the position of traces of discharge damage to the surface was determined. Traces of 90-94% of breakdowns were found. All of them turned out to lie inside a region bound by a circle, the intensity of which is 80-82% of the highest value on the lectrode.

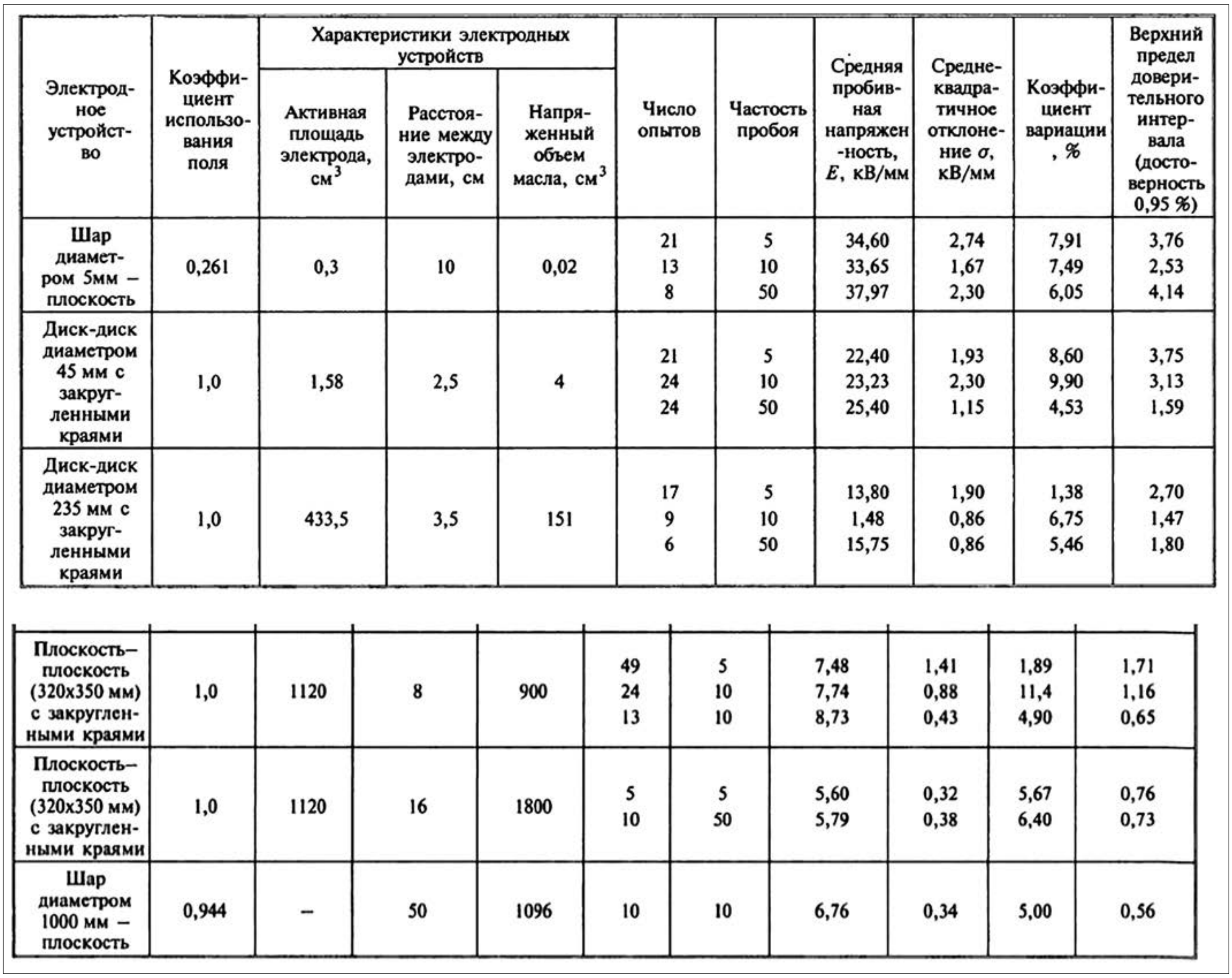
Morozova & Antonov studied the effect of oil volume on the dielectric strength of gaps with different electrodes and published the publication with detailed statistics of their experiments

Table 5. Oil gaps test results acc. to Antonov



Воздействие	Объем, см^3	Число опытов	Математическое ожидание		Среднеквадратическое отклонение	
			U, кВ	E, кВ/мм	%	кВ/мм
1,2/50 мкс	0,05	51	182	75,8	3,65	2,77
150/800 мкс		50	124,2	51,75	2,97	1,54
50 Гц		50	56	23,1	5,87	1,37
1,2/50 мкс	5	51	127,3	50,92	9,2	4,71
150/800 мкс		50	106,4	42,56	4,0	1,72
50 Гц		50	64,5	25,8	6,21	4,01
1,2/50 мкс	170	51	149,3	42,67	6,20	2,64
150/800 мкс		64	108,2	30,85	2,77	8,98
50 Гц		50	54,2	15,5	4,42	0,69

Table 6. Oil test results in different electrode devices acc. to Morozova & Antonov



Электродное устройство	Коэффициент использования поля	Характеристики электродных устройств			Число опытов	Частость пробоя	Средняя пробивная напряженность, E, кВ/мм	Среднеквадратичное отклонение σ, кВ/мм	Коэффициент вариации, %	Верхний предел доверительного интервала (достоверность 0,95 %)
		Активная площадь электрода, см^3	Расстояние между электродами, см	Напряженный объем масла, см^3						
Шар диаметром 5мм – плоскость	0,261	0,3	10	0,02	21 13 8	5 10 50	34,60 33,65 37,97	2,74 1,67 2,30	7,91 7,49 6,05	3,76 2,53 4,14
Диск-диск диаметром 45 мм с закругленными краями	1,0	1,58	2,5	4	21 24 24	5 10 50	22,40 23,23 25,40	1,93 2,30 1,15	8,60 9,90 4,53	3,75 3,13 1,59
Диск-диск диаметром 235 мм с закругленными краями	1,0	433,5	3,5	151	17 9 6	5 10 50	13,80 1,48 15,75	1,90 0,86 0,86	1,38 6,75 5,46	2,70 1,47 1,80
Плоскость–плоскость (320x350 мм) с закругленными краями	1,0	1120	8	900	49 24 13	5 10 10	7,48 7,74 8,73	1,41 0,88 0,43	1,89 11,4 4,90	1,71 1,16 0,65
Плоскость–плоскость (320x350 мм) с закругленными краями	1,0	1120	16	1800	5 10	5 50	5,60 5,79	0,32 0,38	5,67 6,40	0,76 0,73
Шар диаметром 1000 мм – плоскость	0,944	–	50	1096	10	10	6,76	0,34	5,00	0,56

Table 7. Type I oil test results with varying electrode spacing acc. to Morozova & Antonov

Расстояние между электродами, см	Диаметр шара (цилиндра), см	Коэффициент использования поля	Объем масла, напряженность в котором выше $0{,}8E_{max}$, см^3	Число опытов	Среднее пробивное напряжение, кВ	Средняя пробивная напряженность у электрода, кВ/мм	Среднеквадратичное отклонение		Верхний предел доверительного интервала с достоверностью 0,95
							кВ/мм	%	
47	1000 (шар)	0,949	1096	10	280	6,27	0,40	6,27	0,66
50	500 (шар)	0,887	377	10	278	6,26	0,45	7,25	0,74
	250 (шар)	0,786	88	10	284	7,21	0,64	9,00	1,06
	62,5 (шар)	0,448	17/20	26	210	9,38	1,63	18,00	2,15
	800 (цилиндр)	0,95	7797	10	211	4,42	0,28	6,30	0,46
	800 (цилиндр с покрытием)	0,96	7797	7	222	4,60	0,29	6,30	–
100	1000 (шар)	0,887	3186	11	552	6,21	0,326	5,30	0,52
	500 (шар)	0,787	643	7	507	6,45	0,47	7,30	0,90
	250 (шар)	0,630	235	10	454	7,20	0,52	7,35	0,86
	62,5 (шар)	0,264	24	22	304	11,51	1,01	8,80	1,37
	800 (цилиндр)	0,930	19394	10	320	3,50	0,15	4,30	0,215
	800 (цилиндр с покрытием)	0,930	19394	10	337	3,63	0,154	4,20	–
150	800 (цилиндр)	0,895	29891	10	380	2,84	–	–	–

> Many researchers accepted the volume of oil limited by the electrode and the equigradient surface, the intensity of which was 90% of the maximum intensity on the electrode surface

One of the results of these experiments is the significant dependence of the scatter of strength on the stressed (80%) oil volume (Fig. 19).

Conclusion to Parts II and III

1. The work of Panov, a leading figure in the field of insulation of power transformers, formed the basis for the creation of reliable 3-220 kV Soviet transformers.

2. Research by the VEI team in the post-Panov era, under the leadership of Morozova and Lokhanin, formed the basis for the requirements for insulation of HV and EHV transformers in accordance with GOST 1516.1-76, and subsequently for transformers with insulation levels below the standard. All transformers, 330 kV and above, were designed and manufactured in Zaporizhzhia. Many years of experience in operating both groups of transformers have proven their high reliability. In particular, the reliability of transformers with an insulation level below GOST has been demonstrated by successful operation:

a) more than 25 years (at that time, the standard service life) of an experimental group of single-phase transformers of 135 MVA, 500 kV at the Volzhskaya HPP; b) four groups of similar transformers at the Volgograd HPP; c) autotransformers 167 MVA, 500/220 kV at substations Tashkent, Novo-Donbas, Chimkent, Kustanai, Armavir; d) three-phase transformers of 210 MVA, 500 kV at the Bratskaya HPP; e) three-phase transformers of 660 MVA, 500 kV at the Ragun HPP; f) autotransformers of 667 MVA, 1150 kV.

All this indicates large (but unknown) insulation safety margins and encourages prospects for optimizing transformers by removing excess reserves.

3. Important conclusions for optimizing the main insulation design is the understanding that:

a) breakdown of the insulation when entering into the middle of the winding and at the end of the winding with long-term (up to 1000 h) AC voltage is recorded as a powerful PD (1-5) -10’7 C, which is not prepared by a low-intensity PD (Morozova);

b) up to 25 years, the electrical strength of the insulation is determined by the formation of bridges from impurities in oil, and there are no processes of gas formation under the influence of an electric field, as well as a PD of more than 100 pC (Marushchenko & Danishina).

4. We note the following important information about the scatter values of the breakdown voltage of transformer insulation:

- For inhomogeneous fields, the deviations of the breakdown voltages of transformer oil (45 kV / 2.5 mm at a temperature of 15-20ºC) from the average values at distances of more than 25 mm are less than 5%; for relatively homogeneous fields, the scatter is significant and varies depending on the degree of field homogeneity (Panov);

- The coefficients of variation of breakdown voltages of transformer insulation models are (2.9-4.4)% (Panov, see Table 1);

- The switching impulse of 170/1200 µs has the largest scatter of breakdown voltages for the “lead-to-plane” design (Danishina & Morozova, see Table 4);

- The breakdown voltage distribution of large oil gaps (more than 100-150 mm) under the influence of lightning and switching pulses (150/800 µs) obeys the Weibull law. For power frequency voltage, the Weibull distribution turned out to be preferable only for a stressed 90% oil vol-

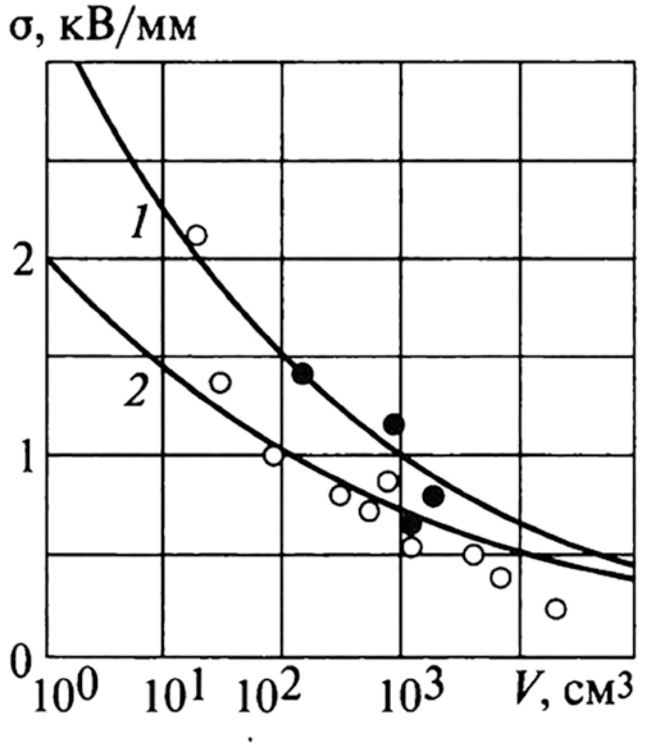


Figure 19. Dependence of the standard deviation σ of the breakdown intensity E10% on the stressed (80%) oil volume acc. to Morozova & Antonov

ume of 0.05 cm^3 and for volumes of 5 and 170 cm^3 - the normal law (Antonov).

- The scatter of the breakdown intensity of transformer oil significantly (2-3 times) decreases with an increase in the stressed 80% oil volume in the range from 10 to 10^3 cm^3 (Morozova & Antonov);

This information, together with the data in Tables 1-7 and Fig. 19 is sent to our data box, which will be analyzed in the last part of the article.

> **The scatter of the breakdown intensity of transformer oil significantly (2-3 times) decreases with an increase in the stressed 80% oil volume in the range from 10 to 10^3 cm^3**

Bibliography to Part III

[8] A.V. Panov, T.I. Morozova, *Electrical characteristics and methodology for calculating the main insulation of large high-voltage transformers*, VEI Proceedings, Vol. 79, pp. 13-32, 1969 (in Russian)

[9] A.A. Danishina, T.I. Morozova, *Volt-second characteristic of the insulating design lead-plane*, VEI Proceedings, Vol. 85, pp. 23-33, 1977 (in Russian)

[10] P.I. Marushchenko, A.A. Danishina, *Investigation of the long-term electrical strength of the lead-plane type in high-voltage power transformers*, VEI Proceedings, Vol. 91, pp. 3-17, 1982 (in Russian)

[11] V.I. Antonov, *Experimental studies of the dependence of the electric strength of transformer oil from "stressed" volume in a uniform electric field*, VEI Proceedings, Vol. 91, pp. 17-22, 1982 (in Russian)

[12] T.I. Morozova, V.I. Antonov, *Experimental study of the effect of oil volume on the dielectric strength of transformer insulation*, Electrotechnika, No. 3, pp. 41-43, 1986 (in Russian)

Author

Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduated from school at the Leningrad Polytechnic Institute. Candidate of technical sciences in the Soviet scientific system (1970). For 30 years, he tested transformers up to 1,150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years, he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair, and modernisation in the operating conditions of transformers 20–750 kV). He has authored about 150 publications in Russian and Bulgarian and is the main co-author of GOST 21023.