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Volt-time curves of oil-filled power transformer insulation

Survey of 100 years of research – Part V

Vitaly Gurin

ABSTRACT

This fifth part of the article examines the significant contributions of Okabe to the statistical analysis and modeling of insulation behavior in EHV and UHV power transformers. Okabe's approach is grounded in the probabilistic treatment of partial discharge inception (PDI) under AC voltage over extended periods, ranging from milliseconds to several months. The article outlines how Okabe derived voltage–time (V–t) characteristics using simplified insulation models for core- and shell-type transformers, focusing on turn-to-turn, coil-to-coil, and barrier-oil-duct structures. By applying Weibull statistics to experimental data, Okabe proposed an equation describing the relationship between voltage, time, and the probability of partial discharge occurrence, thus providing a foundation for statistically optimized insulation design. Despite the innovation in duration and methodology, the relative simplicity of Okabe's models and the absence of breakdown voltage data is noted, highlighting that his work complements but does not replace more advanced Soviet research.

KEYWORDS:

breakdown voltage, coefficient of variation, EHV, IEC, IEEE, internal insulation, PD, probability distribution, shell-type transformer, transformer oil, UHV, volt-time curve

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To justify the choice of experimental models, Okabe describes the insulation structure of modern EHV and UHV core- and shell-type transformers

9.3. Okabe's works, 2006 [6, 7]

Okabe's first article begins by explaining that creating more rational and reliable insulation designs for EHV and UHV transformers is possible based on the probability of insulation breakdown under overvoltages and operating voltage in the power system during their entire service life. This approach enables optimized and statistically coordinated internal insulation for transformers. Such characteristics can be obtained from insulation models. To justify the choice of experimental models, Okabe describes the insulation structure of modern EHV and UHV core- and shell-type transformers.

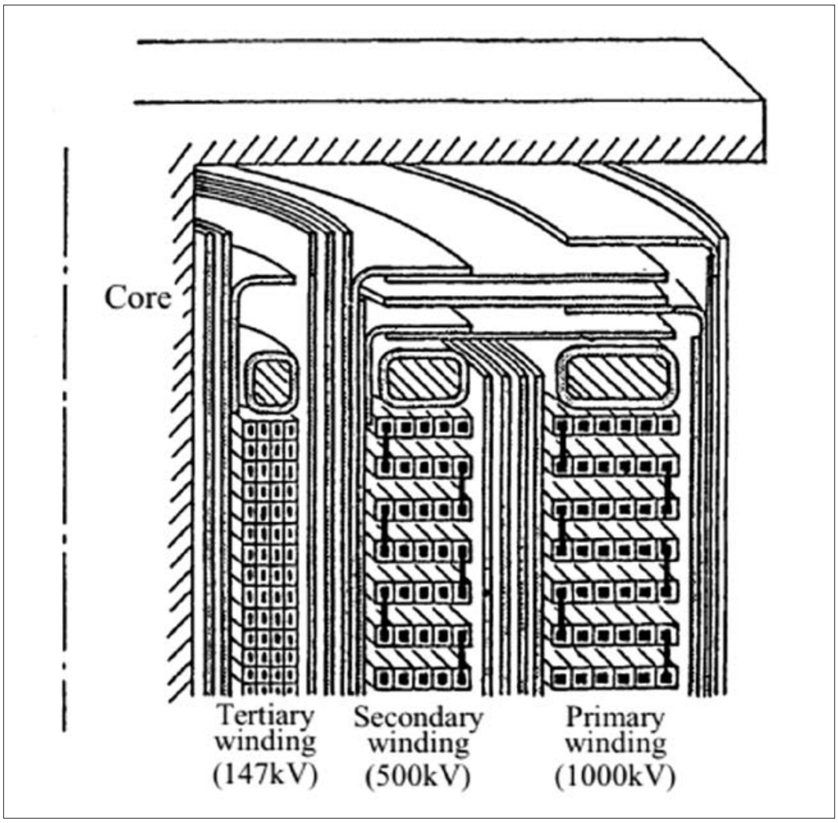

Figure 16. Insulation structure of a core-type transformer according to Okabe

Fig. 16 illustrates an image of the winding structure of a core-type transformer using an UHV apparatus as an example. The major insulation elements of a transformer are the main insulation between the primary and secondary windings and insulations towards the tank and between coils and between turns in the windings. In general, the main insulation and the tank insulation, being barrier-oil-duct structures, are characteristically determined by the AC voltage, due to the ratio of the AC withstand voltage test and the lightning impulse withstand voltage test, the potential distribution, and the characteristics of oil-immersed insulation structures such as the impulse ratio. On the other hand, the coil-to-coil and turn-to-turn insulations in the windings are characteristically determined by the lightning impulse due to potential oscillation.

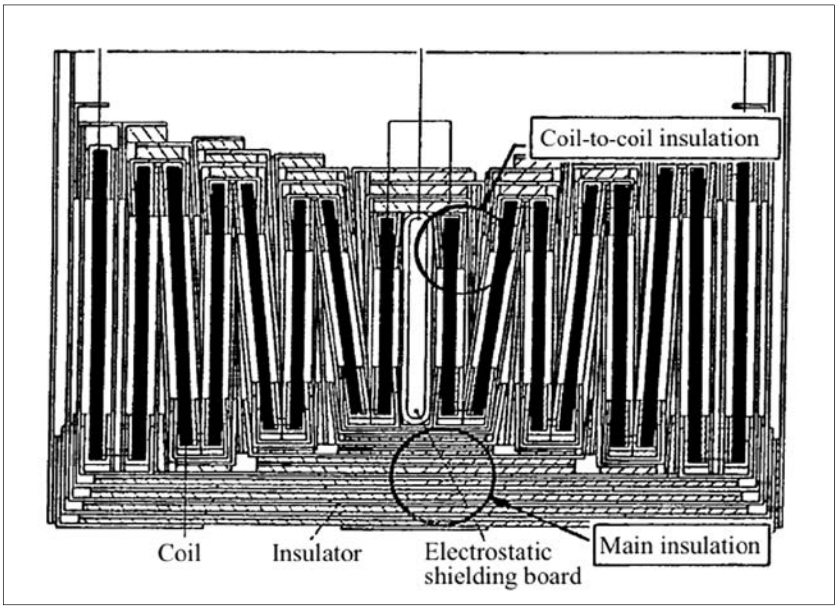

Figure 17. Insulation structure of a shell-type transformer according to Okabe

Fig. 17 illustrates an image of the winding structure of a high-voltage, high-capacity shell-type transformer. Due to its structure, there is no part that corresponds to the main insulation of the core-type and the insulation towards the tank and iron core is in a barrier-oil-duct structure. Unlike the core-type, the insulation between coils is a barrier-oil-duct structure, whereas the insulation between turns is the same as the core-type.

The study of the insulation structure of transformers allows the author to select the insulation models shown in Figs. 18 and 19.

Fig. 18 shows the structures of insulation models used in the experiment for V-T characteristics under AC voltage. These three models are considered to cover

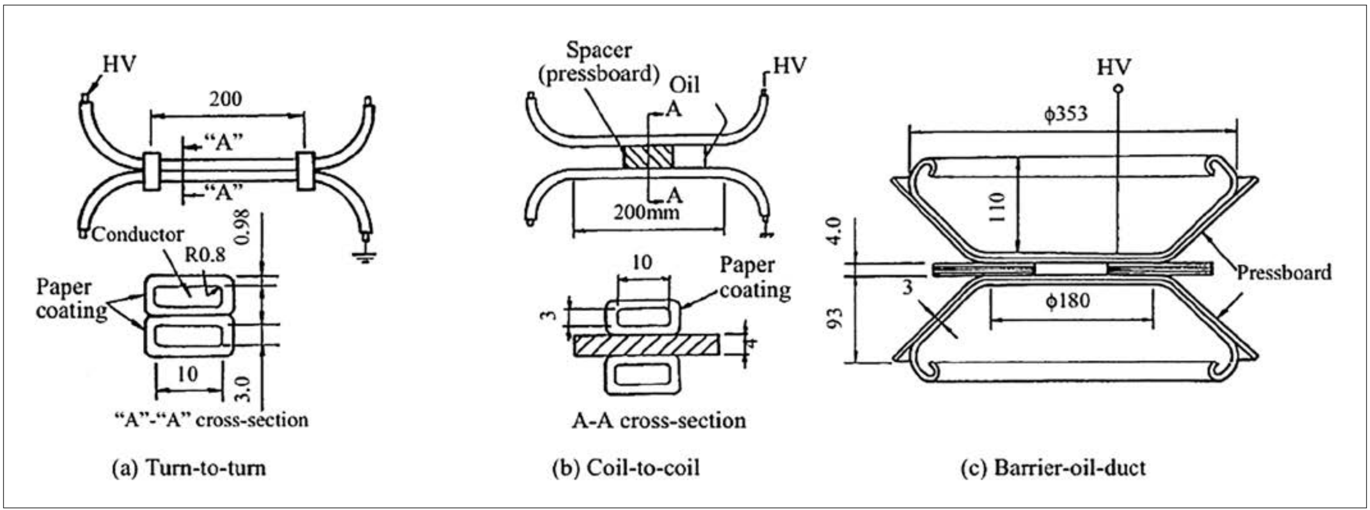

Figure 18. Insulation models of a core-type transformer according to Okabe

all the major insulation compositions of transformers. As for dimensions, the turn-to-turn insulation model shown in Fig. 18 (a) has rectangular copper wires 3 x 10 mm in dimensions and insulating paper coating 0.98 mm in thickness.

The coil-to-coil insulation model shown in Fig. 18 (b) has the same rectangular copper wires with insulating paper coating as the turn-to-turn model, which oppose each other via a spacer 4 mm in thickness. In the barrier-oil-duct insulation model shown in Fig. 18 (c), a pressboard 3 mm in thickness is in close contact with an electrode and a spacer is used to constitute a 4 mm oil-duct.

Note that the turn-to-turn and coil-to-coil models differ from similar models used by Ikeda et al., and the barrier-oil-duct insulation model is completely similar to Ikeda et al. (compare Fig. 6 (A, B, C) - see Part IV of this article - and Fig. 18).

Fig. 19 shows the structure of shell-type insulation models used in this experiment. Two pressboard barriers (2.3 mm in thickness) and a spacer (3 mm in thickness) for forming an oil gap are set between stainless electrodes 105 mm in diameter of the flat section, to constitute a composite insulation model in a parallel flat board shape. The wedge-shaped gap between the electrodes and oil-immersed paper, which was not an object in this experiment, was filled with epoxy resin to enhance insulation.

Okabe studied "partial discharge inception voltage-time characteristic (V-t characteristic)" at alternating voltage

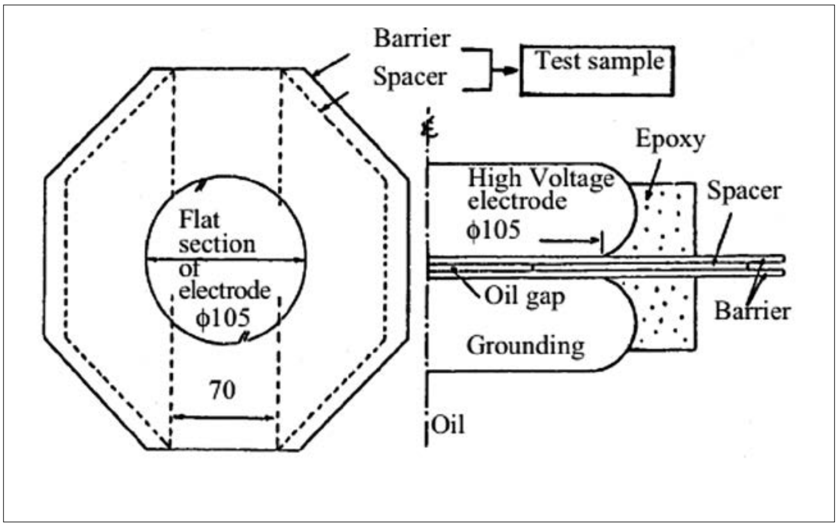

Figure 19. Insulation models of a shell-type transformer according to Okabe

The wedge-shaped gap between the electrodes and oil-immersed paper, which was not an object in this experiment, was filled with epoxy resin to enhance insulation

observed in the time range from several tens of milliseconds to a long time range from three to four months. Assuming the average partial discharge inception (hereafter, PDI) voltage (PDIV) value obtained through the one-minute step-up method is 100%, six to seven levels were set up between 80% and 110%, made sudden application of such voltages, and the time elapsed was obtained from the voltage application to PDI. Partial discharge was measured using the ERA method at a detection sensitivity of 5-10 pC.

Fig. 20 shows experimental results for the turn-to-turn model. Assuming 50 kV is 100%, which is 50% of the PDIV obtained through the one-minute step-up method, the time elapsed was obtained from the sudden application of 80 % to 110 % voltage until PDI.

Fig. 21 shows experimental result for the coil-to-coil model. Assuming 80 kV is 100%, which is 50% of the PDIV obtained through the one-minute step-up method, the time elapsed was obtained from the

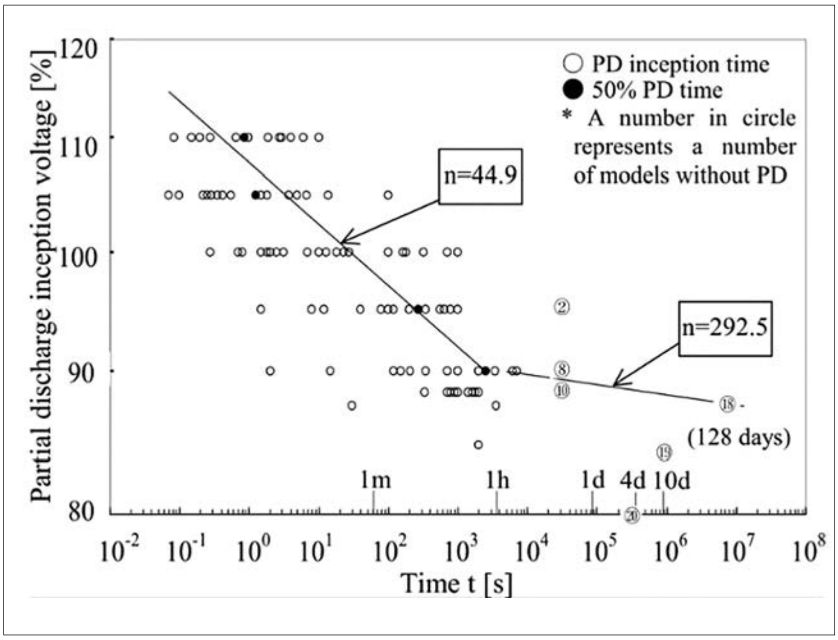

Figure 20. V-t characteristic of the turn-to-turn model of a core-type transformer according to Okabe

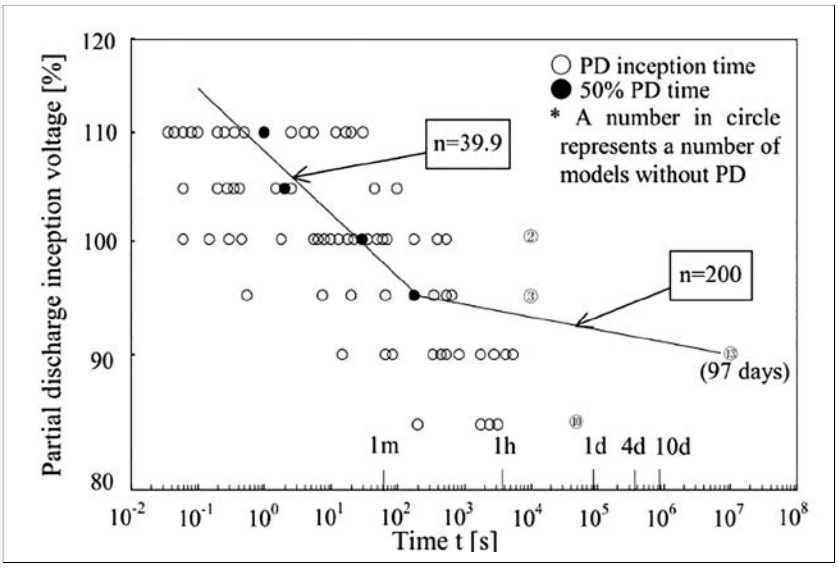

Figure 21. V-t characteristic of the coil-to-coil model of a core-type transformer acc. to Okabe

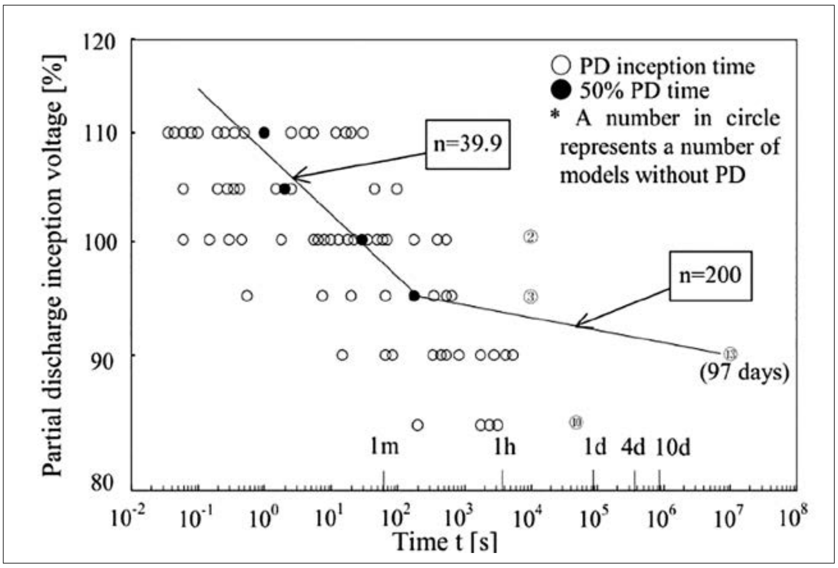

Figure 22. V-t characteristic of the barrier-oil-duct model of a core-type transformer according to Okabe

sudden application of 85% to 110% voltages until PDI.

Fig. 22 shows experimental result for the barrier-oil-duct model. Assuming 135 kV is 100%, which is 50% of the PDIV obtained through the one-minute step-up method, the time elapsed was obtained from the sudden application of 80% to 110% voltages until PDI.

Fig. 23 shows the experimental result of V-t characteristic of PDI under AC voltages a shell-type transformer. In this figure, values enclosed in the squares represent the number of cases where partial discharges occurred while the voltage is raised, and values enclosed in circles represent the number of cases where partial discharges did not occur until the experiment was stopped.

As seen in Figs. 20-23, the scatter of PDIV in time is very large. In all figures, the characteristic of 50% of the PDIV is presented as two approximating straight lines. The points of inflection of the lines inexplicably differ in time: in Figs. 20 and 23 they are around 1 hour, in Figs. 21 and 22 - a little over 1 min. Near the straight lines are the values of n (slope) associated with the shape parameter of the Weibull distribution as a function of time and voltage. Okabe proposed an equation relating the probability of occurrence of partial discharges, voltage and time, which also has two constant values (constant *a* and Weibull distribution shape parameter *m*) and, as a result, the formula for testing transformer insulation with alternating current:

"1.5 *pu* × 1 *hour* + √3 *pu* x 5 min *utes* + 1.5 *pu* × 1 hour"

Okabe also studied impulse breakdown voltage-number of voltage applications characteristic (V-N characteristic) observed for up to 1,000 times of application under lightning and switching im-

Partial discharge was measured using the ERA method at a detection sensitivity of 5-10 pC.

Okabe proposed an equation relating the probability of occurrence of partial discharges, voltage and time, which also has two constant values

pulse voltages, which are of less interest to us.

In his second paper [7] Okabe explored the same models as in the first paper, plus "low dielectric constant pressure boards", but taking into account the use of transformers in the field. Experiments included "clean oil" and "hot oil", "trapezoidal waves", "alternating application of positive and negative voltages", "steep frontal waves". The results obtained were satisfactory in almost all cases, but are also of no interest to us.

Conclusions

1. The works of Yakov and Okabe marked a key stage in developing an AC insulation test formula. This formula has evolved over decades based on experience from testing actual transformers and accounts for achievable interference levels when measuring partial discharges at test stations. It has now been standardized, as illustrated in Fig. 24.

2. The following conclusions from the study by Ikeda et al. are important for optimizing the design of transformers insulation: a) for turn-to-turn insulation, PDV depends on partial discharge in the wedge-shaped oil gap between turns, while BDV depends on the puncture strength of insulation paper; b) despite the significantly different insulating structure of the models of turn-to-turn, section-to-section, and oil-duct insulation between barriers, the characteristics of PDV and BDV are similar; c) the PDV and BDV v-t characteristics of all three types of models practically converge (coincide) for durations longer than a few minutes, as shown in the summary Fig. 25.

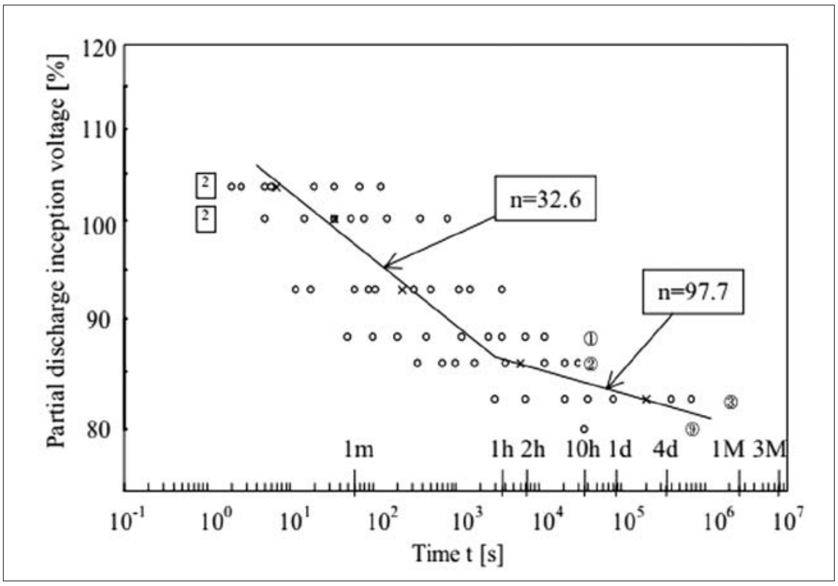

Figure 23. V-t characteristic of the barrier-oil-duct model of a shell-type transformer according to Okabe

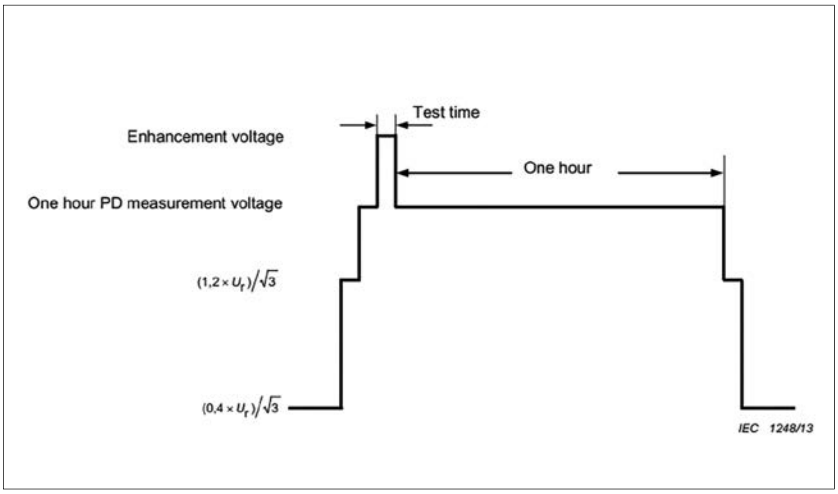

Figure 24. Time sequence for the application of test voltage for induced voltage test with partial discharge measurement (IVPD) according to IEC 60076-3 [8]

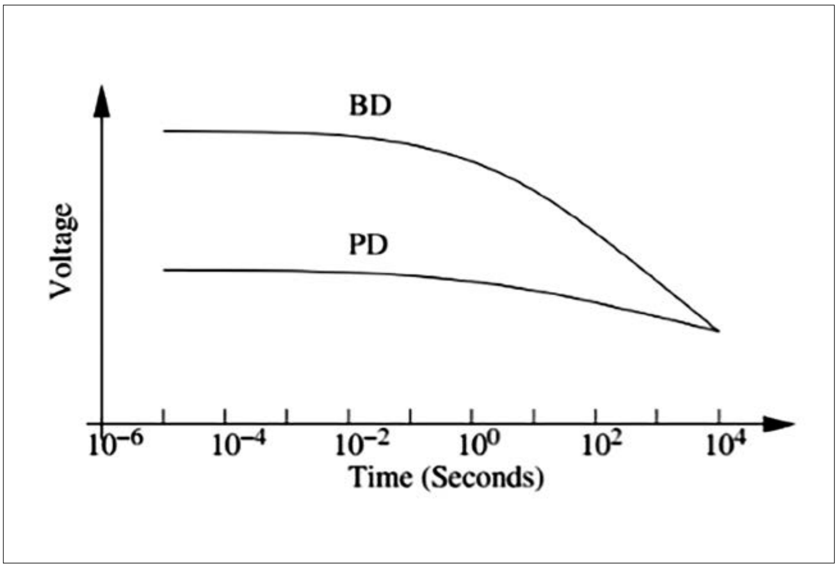

Figure 25. Breakdown and partial discharge volt-time curve (summarizing figure from Ikeda et al. [5])

The works of Yakov and Okabe marked a key stage in developing an AC insulation test formula

3. Okabe's publications expand the range of VTC from 1000 hours (as in the works of Soviet specialists - see Parts II and III of this article) to four months. However, Okabe's models are much more primitive than the Soviet ones, and he only gives data for the inception of partial discharges, but not for breakdown voltages. Therefore, we believe that Okabe's works complement, but do not replace the works of Soviet specialists. He is one of the first specialists to clearly point out the need for a statistical approach to optimizing the internal insulation of power transformers.

4. The important information for us: a) from the work of Ikeda & Menju: CV% of breakdown voltages of transformer oil used in EHV transformers is approximately 15% in the time range from 0.1 to 10^3 min. (Fig. 5 - see Part IV of this article); b) CV%, extracted from the work of Ikeda et at., is in the range of 5 ÷ 9.6 (Table 3 - see Part IV of this article);c) Yakov and all Japanese specialists used Weibull probabilistic paper to process test results. We send this information to our data box, which will be analyzed in the last part of the article.

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