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Volt-time curves of oil-filled power transformer insulation

Survey of 100 years of research – Part IV

Vitaly GURIN

ABSTRACT

The fourth part of the article discusses the well-known work of Yakov and data from Japanese experts on partial discharge and breakdown volt-time curves of models of insulation of power transformers and probability distributions. Coefficients of variation of breakdown voltage models are extracted from the work of Ikeda et at. for data collection in order 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, coefficient of variation, EHV, IEC, IEEE, internal insulation, PD, probability distribution, shell-type transformer, transformer oil, UHV, volt-time curve

In the mid-1970s, the issue of determining the duration of the test and the magnitude of the ACLD test voltage, along with the evaluation of the test results using the PD criterion, became a central topic

8. Volt-time relationships for PD inception by Yakov, 1979 [1]

In the mid-1970s, the issue of determining the duration of the test and the magnitude of the ACLD test voltage, along with the evaluation of the test results using the PD criterion, became a central topic. PD has fascinated specialists in transformer engineering for over a decade. The term "PD-free transformer" was on everyone's lips and in advertising brochures. WG 12.03 WC 72.03 of Study Committee No. 72 (Transformers) in CIGRE conducted an international study to define a "volt-time curve," which shows the relationship between test voltage and the time to PD onset, represented as "equiprobability curves." These curves illustrate how to adjust the test voltage to maintain the same probability of PD onset across different test durations. The study involved contributions from various countries: France (EDF and Alsthorn-Unelec), F.R. of Ger-

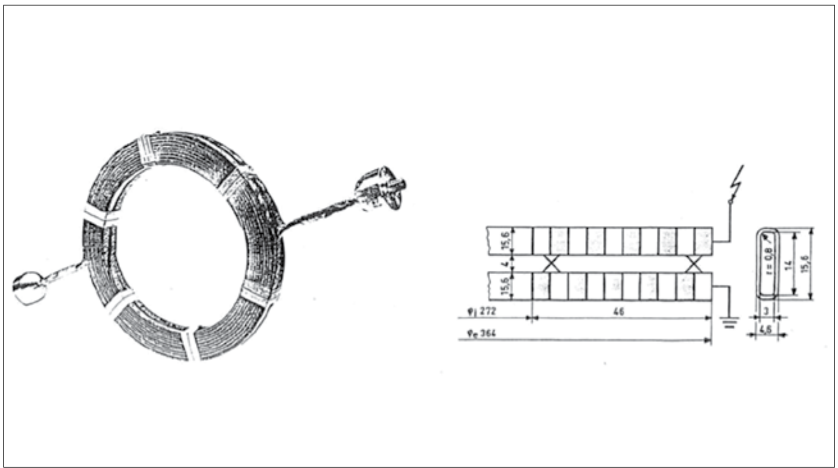

Figure 1A. from Italy

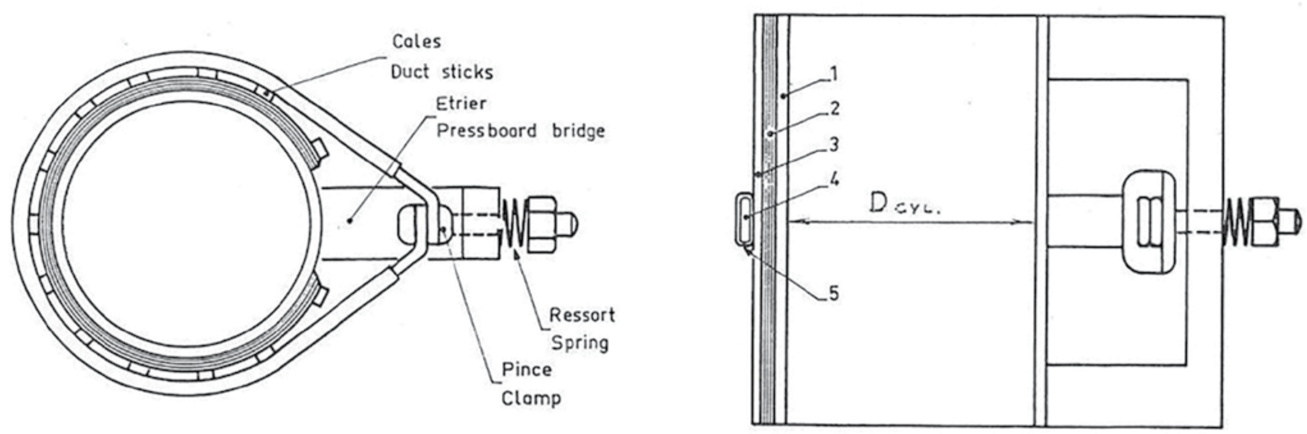

FIGURE 1 B

	Echantillon – *Samples* – B1	Echantillon – *Samples* – B2
1. Cylindre en métal – *Metal cylinder*	Dcyl = 140 mm	Dcyl = 120 mm
2. Rubannage en pressboard – *Pressboard wrap*	1.5 mm épaisseur *thick*	1.5 mm épaisseur *thick*
3. Cales – *Duct sticks*	3 mm épaisseur *thick*	3 mm épaisseur *thick*
4. Conducteur – *Conductor*	12 x 2.5 mm $r = 0.5$ mm	12 x 2.5 mm $r = 0.5$ mm
5. Papier de recouvrement (2 côtés) *Paper covering (two sides)*	1.8 mm	2.25 mm

Figure 1B. from France and the UK

The criterion for PD inception used in the tests was the appearance of a PD impulse with an intensity higher than a specified limit depending upon model geometry and testing conditions

many (Transformatoren Union A.G.), Italy (ENEL and group of transformer manufacturers such as IEL, Italtrafo and TIBB), U.K. (CEGB and NEI Bruce Peebles Ltd. - Parson Peebles Research Laboratory), USSR (Manufacturers' union "ELECTROZAVOD"). The results of the study were published in the journal Electra [1], authored by S. Yakov from CESI, Milan, Italy, the convener of WG 12.03.

The tests were performed using the types of samples shown in Figs. 1. It can be seen that sample A represent the insulation between turns while the others are, respectively, a straightforward and more complex representation of the main insulation of a transformer. The processing of the samples prior to the test followed, on broad lines, the usual practice for the treatment of HV transformers: heating, vacuum drying, and oil impregnation with dry, degassed, and filtered oil.

A set of test voltage levels was chosen based on preliminary tests on the samples, ensuring that the levels correspond to low, medium, and high probabilities of PD inception. For sample A, the series was: 30, 32, 34, 36, 38, 40, 42 kV; for sample B1: 55, 60, 65, 70 kV; for sample B2: 50, 55, 60, 65, 70 kV; for sample C: 90, 100, 110, 120, 130, 140 kV; for sample D: 64, 72, 80, 88 kV. Each sample was subjected to one of these voltage levels until PD inception occurred or, in the event of no discharge, until one hour had elapsed.

The criterion for PD inception used in the tests was the appearance of a PD impulse with an intensity higher than a specified limit depending upon model geometry and testing conditions. The actual values adopted for each type of sample are given in Table 1, together with some informa-

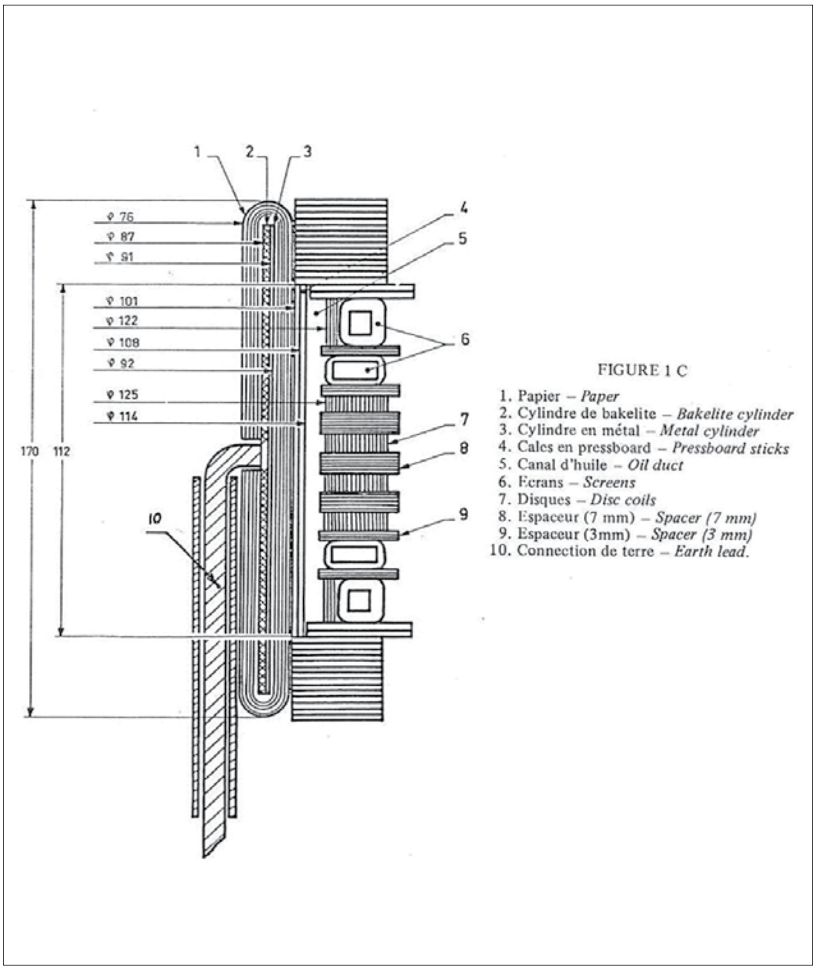

Figure 1C. from the USSR

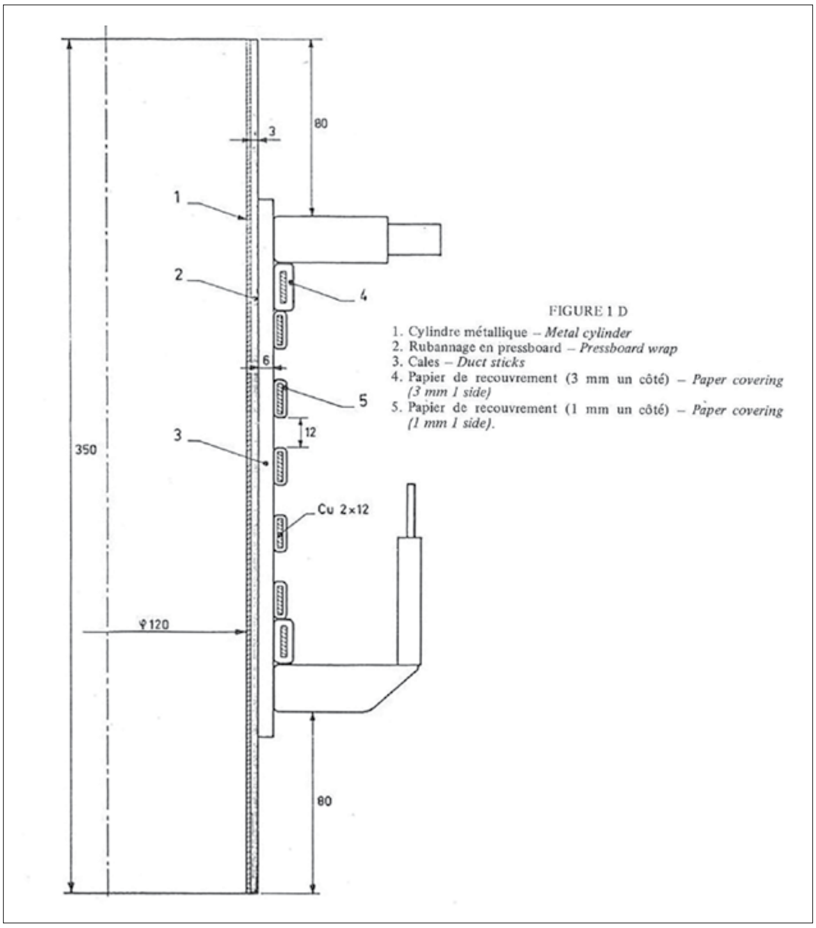

Figure 1D. from Germany

Table 1. Type of sample and test conditions according to Yakov

Type d'échantillon *Type of sample (Fig. 1)*	Nombre total d'échantillons essayés *Total number of samples tested*	Nombre d'essais répétés sur le même échantillon (moy) *Nr of tests repeated on the same sample (average)*	D.P. Critère de seuil *PD inception criterion (pC)*	Temps de repos entre deux essais sur le même échantillon (heures) *Rest time between two tests on the same sample (hours)*
A (Italie) *(Italy)*	10	78	200	12
B_1 (France)	3	150	1 000	5
B_2 (Royaume-Uni) *(U.K.)*	60	7	400	48
C (URSS) *(USSR)*	63	12	10 000	48
D (Allemagne) *(Germany)*	4	25	500	12

The number of PD inceptions Ni, occurred within each of the intervals, expressed as a percentage of the total number of tests N performed at that voltage level, gives the PD inception probability P

tion regarding other differences in the test conditions.

For each voltage level, the test results consist of a series of values of the time elapsed until the PD inception. To simplify the data processing, these values were grouped in a few arbitrarily chosen time intervals. The number of PD inceptions Ni, which occurred within each of the above intervals, expressed as a percentage of the total number of tests N performed at that voltage level, gives the PD inception probability P in percent.

The selected time intervals and the corresponding values of Ni and P obtained when testing sample A at various voltage levels are shown in Table 2. Similar tables were compiled for all other samples.

The experimental points (P, U) of Table 2 for each time (from ≤ 0.1 min to ≤ 60 min) were plotted on the Weibull probability paper. A family of parallel straight lines was then constructed using the least squares method, from which points were determined for the value P = 50 percent and were plotted on logarithmic paper. Applying the least squares method once again, the best straight line through the points was obtained (Fig. 2). This is the

Table 2. The values of Ni and P, obtained when testing sample A

KV	N	$t \leq 0.1$ min		$t \leq 0.3$ min		$t \leq 1$ min		$t \leq 3$ min		$t \leq 10$ min		$t \leq 30$ min		$t \leq 60$ min	
		Ni	P %	Ni	P %	Ni	P %	Ni	P %	Ni	P %	Ni	P %	Ni	P %
30	130	8	6.2	10	7.7	13	10.0	13	10.0	15	11.5	17	13.1	18	13.8
32	130	11	8.5	12	9.2	16	12.3	17	13.1	17	13.1	20	15.4	24	18.5
34	120	8	6.7	13	10.8	22	18.3	32	26.7	36	30.0	43	35.8	45	37.5
36	100	24	24.0	26	26	33	33.0	39	39.0	47	47.0	54	54.0	63	63.0
38	100	31	31.0	37	37	45	45.0	52	52.0	64	64.0	75	75.0	80	80.0
40	100	51	51.0	61	61	70	70.0	76	76.0	83	83.0	89	89.0	90	90.0
42	98	73	74.5	80	81.6	87	88.8	96	98.0	98	100	98	100	98	100

In the equiprobability time-voltage curve, although the tests were limited to 1 hour, they can be extrapolated to 104 minutes (nearly 7 days)

required equiprobabilistic time-voltage curve (straight line on the log-log paper). Although the tests were limited to 1 hour, the line was extrapolated to 10^4 minutes (nearly 7 days).

The equiprobabilistic time-voltage curves were obtained similarly for the rest of the samples. An attempt to combine all five curves was unsuccessful. With an increase in the extrapolation time, they diverge sharply (Fig. 3). Yakov explains this circumstance by the fact that the occurrence of partial discharges in oil paper insulation is a random phenomenon. The physical mechanism for the occurrence of PD is not well known, it depends on the type of insulation design and may change over time.

Other attempts at the definition of partial discharge inception voltage-time characteristics are considered in Chapter 9.

9. Data from Japanese scientists

9.1. Work by Ikeda and Menju, 1979 [2]

Authors from Tokyo Shibaura Electric Co. investigated breakdown probability distributions of transformer oil by repeat-

An attempt to combine all five curves was unsuccessful, and Yakov explains that it is caused by the fact that the occurrence of partial discharges in oil paper insulation is a random phenomenon

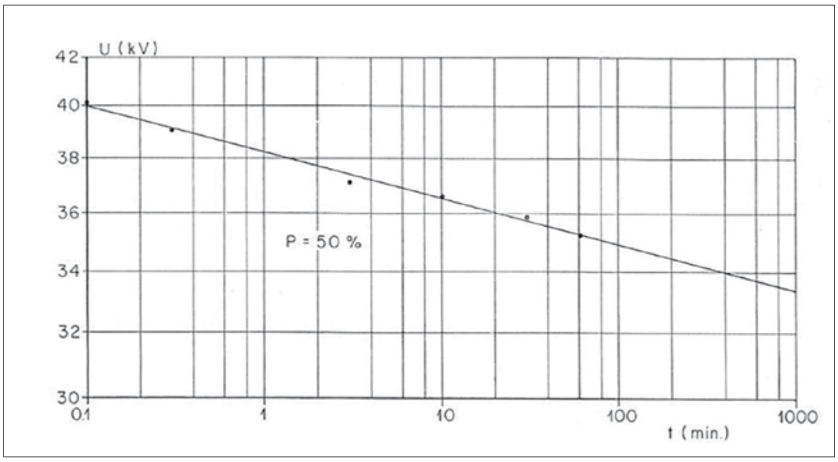

Figure 2. The equiprobabilistic time-voltage curve for sample A

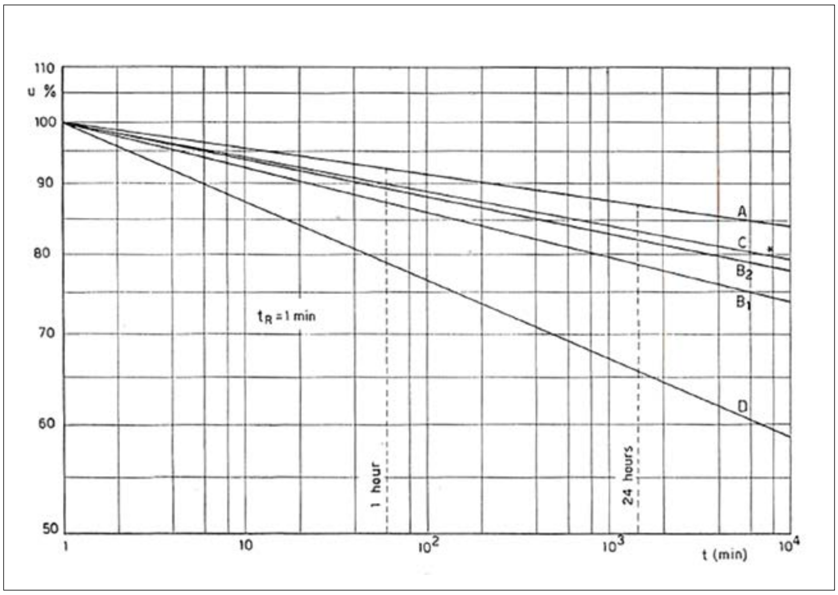

Figure 3. Failure to define a generalized equiprobabilistic time-voltage curve [1]

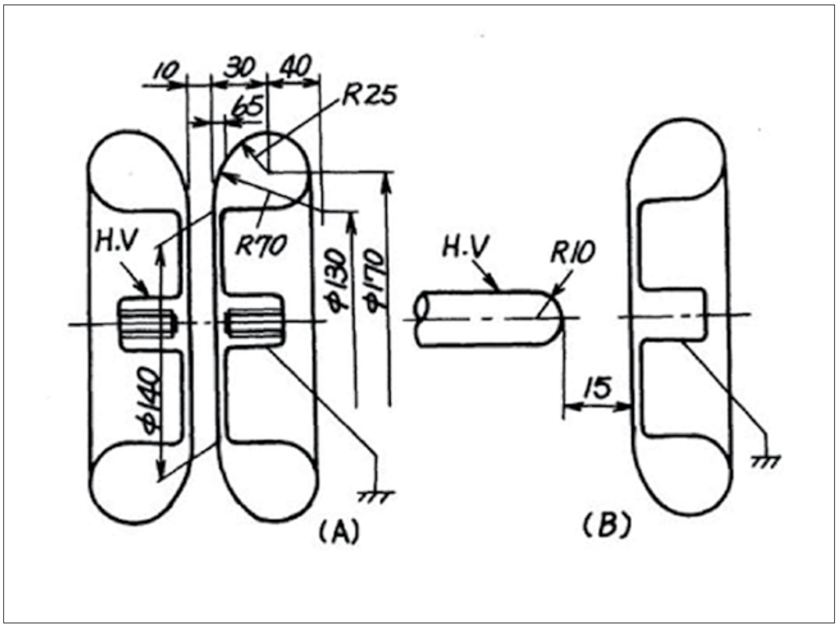

Figure 4. Electrode configurations of test oil gap acc. to Ikeda & Menju
A: Uniformly stressed oil gap
B: Non-uniformly stressed oil gap

For the breakdown probability, the Weibull distribution was applied, and it can be shown that the coefficient of variation of breakdown voltages is about 15% and does not depend on the stressing time

edly applying AC voltages with various durations. Their paper was recommended and approved by the IEEE Transformers Committee.

Two types of oil gaps, a uniformly stressed oil gap and a non-uniformly stressed oil gap, were used. The electrode shapes are shown in Figs. 4 (A) and (B), respectively. The electrodes were made of stainless steel, and their surfaces were polished with 0.25 mm diamond wax. In the case of the uniformly stressed oil gap, the gap length ranges from 10 mm ± 1%.

Oil quality is the same as that of general practice for EHV transformers. Breakdown voltages were obtained at the stressing time 10 sec, 1 min, 10 min, 1 hr, 10 hr.

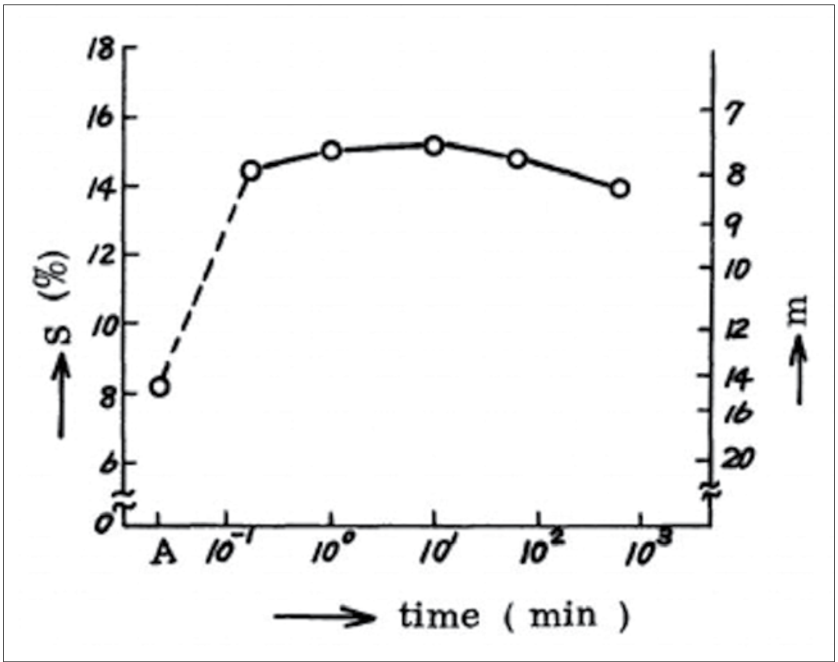

Figure 5. Time dependency on the coefficient of variation of breakdown voltages of transformer oil according to Ikeda & Menju
S: Coefficient of variation of breakdown voltages
m: Shape parameter of Weibull distribution
A: Continuously increasing voltage

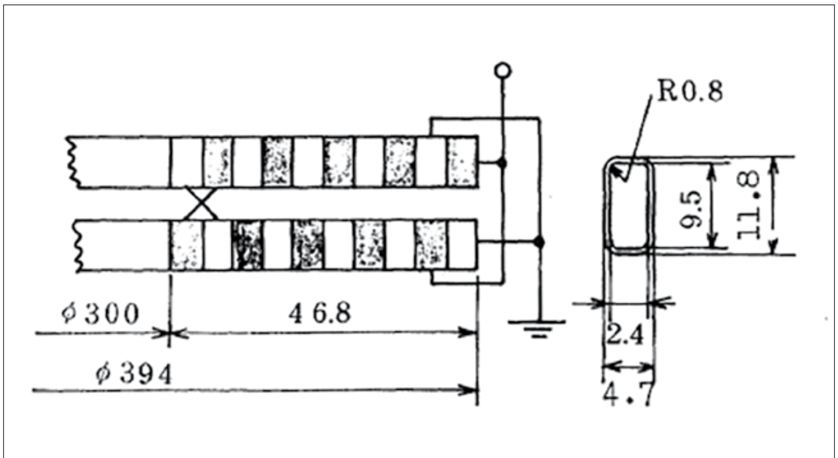

Figure 6A. Test piece of turn-to-turn insulation acc. to Ikeda et al.

For the breakdown probability, the Weibull distribution was applied (*other distributions were not considered, although, based on the physical nature of the breakdown of liquids, the distributions of extreme values of Gumbel should also have been considered. - Vitaly Gurin)*. The authors showed that the coefficient of variation of breakdown voltages is about 15% (Fig. 5) and practically does not depend on the stressing time. The Weibull distribution with a shape parameter *m* of about 8 also does not depend on the stressing time. The obtained results are used to construct equiprobabilistic V-t characteristics of transformer oil.

Furthermore, the authors, based on the fact that the oil breakdown voltage is lower than the breakdown of solid insulation, and when the stressing time has elapsed about 10 hours, the V-t characteristics become almost flat, transfer their conclusions to the entire insulation system of the transformer. Defending the abolition of the one-minute test ACSD and the introduction of the one-hour ACLD test [3], they recklessly claim that an ACLD test at 1.5 Um is equivalent to running a transformer for 114 years. The erroneousness of this conclusion was shown by the negative experience of the operation of 735 and 765 kV transformers in the mid-1980s [4].

9.2. Work by Ikeda, Yanari and Okubo, 1982 [5]

In the work discussed in paragraph 9.1, Ikeda investigated transformer oil. His work, together with that of other colleagues from Toshiba Corporation, is a logical continuation of [2] and is devoted to the major insulation components of a transformer. Investigated here are turn-to-turn insulation, section-to-section insulation and oil duct insulation between barriers shown in Figs. 6. Probability distributions of partial discharge (PD) and dielectric breakdown voltage have been determined.

The paper dielectric used for turn-to-turn and section-to-section insulation is kraft paper, with a density of 0.8 and a thickness of 0.076 mm. The desired insulation thickness, ranging from 1 to 2 mm, was achieved by wrap-winding multiple layers of the paper.

The test piece was subjected to conditions of a temperature of 110°C and an atmospheric pressure of less than 10^{-1} Torr, for more than 72 hours and was impregnated with transformer oil under 10^{-1} Torr. After the oil filling, the water content in oil was 2 to 7 ppm, and the gas content in the oil was 0.3% to 0.7%. These treatment conditions would be identical to those for the general EHV transformer.

Fig. 7 plots on the Weibull distribution chart the probabilities of the PD inception voltage (PDV) and breakdown voltage (BDV) of turn-to-turn insulation against the lightning, switching impulse voltage and 0.2 seconds and 1 minute of AC voltage to determine the regression lines. This figure reveals that the measured PDV and BDV points of turn-to-turn insulation are well covered by lines on the Weibull distribution chart.

Weibull distribution parameters were determined from regression lines in the

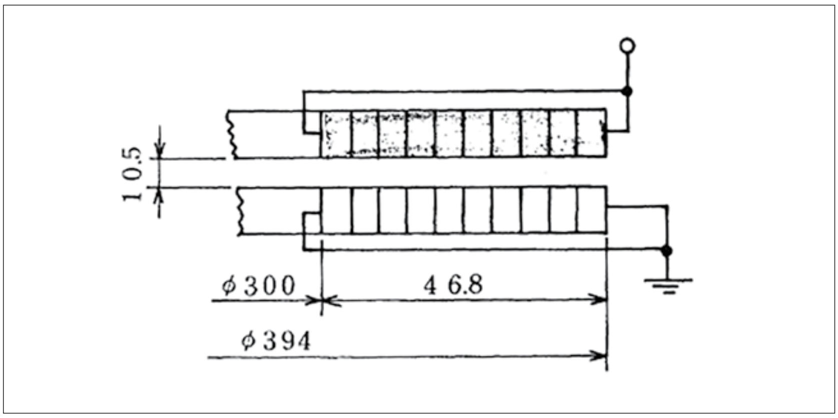

Figure 6B. Test piece of section-to-section insulation acc. to Ikeda et al.

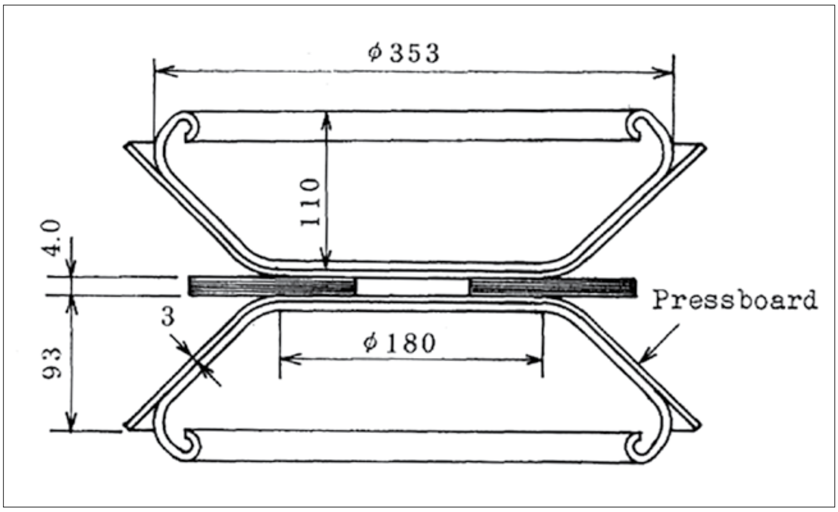

Figure 6C. Test piece of oil duct insulation between barriers acc. to Ikeda et al.

The test piece was subjected to conditions of a temperature of 110°C and an atmospheric pressure of less than 10^{-1} Torr, for more than 72 hours and was impregnated with transformer oil under 10^{-1} Torr

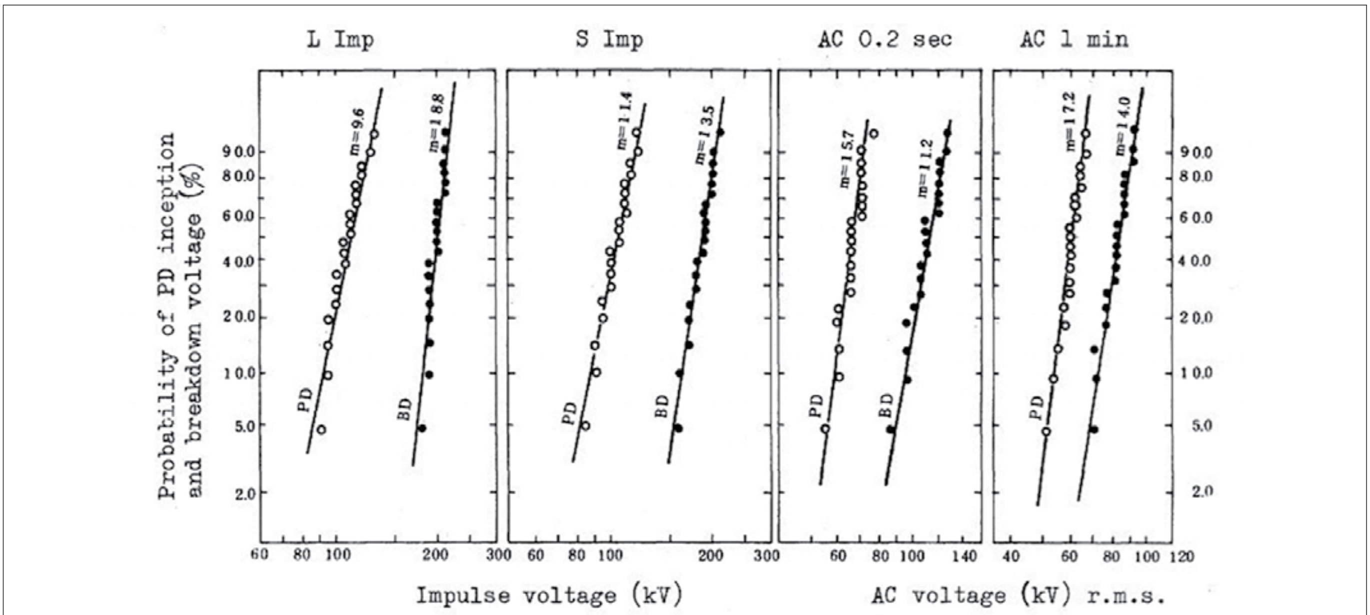

Figure 7. Probability distribution of partial discharge and dielectric breakdown voltage of turn-to-turn insulation acc. to Ikeda et al. of turn-to-turn insulation acc. to Ikeda et al.

Numerical value on the vertical axis for 4d (4 days) indicates the number of experiments where no partial discharge occurred with a voltage of 46 kV applied to 20 test pieces connected parallel for four days

figure. The greater the inclination of the regression line, the higher the shape parameter m. The greater the deviations of PDV and BDV, the smaller m. For the impulse voltage, deviations of PDV are greater than those of BDV. PDV depends upon the partial discharge in the wedge-shaped oil gap between turns, while BDV depends upon the puncture strength of insulation paper.

Fig. 8 shows the results of PDV-t characteristics of the AC long term on turn-to-turn insulation. In this experiment, if no partial discharge occurred, testing on the test piece was terminated, even though a voltage had been applied for 10 hours. The number of test pieces whose testing was terminated is shown on the vertical axis for 10 h (10 hours) in the figure. The numerical value (20) on the vertical axis for 4d (4 days) indicates the number of experiments where no partial discharge occurred with a voltage of 46 kV applied to 20 test pieces connected parallel for four days.

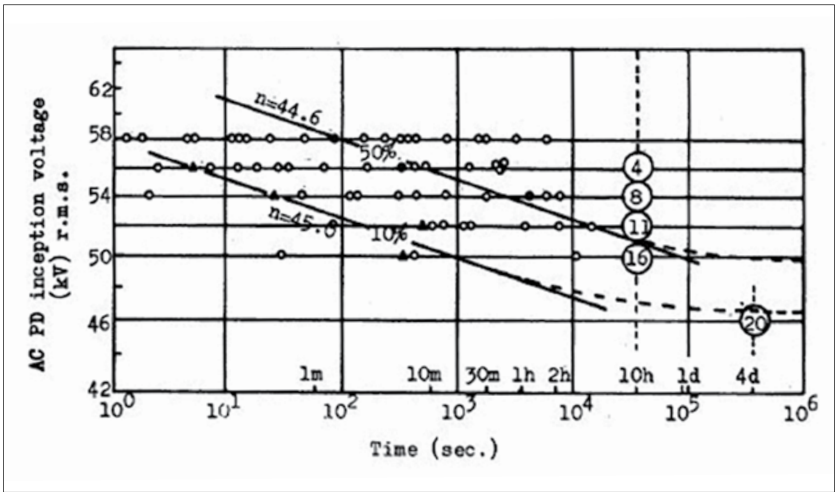

Figure 8. Long term V-t characteristics of turn-to-turn insulation for ac voltage acc. to Ikeda et al.

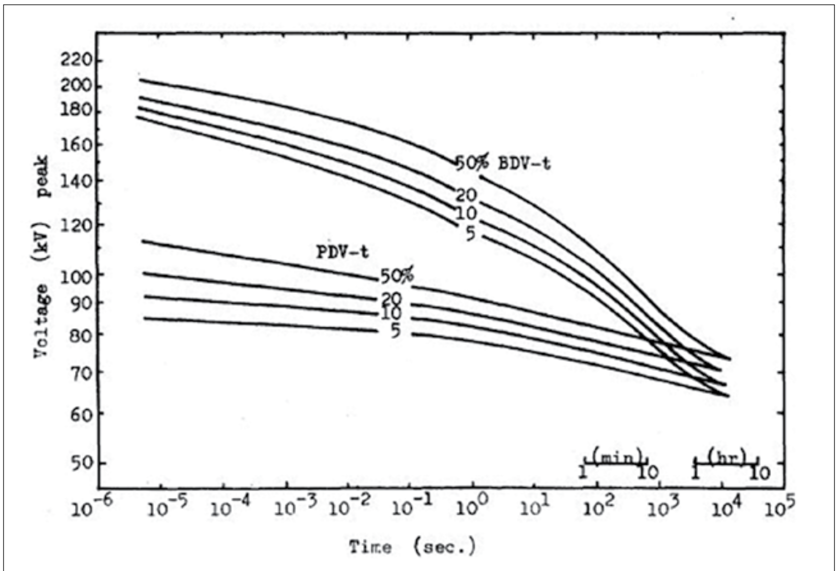

Figure 9. Long term equi-probabilistic V-t characteristics of turn-to-turn insulation acc. to Ikeda et al.

Based on the results shown in Figs. 7 and 8, PDV-t and BDV-t characteristics from several msec to several hours may be derived, which are shown in Fig. 9.

Fig. 9 reveals that the PDV-t curve is located at a low level, being approximately 30 to 50% of the BDV-t curve within several tens of seconds, while, in the ac long-term region of more than several tens of minutes, the PDV curve is close to the BDV-t one. This is because the occurrence of PD causes the puncture of paper dielectrics in a time delay of several minutes or several tens of minutes, even at the same voltage. Compared to BDV-t characteristics, PDV-t characteristics are featured by their flatness with little inclination over the whole-time region.

Fig. 10 shows the probability distribution for PDV and BDV of section-to-section insulation. The distinction between section-to-section insulation and turn-to-turn insulation is that, in the former, there is an oil duct of approximately 10 mm in addition to the paper dielectrics between turns. The results of section-to-section insulation are reviewed by contrast with those of turn-to-turn insulation.

Concerning section-to-section insulation, its PDV and BDV have greater deviations compared to turn-to-turn insulation, which is particularly noticeable in the AC time region. This may be because deviations of discharge inception in the oil duct between sections cause influence. In section-to-section insulation, PDV is approximately 60% of BDV. The S.Imp/L.Imp ratios of PDV and BDV are 93% and 89%, respectively. These values are a little different compared to those for turn-to-turn insulation.

Fig. 11 shows AC long-term V-t characteristics of section-to-section insulation. There are a few differences between both the probabilities. But the inclination is considerably steep vis-a-vis turn-to-turn insulation. Regarding 20 test pieces, it has been confirmed that no PD occurs for 10 hours at 55 kV and for four days at 53 kV.

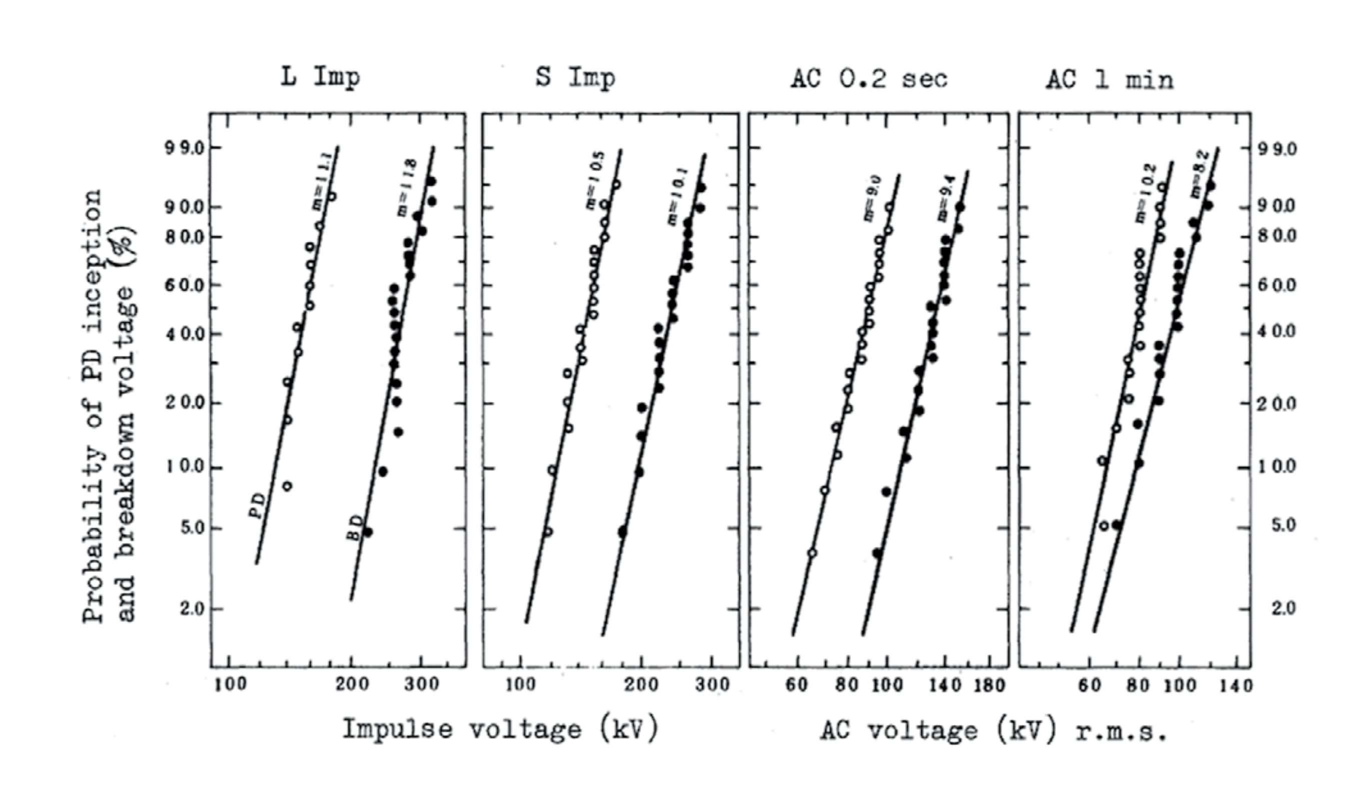

Figure 10. Probability distribution of partial discharge and dielectric breakdown voltage of section-to-section insulation acc. to Ikeda et al.

Concerning section-to-section insulation, its PDV and BDV have greater deviations compared to turn-to-turn insulation, which is particularly noticeable in the AC time region

Fig. 12 shows probabilistic V-t characteristics of section-to-section insulation for the long-term region. The tendency of the curve is similar to that for turn-to-turn insulation. The former is closer to a linear line than 10 to 10^6 sec.

Fig. 13 shows the probability distribution of PDV and BDV of Oil Duct Insulation between Barriers. Fig. 14 shows PDV-t characteristics for the AC long term, and Fig. 15 shows V-t characteristics for the long-term region.

Fig. 15, which displays the probability distribution and parameters of V-t characteristics, reveals that oil duct insulation provides greater lightning and switching impulse ratios than turn-to-turn insulation and section-to-section insulation because the pressboards located at both sides of the oil duct are thick, providing high puncture strength. Regarding deviations, there is no significant difference between turn-to-turn insulation and section-to-section insulation, which show very similar tendencies. Turn-to-turn insulation, section-to-section insulation and oil duct insulation have considerably different insulating structures. For these insulation structures, the oil-impregnated solid dielectrics and oil gaps are arranged between electrodes in a similar fashion and similar PDV and BDV characteristics are obtained.

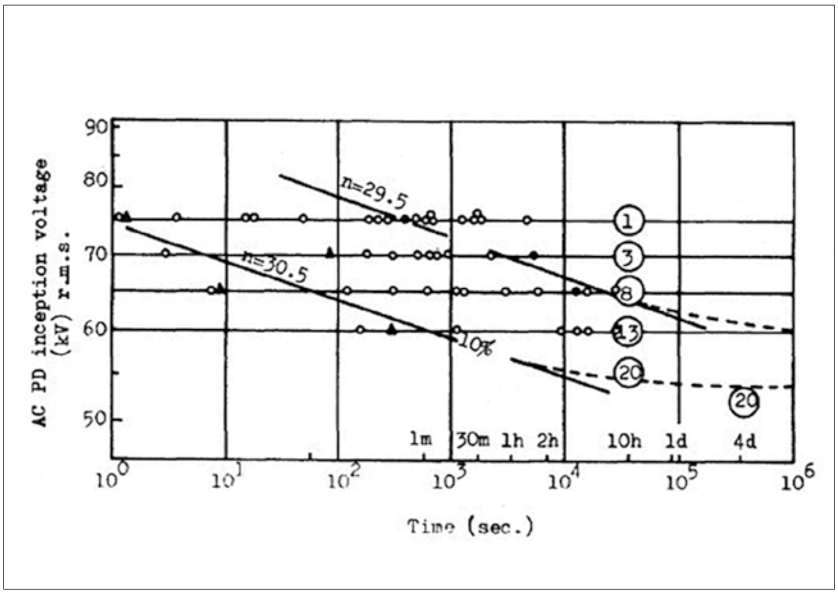

Figure 11. Long term V-t characteristics of section-to-section insulation for AC voltage acc. to Ikeda et al.

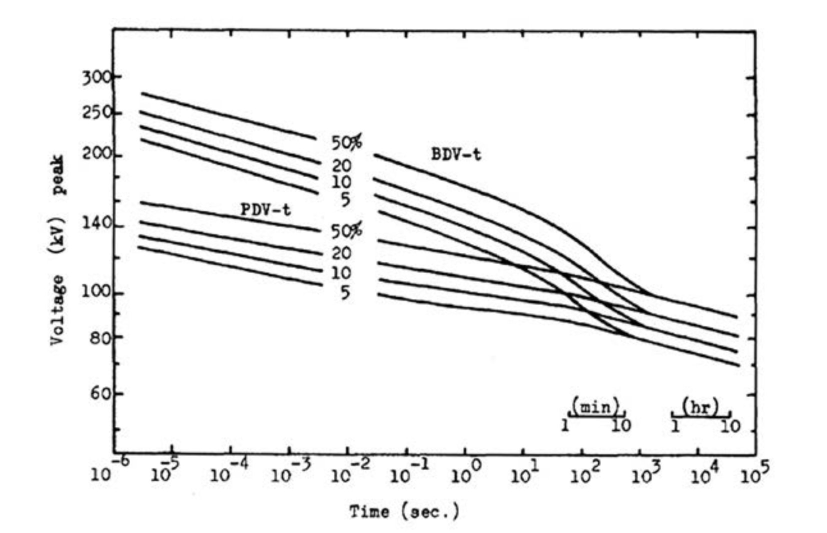

Figure 12. Long term equi-probabilistic V-t characteristics of section-to-section insulation acc. to Ikeda et al.

The inclination of PDV-t characteristics over the long term, shown in Fig. 10, is steeper than that of turn-to-turn insulation but less than that of insulation. Equiprobabilistic V-t characteristics for the long term show a considerably steep BDV inclination in the lightning and switching impulse region. Unlike turn-to-turn insulation and section-to-section insulation, BDV and PDV converge in the relatively short-term AC region because there are few differences between PDV and BDV at one minute AC.

The coefficients of variation of breakdown voltage, extracted from Figs. 7, 10, and 13, are shown in Table 3.

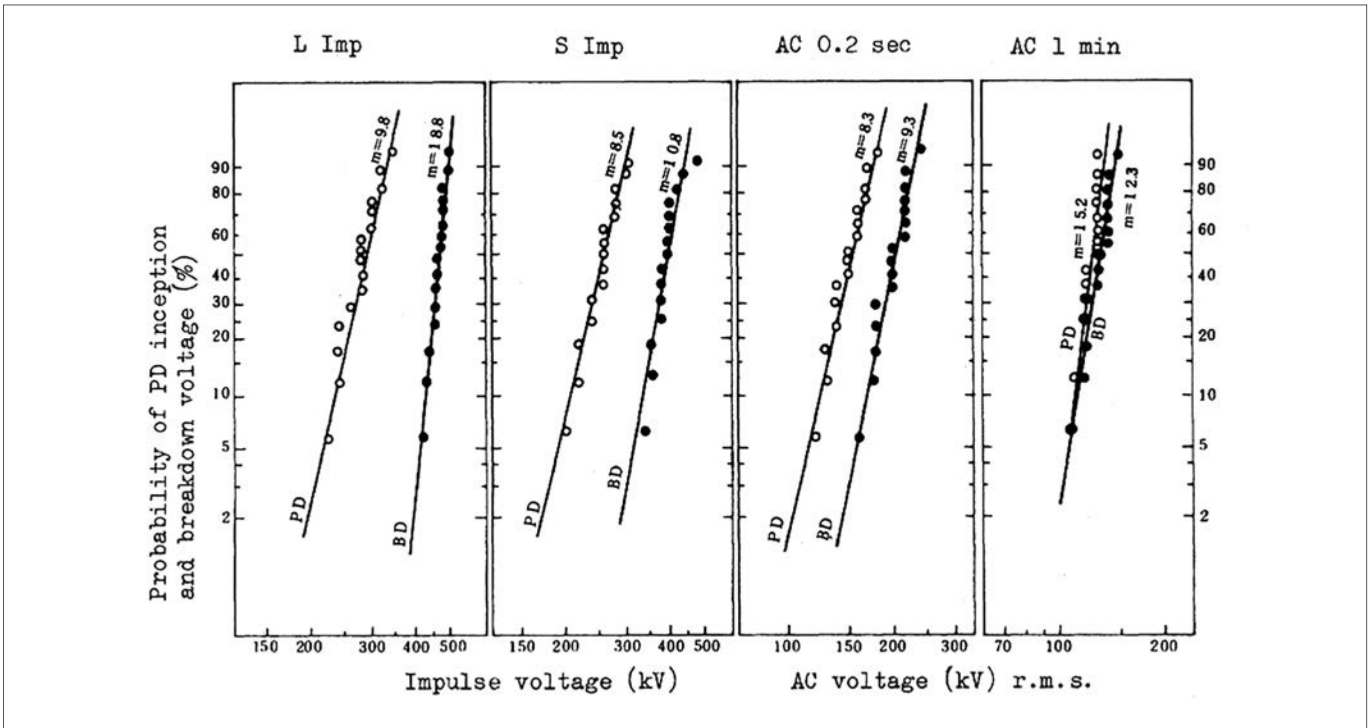

Figure 13. Probability distribution of partial discharge and dielectric breakdown voltage of oil-duct insulation between barriers acc. to Ikeda et al.

Table 3. Statistics from Figs. 7, 10 and 13 (Ikeda et at. [5])

Test name	Insulation models	Number of points, N	Mean/kV	CV%
LI	Turn-to-turn	20	200	7.6
LI	Section-to-section	20	268	9.6
LI	Oil-duct between barriers	16	438	5.0
SI	Turn-to-turn	20	186	8.2
SI	Section-to-section	20	237	12
SI	Oil-duct between barriers	15	398	9.3
1 min. 50 Hz	Turn-to-turn	20	81.4	7.7
1 min. 50 Hz	Section-to-section	18	102	9.1
1 min. 50 Hz	Oil-duct between barriers	15	126	7.8

A quarter of a century later, Okabe continued studies of transformer insulation models [6, 7]. Find out more about this topic in the next issue.

Bibliography

[1] S. Yakov, *Volt-time relationships for PD inception in oil paper insulation,* Electra, No. 67, 1979, pp. 17-28

[2] M. Ikeda, S. Menju, *Breakdown Probability Distribution and Equi-probabilistic V-T characteristics of transformer oil,* IEEE Trans. on Power Apparatus and Systems, Vol. 98, No. 4, July/Aug 1979, pp. 1430 – 1438. DOI: 10.1109/TPAS.1979.319345

[3] *Dielectric Tests and Test Procedures for EHV Transformers Protected by Modern Surge Arresters and Operated on Effectively Grounded Systems 345 kV Through 765 kV*, IEEE Trans. on Power Apparatus and Systems, Vol. 92, No. 5, Oct. 1973, pp. 1752-1762. DOI: 10.1109/TPAS.1973.293724

[4] Vitaly Gurin, Terrence O'Hanlon, *The SDIPF Reliability Curve of old EHV Power Transformers. Historical review for utilities when developing specifications for new transformers. Part III and IV,* Transformers Magazine, Vol. 10, Issue 2, pp. 66-75; Vol. 10, Issue 3, pp. 56-65, 2023

[5] M. Ikeda, T. Yanari, H. Okubo, *PD and BD probability distribution and equi-probabilistic V-t characteristics of oil-filled transformer insulation*, IEEE Trans. on Power Apparatus and Systems, Vol. 101, No. 8, August 1982, pp. 2728–2735. DOI: 10.1109/TPAS.1982.317644

[6] S. Okabe, *Voltage-time and voltage-number characteristics of Insulation elements with oil-filled transformers in EHV and UHV classes,* IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 13, No. 2, April 2006, page 436 – 444. DOI: 10.1109/TDEI.2006.1624290

[7] S. Okabe, *Voltage-time and voltage-number characteristics of insulation elements with large scale oil-immersed transformers under field-use conditions,* IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 13, No. 6, December 2006, page 1261 – 1271. DOI: 10.1109/TDEI.2006.258198

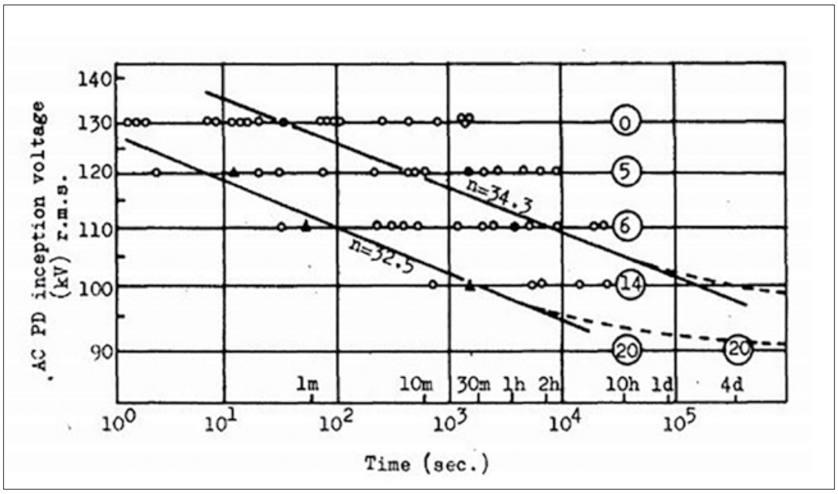

Figure 14. Long term V-t characteristics of oil-duct insulation between barriers acc. to Ikeda et al.

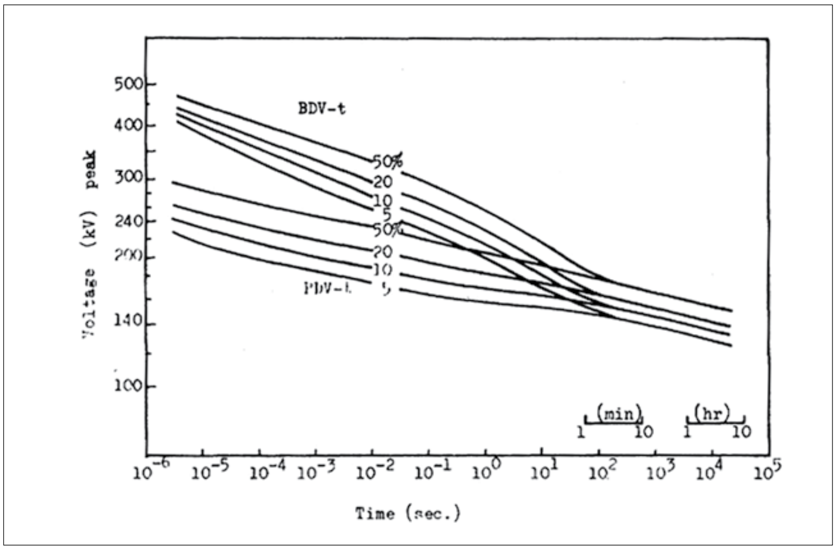

Figure 15. Long term equiprobabilistic V-t characteristics of oil-duct insulation between barriers acc. to Ikeda et al.

The occurrence of PD causes the puncture of paper dielectrics in a time delay of several minutes or several tens of minutes, even at the same voltage

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.