ABSTRACT

The second part of the article 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

Panov obtained dependences of the breakdown voltages of transformer oil on the distance between the electrodes (up to a maximum distance of 50 cm)

Volt-time curves of oil-filled power transformer insulation

Survey of 100 years of research – Part II

4. Panov's works

In the Soviet Union, Panov (1903-1966) started doing research on transformer insulation in the 1930s at VEI (Moscow). Panov began his experiments by determining the breakdown voltage of transformer oil (45 kV / 2.5 mm at a temperature of 15-20°C) in the electrode system: needle-needle, needle-plane, bolt-plane, ball-ball, ball-plane, disks with a diameter of 10 cm with right angles. He then continued experiments on oil barrier insulation models. He applied 50 Hz smooth and stepped voltage rises and 1.5/40 µs impulses of positive and negative polarity.

Panov obtained dependences of the breakdown voltages of transformer oil on the distance between the electrodes (up to a maximum distance of 50 cm). We note Panov's conclusion, which is important to us: *"For inhomogeneous fields, the deviations of breakdown voltages from 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."*

Further, Panov studied cylindrical models of oil-barrier type insulation, simulating the introduction of an HV winding into the middle, structurally representing a similarity to the main insulation of a transformer

The first dependences of oil strength and elementary insulation models on time obtained by Panov (Panov called them volt-second characteristics) are shown in Fig. 1 [1]. Some of them have a monotonically decreasing character, others resemble Montsinger and Bellaschi curves in shape. A dotted line in the area of switching impulses indicates four of the five curves seen in Fig. 1.

Further, Panov studied cylindrical models of oil-barrier type insulation, simulating

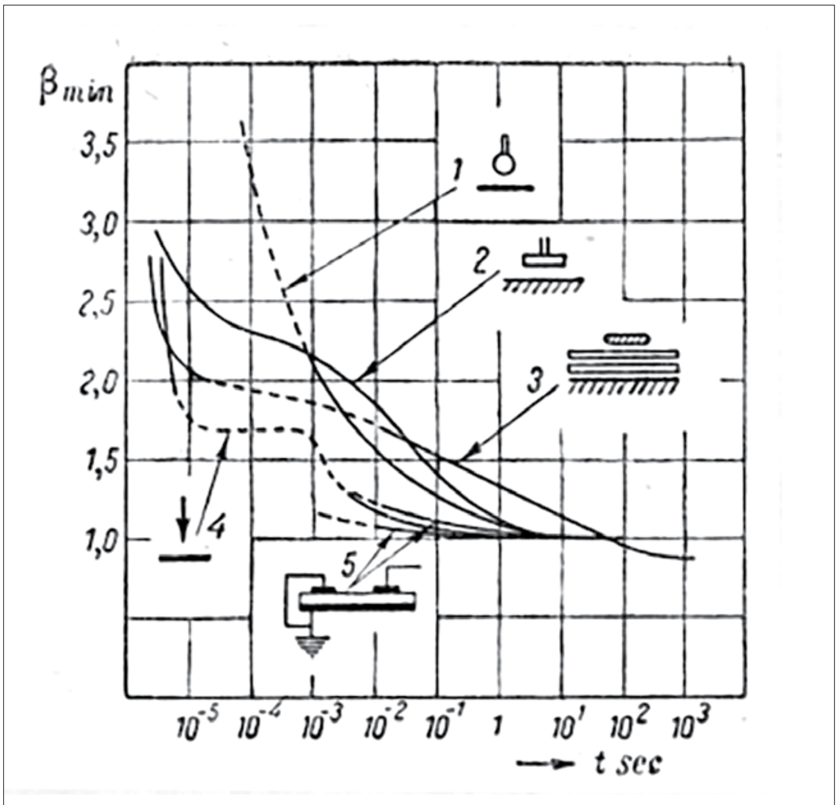

Figure 1. Volt-second characteristics of different types of oil insulation acc. to Panov = *Fig. 13, Panov* [1]

From these first experiments on models with a small number of experimental points, Panov draws two fundamental conclusions for the further development of transformer insulation research in the USSR

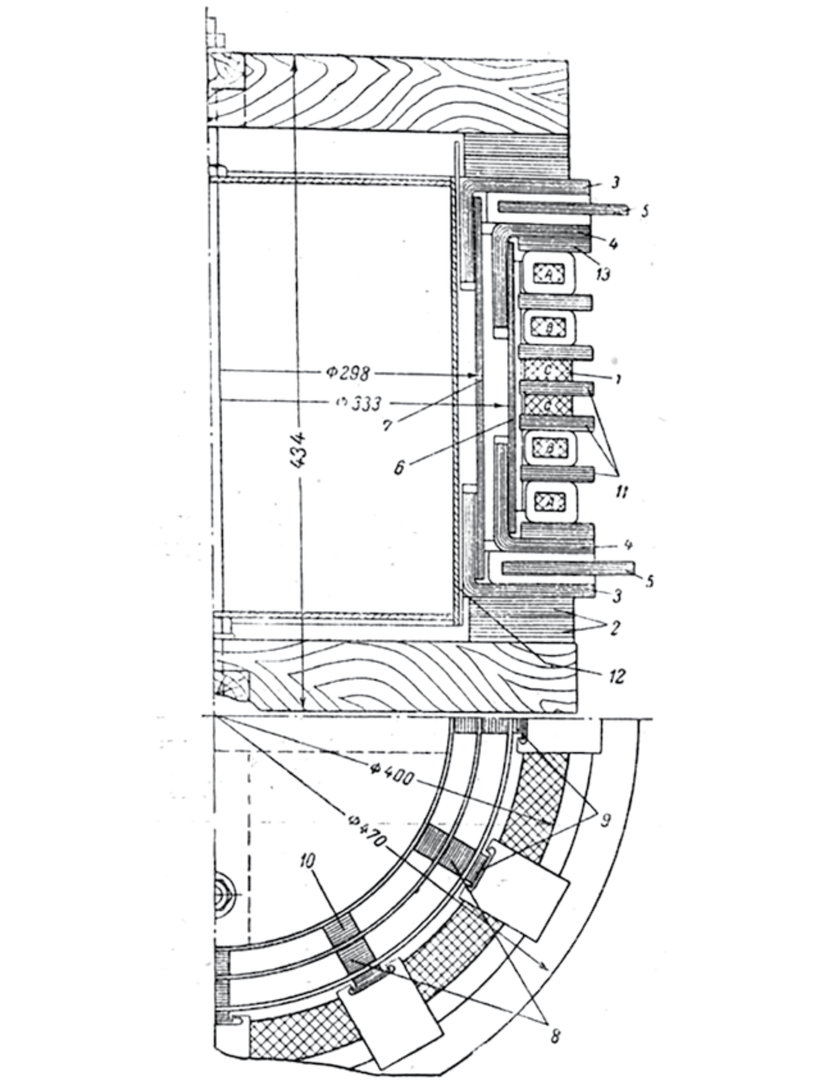

Figure 2. Main insulation model with the entry in the middle of the winding acc. to Panov = *Fig. 2 Panov [1]*

A, B - coils with reinforced insulation; 1 - coils without reinforced insulation; 2 - support ring; 3, 4 - corner washers; 5 - barrier made of pressboard; 6, 7 - insulating cylinders; 8, 9, 10 - remote rails; 11 - gaskets; 12 – metal screen imitating LV winding

Table 1. The coefficients of variation of breakdown voltages of transformer insulation models acc. to Panov

Test name	Number of points, N	Average/kV	CV%
1 minute voltage 50 Hz	5	195	3.4
1.5/40 μs negative polarity	11	565	4.4
1.5/40 μs positive polarity	5	565	2.9

the introduction of an HV winding into the middle, structurally representing a similarity to the main insulation of a transformer (Fig. 2). In order to prevent discharges through the yoke insulation, the latter was strengthened by sufficient insulation of the end coils and the use of corner washers. The solid insulation of the model was preliminarily dried and impregnated with transformer oil under a vacuum at a temperature of 60–65°C. After assembly, the model was immersed in a test tank with oil. A vacuum of the order of 700 mm Hg was created in the space above the oil mirror for 2 h to remove air that may have remained between the barriers after the model was immersed in the test tank. The studies were carried out at an oil temperature of 15–20°C.

A 1-minute breakdown voltage at 50 Hz and a 1.5/40 μs breakdown voltages of positive and negative polarity (the three-shock step method) were determined. Panov gives the initial tabular breakdown voltage data, which allowed us to determine the coefficients of variation CV% (Table 1).

From these first experiments on models with a small number of experimental points, Panov draws two fundamental conclusions for the further development of transformer insulation research in the USSR: 1) the strength of the oil-barrier insulation under conditions of a relatively uniform field does not depend on the polarity of the lightning impulse 1.5/40 μs; 2) it determines the impulse ratio as the ratio of the average breakdown voltages at impulses 1.5/40 μs and at a minute voltage of 50 Hz:

$$\frac{565}{\sqrt{2}\cdot 195} = 2{,}05$$

To determine the volt-second characteristic of the main insulation between the windings, Panov studied the models at 50 Hz and time delay up to 1 h, as well as under influences simulating switching overvoltages in operation (Fig. 3).

Panov found that both at impulses and at a voltage of 50 Hz, the breakdown of the insulation of models occurs in the form of a weak single spark that spans the entire gap. The breakdown may then not be repeated, despite the sufficiently long exposure time of 50 Hz and even with a

Panov found that both at impulses and at a voltage of 50 Hz, the breakdown of the insulation of models occurs in the form of a weak single spark that spans the entire gap

slight increase in the voltage of both 50 Hz and impulses. Breakdown in the form of frequent, successive discharges or in the form of an arc is established only at voltages significantly exceeding the voltage of the first single spark. During the research, Panov recorded both values, with the first value called the "minimum", and the second the "maximum" breakdown voltage.

Panov's VTCs [2] is shown in Fig. 4 at impulses 1.5/40 µs and Fig. 5 at 50 Hz. Note that at impulses, it is the lower envelope, and at 50 Hz, this is the middle curve. Also, note that Panov failed to obtain reliable data in the range of switching overvoltages.

Fig. 6 shows Panov's resulting VTC. Here is Panov's explanation. As we can see, the volt-second characteristic of the oil-barrier insulation in a relatively uniform field has a complex stepped character. It can be divided into 3 or even 4 characteristic areas.

The first area extends from very short times to tens of microseconds, the second area - from tens of microseconds to hundredths of a second, the third - from hundredths of a second to several minutes, and the fourth region - from 2-3 minutes to a very long duration. It should be considered that each of these areas is associated with a certain destruction mechanism. For a short time, apparently, a purely electrical type of breakdown takes place, and the second area, indicated by the dotted line (overvoltage switching area), barely has a physical existence and can hardly be interpreted as an area which is accompanied by its own special breakdown mechanism. Rather, this area is a link between the first and third areas, each having a specific destruction mechanism.

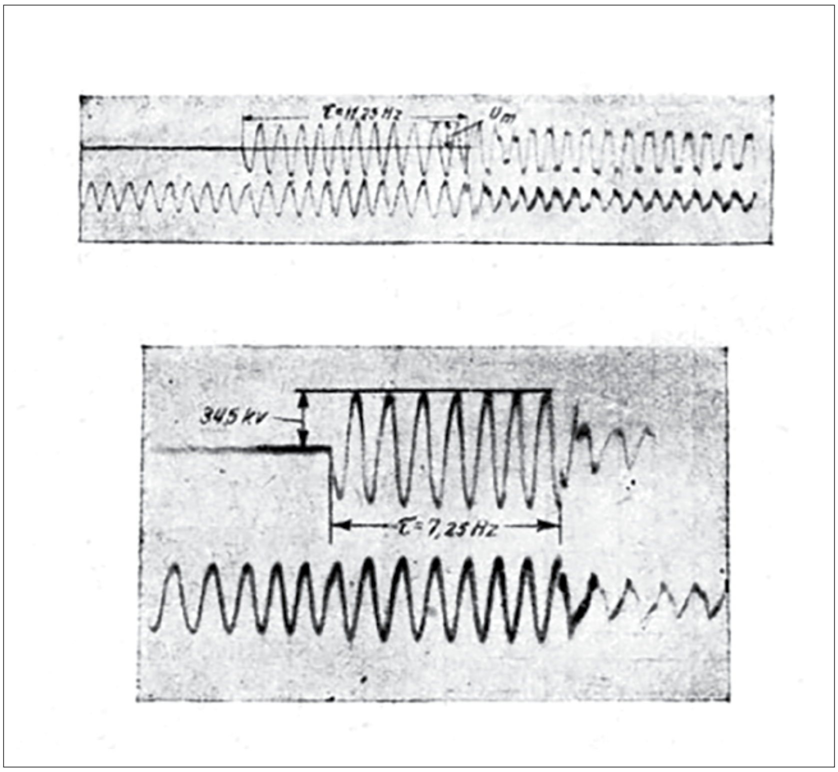

Figure 3. Typical oscillograms of insulation breakdown of models in the study in relation to switching overvoltages acc. to Panov = *Fig. 9, Panov [1]*

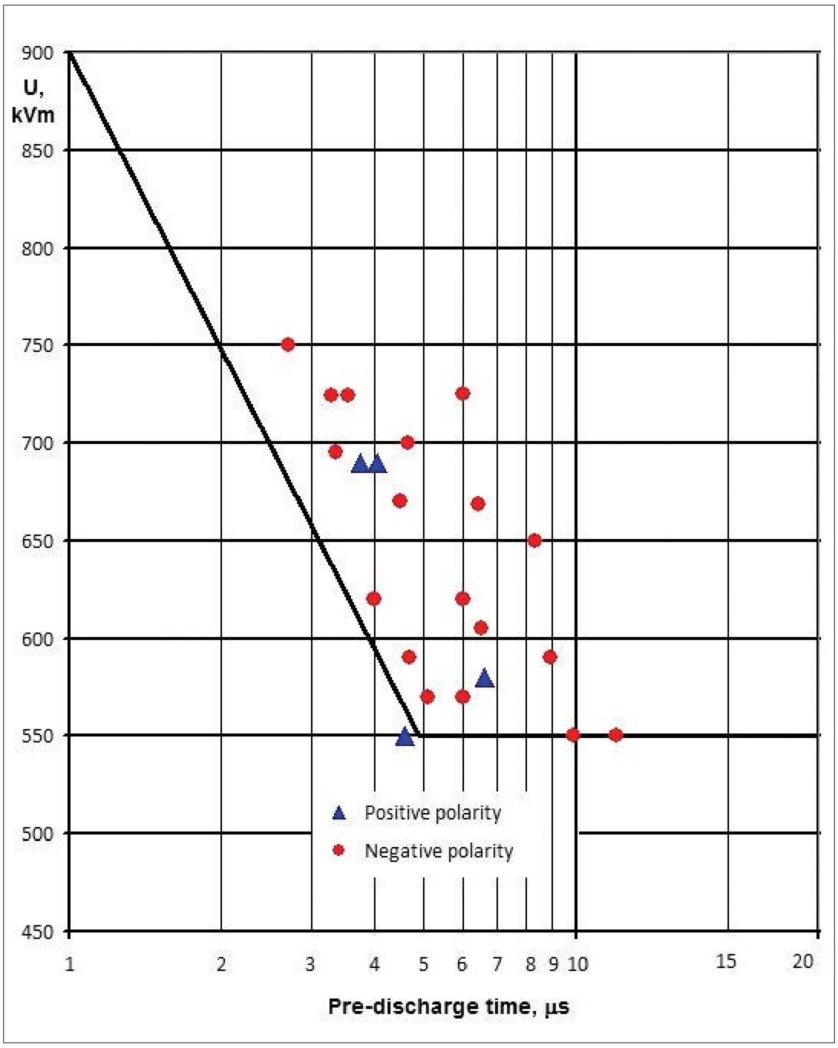

Figure 4. Volt-second characteristic of oil barrier insulation at exposure time 1 – 15 µs, impulses 1.5/40 µs acc. to Panov (rebuilt from Fig. 25-15 [2])

The results show that the volt-second characteristic is a function of many variables, such as the shape of the electric field, the design of the insulation, and the absolute value of the dimensions of the insulation

In the third area of the volt-second characteristic of the oil-barrier insulation, the breakdown is formed according to a mechanism that is mainly associated not with the phenomenon of a statistical discharge delay but with processes that require a certain time for their development. Here, the processes associated mainly with thermal, electromechanical, and accompanying electrical phenomena in insulation are already beginning to play a significant role, such as the heating of a solid dielectric due to conductivity and dielectric losses and, as a result, redistribution of the field, the concentration of mechanical impurities, displacement of oil from the solid fibrous material of the barriers, ionization of air inclusions in the oil and in the fibrous material.

The fourth area is characterized by a relatively very weak dependence on the exposure time and is apparently associated with the processes of slow aging of the fibrous insulation.

In our time, three quarters of a century after what was written, of the processes listed by Panov in the third and fourth areas, preference is given to the influence of impurities and partial discharges (ionization, according to Panov)

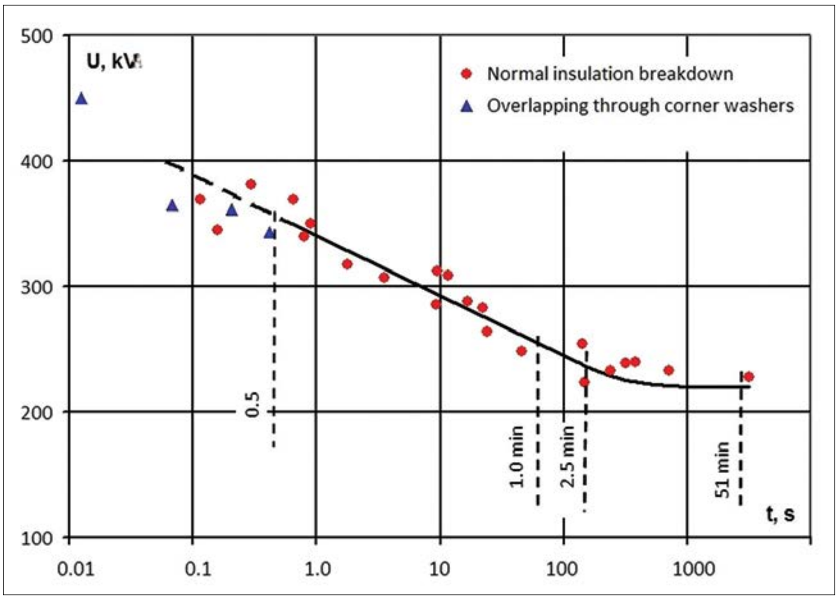

Figure 5. Volt-second characteristic of oil barrier insulation at the exposure time 0.1 sec - 51 min., 50 Hz acc. to Panov (rebuilt from Fig. 25-14 [2])

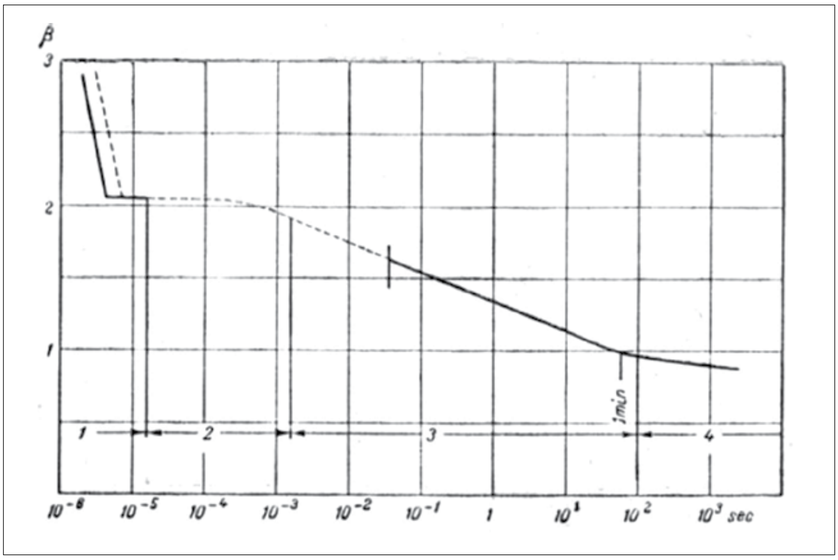

Figure 6. Volt-second dependence of the main insulation between the HV and LV windings acc. to Panov = *Fig. 12, Panov* [1]

The results show that the volt-second characteristic is a function of many variables, such as the shape of the electric field, the design of the insulation, and the absolute value of the dimensions of the insulation. As a result, the volt-second characteristic of the main insulation of transformers cannot be considered the same, regardless of its design.

Panov also obtained the dependences of the minimum values of the surface discharge voltage at 50 Hz and at impulses of 1.5/40 µs on the distance between the electrodes up to 50 cm inclusive, and the formula for the voltage of the occurrence of sliding discharges depending on the thickness of the solid dielectric.

Based on the fact that the intensity of the electric field in oil is much higher than in solid insulation due to the lower dielectric constant of the oil, and the strength of the oil is lower than solid insulation, Panov accepted that the strength of the entire insulating structure of the transformer is determined by the strength of the most loaded oil duct, which is the one that is adjacent to the HV winding. This became a law axiom for Soviet transformer engineering.

Panov's research served as the basis for the design of the insulation of Soviet 3-220 kV transformers. The use of Panov's concept of the minimum breakdown voltage provided large margins of insulation strength and thus, the reliability of these transformers.

5. Volt-second characteristic by Kaplan and Morozova, 1960s

> **Massive failures of the first Soviet 330-500 kV transformers due to the leakage current discharge required new studies on models, with careful study of partial discharges**

Massive failures of the first Soviet 330-500 kV transformers [3] due to the leakage current discharge [4] required new studies on models, with careful study of partial discharges. The experiments were carried out in Moscow after the death of Panov by his student Morozova with his subordinates in Leningrad and Zaporizhzhia - teams led by Kuchinsky and Beletsky. As a result of these studies, Kaplan and Morozova built a volt-second characteristic that was refined in comparison with the Panov one. It was published in the principal Soviet magazine in the field of electrical engineering, *Electrichestvo*, and in the CIGRE-1970 report [5, 6].

The studies based on which this VTC was built were carried out on models of two different types, simulating the behavior of insulation in the middle and at the end of the winding (Fig. 7). The insulating spacing between the models' windings ranged from 20 to 70 mm, and between the static plate and the yoke from 50 to 140 mm. The authors claim that the findings obtained on the oil-barrier insulation on the said models may be used in transformer insulation designing in spite of the relatively small sizes of the models because the dimensions of the oil duct adjacent to the winding, intercoil ducts and distance elements of the models were on the scale of 1:1 with regard to transformer insulation construction. A special test revealed a good agreement on the dielectric strength for small and large models of transformer insulation made in full size.

The insulation strength was studied at 50 Hz alternating current from 0.02 s to 200 hours, with a standard impulse of 1.5/40 μs, and with various damped oscillations and aperiodic impulses simulating switching overvoltages (Fig. 8).

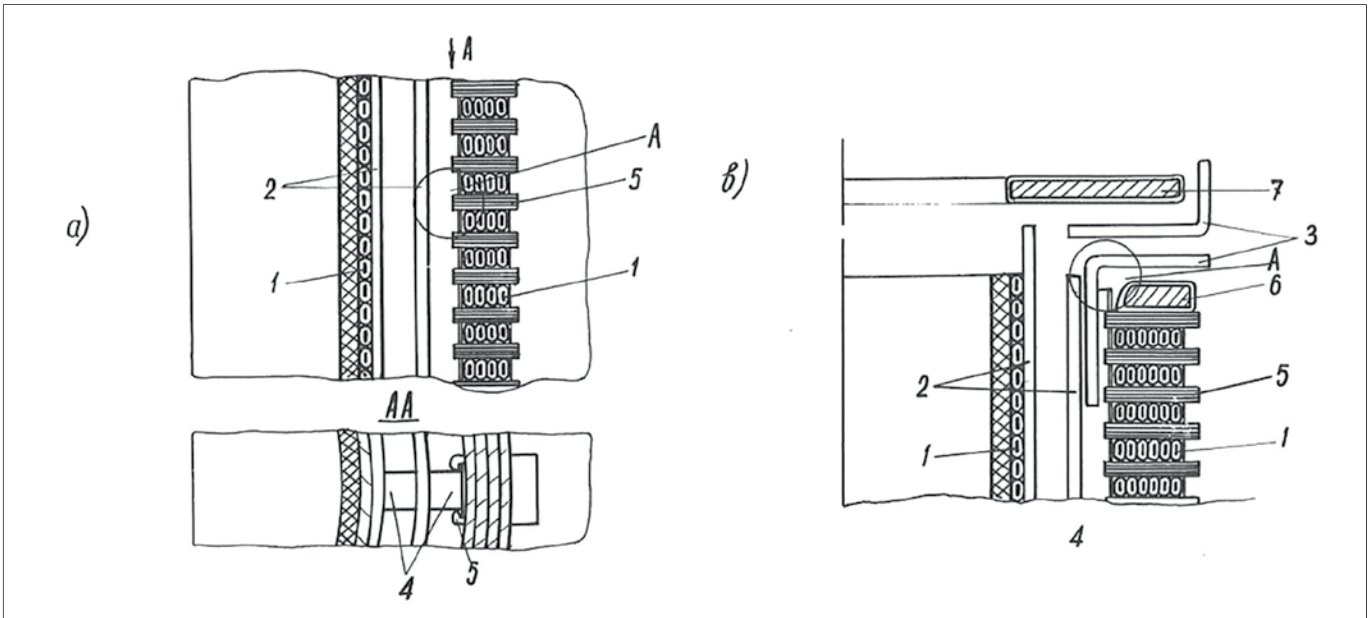

Figure 7. Model of oil-barrier insulation of the middle (a) and of the edge (b) of winding acc. Kaplan & Morozova = *Fig. 1, CIGRE-1970* [6]
1 - winding; 2 - pressboard cylinders; 3 - corner pieces; 4 - distance racks; 5 - spacers; 6 - static plate; 7 - yoke; A - insulation section under study.

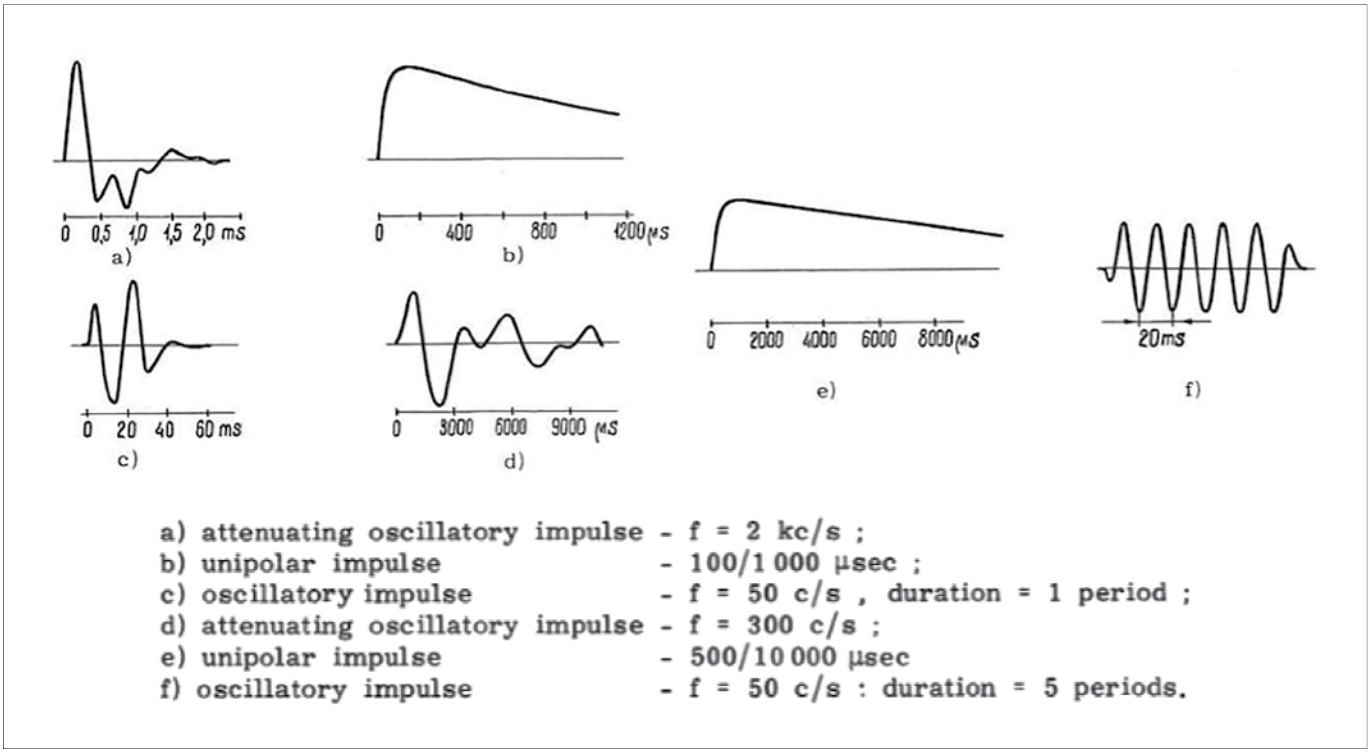

Figure 8. Oscillograms of aperiodic and oscillatory impulses simulating switching surge acc. Kaplan & Morozova = *Fig. 3, CIGRE-1970* [6]

The decrease in breakdown voltage with increasing duration can be considered the result of an increase in the probability of breakdown with a longer duration of exposure to voltage

Fig. 9 shows the test results in the form of the ratio K of the value of the electric strength of the insulation with impulses to the strength index with a one-minute voltage application of 50 Hz. Each point shown in Fig. 9 represents a value obtained from tests on a series of similar specimens. The number of specimens in each series ranged from 3 to 14. The curve takes into account the results of testing models, as well as general current data on oil and oil-barrier insulating gaps. The section of the curve from $3x10^5$ sec (100 h) to 10^9 sec (30 years) is shown as a dotted line because there is no direct experimental data in this area.

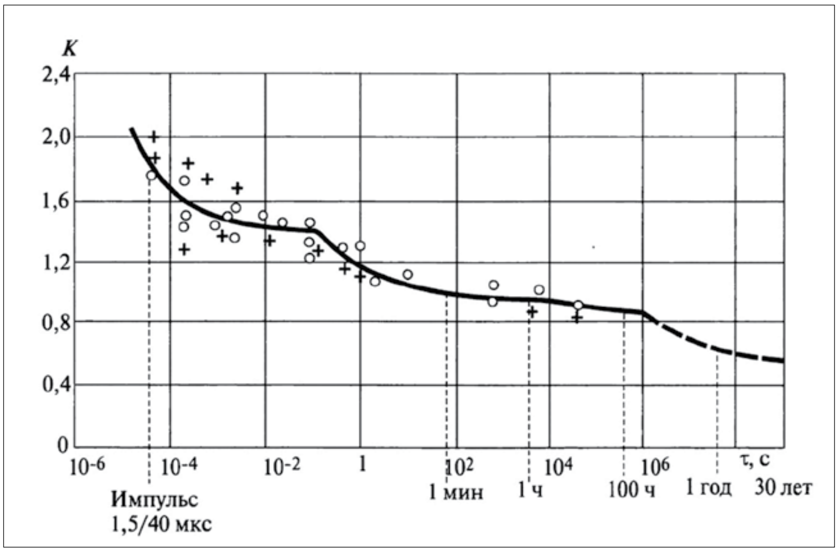

Fig. 9. Dependence of relative breakdown strength on the duration of voltage application (t ≤ 0.1 sec - aperiodic and oscillatory impulses; t > 0.1 sec - 50 Hz alternating voltage) acc. Kaplan & Morozova
O - models of the middle of winding, x - models of the edge of the winding

Analysis of Fig. 9 shows that five areas can be distinguished in it. The first area is from 10^{-5} to 10^{-3} sec., the second - from 10^{-3} to 10^{-1} sec., the third - from 10^{-1} to 10^{3} sec., the fourth - up to 10^{6} sec and the fifth - more than 10^{6} sec.

The first area covers lightning overvoltage impulses and a part of switching overvoltage impulses. The decrease in breakdown voltage with increasing duration can be considered the result of an increase in the probability of breakdown with a longer duration of exposure to voltage. In accordance with Fig. 9 this reduction is 25%.

An almost independent damaging voltage on the exposure time characterizes the second area.

The third area extends from 10^{-1} sec to a duration measured in tens of minutes. This area includes quasi-stationary overvoltage and power frequency test voltages.

Oscillography of PD processes showed that in this area, an oil duct breakdown is not prepared by preliminary low intensity PDs (less than 10^{-7} C).

The fourth area extends to 10^6 sec. In a number of cases, when the models were held for 10^4 – 10^5 sec, a gradual increase in the intensity of the PD during exposure was established. The dependence of the breakdown voltage on time in this area is determined by the intensity of the process of insulation destruction by weak PDs, which prepare the breakdown of the oil duct. Since the course of these processes is influenced by the ratio of the volume of oil and solid insulation, the movement of oil, temperature fluctuations and a number of other factors, research in this area should be carried out both on models and on experimental transformers.

The fifth area has practically no experimental data. However, the results of experiments on model studies of the characteristics of the PD in the oil-barrier insulation allow us to consider acceptable (for the design with input to the middle of the winding) at the highest operating voltage, the average intensity in the oil duct, equal to 40 kV/cm (effective value). For the same oil-barrier insulation design, the allowable tension during one-minute exposure to power frequency voltage is taken to be 70 kV/cm (as recommended by Panov).

The CIGRE report published a less detailed version of the Kaplan & Morozova curve (Fig. 10), which has become widespread in the English-speaking world.

The VTC by Kaplan & Morozova is an improvement on similar GE, Westinghouse and Panov curves. It has retained its relevance to the present day.

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Morozova conducted further research to obtain experimental data on the extension of the volt-second characteristic of the main insulation of transformers for more than 100 hours

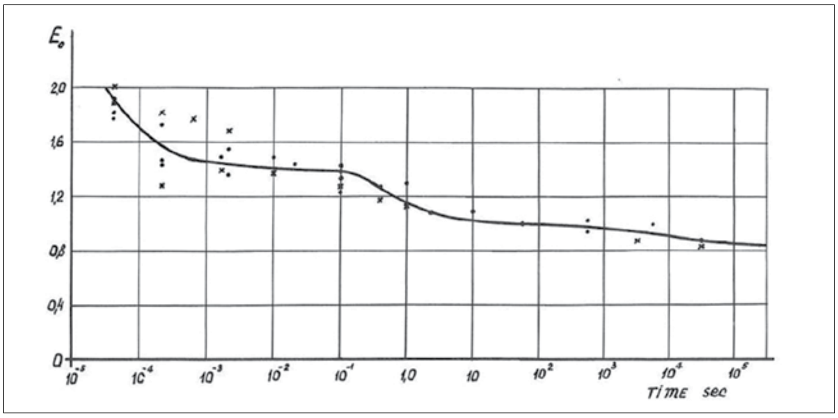

Figure 10. = *Fig. 3, CIGRE-1970* [6]

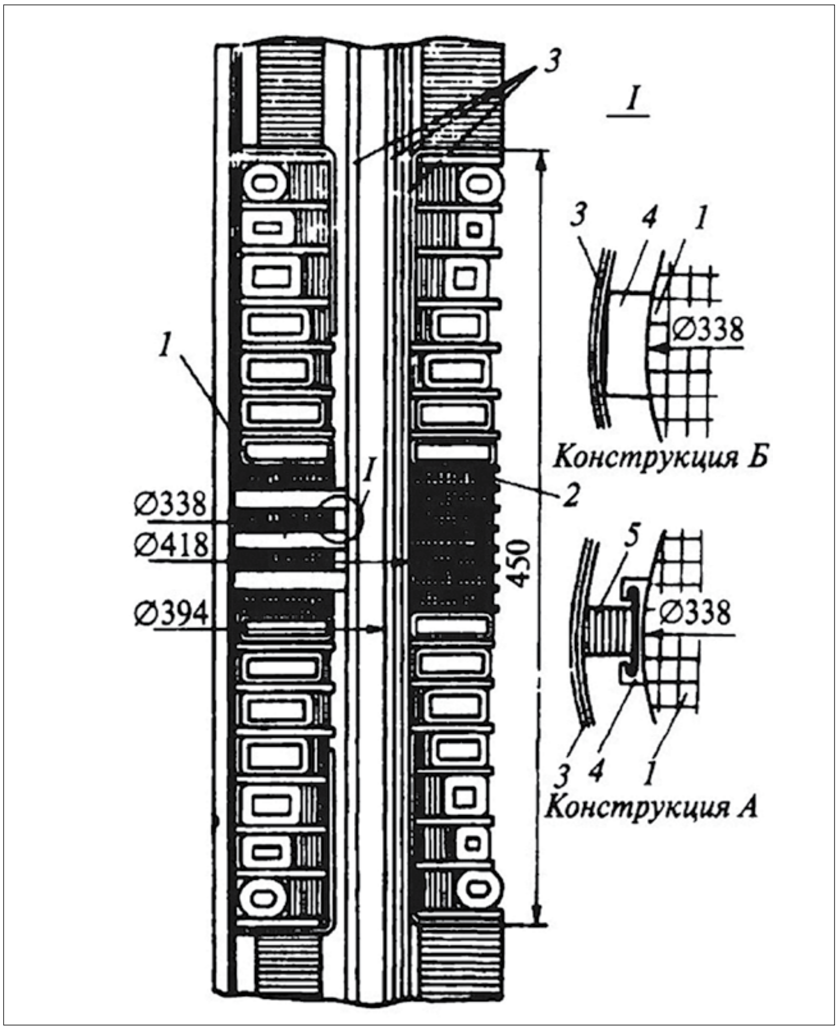

Figure 11. Model of the main insulation with an input in the middle of the winding (MKI) acc. Morozova-1977

1, 2 - windings; 3 - barriers made of electric cardboard; 4 - gasket forming a duct between the coils; 5 - spacer rail; I - the duct under study and the design of the distance closest to the winding barrier

In addition to the MBI and MKI models, the study was also carried out on a simplified model consisting of two toroids of the same diameter (168/132 mm) insulated with cable paper with a thickness of 0.7 mm per side

6. Volt-second characteristic by Morozova, 1977

Morozova conducted further research to obtain experimental data on the extension of the volt-second characteristic of the main insulation of transformers for more than 100 hours [7]. The bottom line is that in EHV and UHV transformers, the excess of test voltages over the operating voltage is significantly reduced, and in these transformers, the operating voltage becomes decisive when choosing the dimensions of the internal insulation relative to the ground. The study of the regularities that determine the long-term strength of the oil-barrier main insulation of concentric windings "with an input in the middle" (linear lead of the winding is at the middle of its height) and "with an input at the end" (linear lead is at the end of the winding), as well as determining the allowable operating intensity of the insulation between windings and between the winding and the magnetic core were the main objectives of these studies.

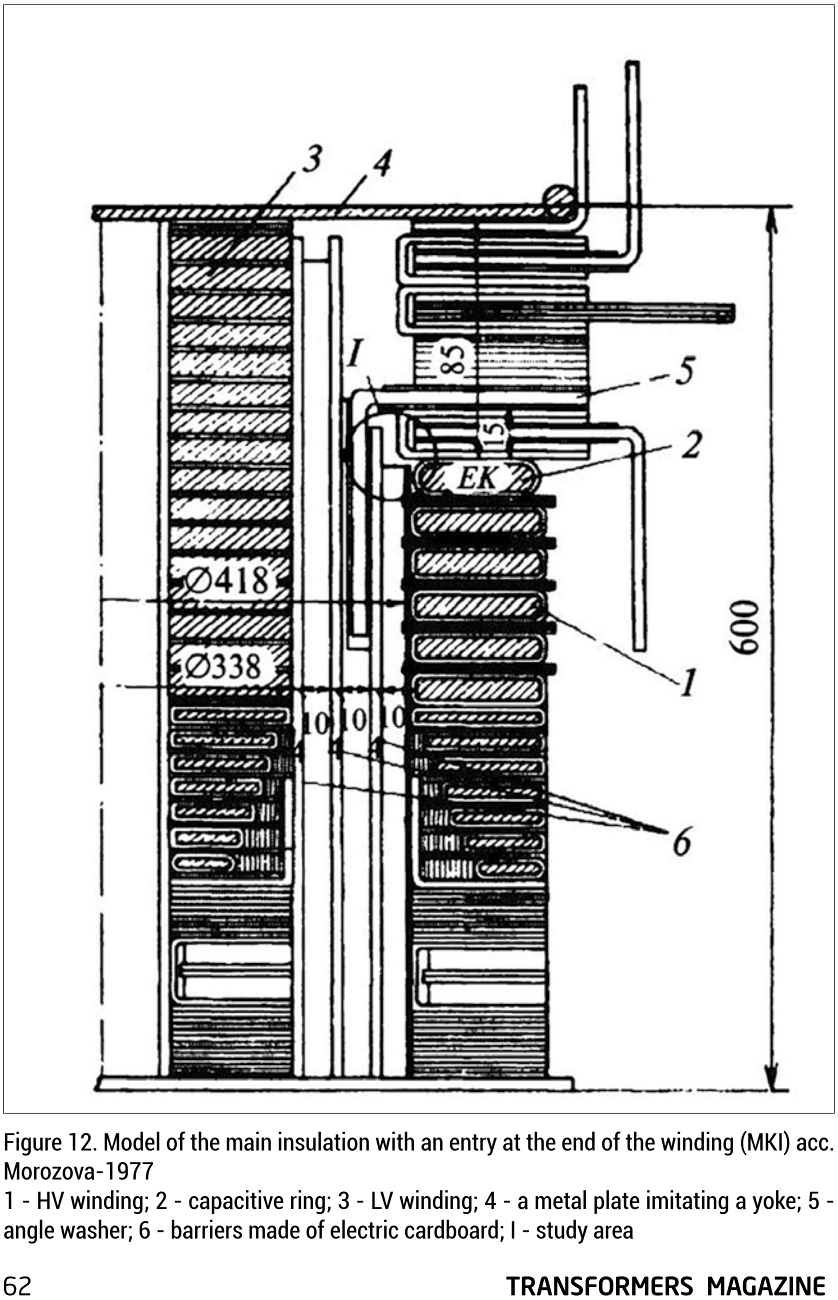

Figure 12. Model of the main insulation with an entry at the end of the winding (MKI) acc. Morozova-1977
1 - HV winding; 2 - capacitive ring; 3 - LV winding; 4 - a metal plate imitating a yoke; 5 - angle washer; 6 - barriers made of electric cardboard; I - study area

Figs. 11 and 12 show the design of the models used in the study: winding insulation models with an entry in the middle (MBI (barrier insulation model)) and with an end entry (MKI (terminal insulation model)). In the MBI, the investigated oil duct is located near the inner winding, in its middle part, where the intensity is higher than in the rest of the model. Three variants of the MBI were used, differing from each other in the size of the studied duct (10 and 24 mm) and in the design of the parts that form the duct: design A, which provides a higher electrical strength of the duct, and design B (Fig. 11).

The MKI models (Fig. 12) reproduce a typical end seal design in which strength determines the oil gap from the capacitance ring to the corner of the barrier, the corner washer.

In addition to the MBI and MKI models, the study was also carried out on a simplified model consisting of two toroids of the same diameter (168/132 mm) insulated with cable paper with a thickness of 0.7 mm per side; gaskets made of electric cardboard, fastened with a rail, form an oil duct between the toroids. Thermal vacuum treatment of the models included vacuum drying, impregnation, and filling with oil under vacuum before testing.

A direct study of the long-term strength could consist of testing models with increasing voltage in steps with a very long holding time (for example, 10,000 h) at each step. Such a test is practically impossible. Therefore, in this work, the models were tested at different voltage exposure times of 50 Hz at each stage from 1 min to 1000 h. Based on the test results, a volt-second characteristic was constructed - the dependence of the breakdown voltage on the time elapsed from the beginning of the exposure of a given voltage stage to the moment of the breakdown of the oil duct (Fig. 13).

Since there is always a certain amount of dissolved gases in the oil of a working transformer, special studies were carried out on the processes of gas evolution during prolonged exposure to an electric field with a strength close to the allowable one, calculated from the volt-second characteristic of Fig. 13. Simplified models (toroids) with a channel of 8 and 10 mm were tested. The models were energized for 500–1000 h. Oil samples were taken every 100–200 h to determine the composition of dissolved gases. During the tests, the intensity in the oil was 50, 60 and 67 kV/cm. At each intensity for a given channel size, 7–8 models were tested.

The test results were as follows. At an intensity of 50 kV/cm for 1000 hours, there is practically no gas evolution. At an intensity of 60 and 67 kV/cm, the gas formation process is more intense, which makes it possible to accept an intensity of 50 kV/cm as a value acceptable at operating voltage, regardless of the size of the duct.

Morozova recommended this intensity value for testing in transformers intended for trial operation. Based on the obtained volt-second characteristic, Morozova gives the following ratio of one-minute E_{1min} and long-term E_{long} strength of oil barrier insulation: $E_{1min} = 0.8\ E_{long}$.

Morozova's conclusions are also important for us: 1) confirmation of Panov's axioms that a) the dielectric strength of the main oil-barrier insulation when inserted into the middle of the winding or at the end (relatively homogeneous field) under long-term (up to 1000 h) exposure to power frequency voltage is determined by the dielectric strength of the oil duct adjacent to the winding (which in turn depends on its size and the shape of the structural details that distance the first barrier from the winding); b) that for the design of insulation, it is necessary to use not average, but minimum values of breakdown voltages; 2) breakdown of the oil duct in the specified time range is recorded as a powerful PD with an intensity of $(1\text{-}5)\times10^{-7}$ C, which is *not prepared by low-intensity PDs.*

to be continued...

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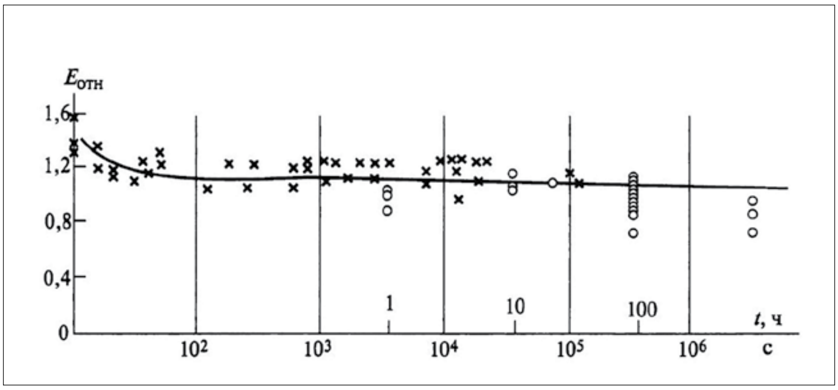

Figure 13. Volt-second characteristic of oil-barrier insulation acc. to Morozova-1977
Eотн - relative intensity - the ratio of the damaging intensity at a given value of t to the minimum damaging intensity during a one-minute exposure; t is the time from the beginning of exposure at a given stage to the breakdown of the oil duct; x - experience with the breakdown of the oil duct; o - experience without the breakdown of the oil duct

At an intensity of 60 and 67 kV/cm, the gas formation process is more intense, which makes it possible to accept an intensity of 50 kV/cm as a value acceptable at operating voltage, regardless of the size of the duct

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