ABSTRACT

One hundred years of data are considered for the electrical strength of power transformer insulation and its dependence on time. Where possible, scatter values of breakdown voltage and partial discharge inception voltage have been extracted from the reference list in order to optimize insulation design and possibly enable future statistical coordination of internal insulation of transformers. This article is intended for young transformer engineers and university faculty teaching undergraduate and postgraduate courses.

KEYWORDS:

breakdown voltage, core-type transformer, General Electric, GOST, failure, EHV, IEC, IEEE, insulation co-ordination, insulation testing, internal insulation, PD, power transformer, probability distribution, shell-type transformer, transformer oil, UHV, volt-time curve, Westinghouse

Over almost a century and a half of transformer development, operating voltages have increased from several hundred volts to 1200 kV, and power ratings from several kVA to 1300 MVA

Volt-time curves of oil-filled power transformer insulation

Survey of 100 years of research – Part I

1. Introduction

Delivering increased electricity consumption, replacing a rapidly aging fleet of existing power transformers, developing transformers for integration with renewable energy sources and deploying smart grids drive upgrades to the global power transformer market. The average annual production volume of transformers for the period 2019-2027 will increase by 7.91% [1]. Often taken for granted, the reliability of the electricity supply, essential for the economy and the well-being of society, is decisively ensured by power transformers. At the same time, the increasing complexity of power systems places an enormous responsibility on the transformer industry to supply reliable transformers.

Power transformers (in this article, transformers for AC power lines) are complex three-dimensional, electromagnetic structures. Over almost a century and a half of transformer development, operating voltages have increased from several hundred volts to 1200 kV, and power ratings from several kVA to 1300 MVA. This progress has been possible thanks to an ever-deeper understanding of electromagnetic, electrodynamic, thermal and dielectric phenomena inside the transformer. Most can now be simulated on computers so that appropriate design changes can be made during the design phase to meet customer requirements without potential problems, as a transformer runs for 35 years or more.

Insulation is studied the least. It consists of a combination of transformer oil, paper and pressboard. Paper wrapped around closely spaced conductors in windings insulates adjacent turns and adjacent layers as a continuous solid insulation. Insulation between windings and from them to the ground is an alternation of oil and barriers to separate heavily loaded oil. Between current-carrying parts of tap-changers, only oil gaps are used. Transformer oil also serves as a coolant; cardboard provides the mechanical strength of an insulating structure. Windings and solid insulation are mostly handmade for transformers above a few MVA. Due to the complexity of physical processes, not only is theory lacking for the breakdown of an entire insulation structure, but even a satisfactory theory lacks for the breakdown of one oil in a transformer.

Theoretical studies established the following main mechanisms of breakdown in liquids:

1) Electrical, with the development of electron avalanche, leaders and streamers

2) Ionic, utilizing the ion conduction in contaminated liquid

3) Suspended particles, which polarize in the field and concentrate, resulting in breakdown

4) Gaseous, where the presence of gas bubbles decreases local dielectric strength

5) Electro-convection, involving dynamics of space charge in liquid and charge deposition on cellulose insulation.

In more than a half-century of the author's experience in factory testing and repairing power transformers in the field, no mechanisms would be required to explain the breakdown of transformer oil other than the influence of often uncontrollable contamination or gaseous bubbles. For free-breathing transformers, the main sources of contamination are moisture, oxygen and other gas inclusions, as well as solid particles that have entered a tank during transformer maintenance or oil treatment. External sources can be minimized by encapsulating a transformer. Internal sources of pollution are non-metallic cellulose particles from paper and cardboard, metal particles from mechanical or electrical wear, moisture from the chemical decomposition of cellulose, and products of the chemical decomposition of oil as a result of its oxidation (acids, aldehydes and ketones). In addition to oil impurities, among other factors affecting the insulation strength (e.g., duration of voltage, frequency, thickness of oil channels, thickness of solid insulation, degree of field uniformity, stressed volume of oil, location of the surface of solid insulation

Every major manufacturer has accumulated data by trial and error for the dielectric strength of insulation in their power transformers

relative to electric field lines, and temperature) the primary factor is time.

Transformer insulation design is an art and usually a manufacturer's expertise. Every major manufacturer has accumulated data by trial and error for the dielectric strength of insulation in their power transformers. For many years, factories have been testing up to the breakdown of various types of models, ranging from the simplest electrodes in oil to reproducing life-size transformer insulation units (in the former USSR, even entire phases of 500 and 750 kV transformers were modeled). The insulation design recommended by the researchers was then tested in situ; results were not always positive. Currently, designers use semi-empirical formulae which are "hardwired" into transformer calculation programs. Software packages do most of the heavy computing that was done by hand in the past. Mistakenly, companies and managers have come to the conclusion that it takes less experience than in the past to do the same job. This has led to a lot of garbage in simulations. Companies do not recognize the advantage of older, experienced engineers. They are paid less because in the opinion of management, less experienced engineers can do work on a computer just as well. This provokes some specialists to leave engineering for a position in management; fewer and fewer experienced engineers are engaged in engineering. Presently, not only young engineers but also experienced designers are guided by what a computer generates without thinking about the physical nature of real-world phenomena. In particular, they only vaguely imagine the meaning of the volt-time curve (VTC).

Volt-time curve (VTC) is also known as: volt-second characteristic, volt-time characteristics, volt-time characteristic curve, v-t characteristic, voltage-time characteristic, volt-time relation, volt-time relationship, volt time factor, voltage/time curves, time-voltage curve and time-voltage relation.

We will use the phrase from the original source below.

VTC is at the heart of transformer insulation coordination.

In the 1920s, insulation failures of power transformers in operation during thunderstorms became more frequent in connection with the development of 220 kV networks. To prevent such failures, engineers considered how far the VTC of an arrester should lie below the VTC of a transformer, i.e., about insulation coordination. *"Systematic efforts at insulation coordination may be said to date from 1926"* (quoted from [2]). In 1930, Montsinger (research engineer of the General Electric Company), as chairman of the Transformer Subcommittee of the Electrical Machinery Committee USA published, together with Dann (a member of this subcommittee from Westinghouse) recommendations for coordinating transformer surge strength and line insulation using suitable lightning arresters [3]. These recommendations reflected contemporary knowledge and intensified further laboratory experiments in these firms to study VTC insulation of oil-filled transformers, not only in the lightning surge range but also at longer exposures in time.

It is interesting to note that in those years, the one-minute insulation test voltage of 220 kV power transformers could be selected from the following values: 461, 510, 570 and 625 kV. At present, the former minimum of 461 kV has become the maximum value in the range of IEC recommended values of 275, 325, 360, 395, 460 kV.

The margin between the VTC (Fig. 1) of a transformer and an arrester has long been actively discussed. It decreases due to the accumulation of knowledge about insulation, improvement of its design and production processes (assembly, drying and oil impregnation) of transformers and improvement of arresters. However, it is still different for HV, EHV, and UHV power systems and in different countries within the same voltage level. Current insulation coordination procedures are described in IEC 60071-1 and IEC 60071-2. These procedures to determine appropriate transformer isolation levels are usually the responsibility of the purchaser. The IEC 60076-3 standard describes applicable tests for transformers of a particular voltage class.

As a rule, the authors cited here take the average curve between scattered points as the VTC of both the transformer and the protective device. Statistical methods of insulation coordination (used in the case of self-healing insulation for quantifying the probability of breakdown) for the internal insulation of oil-filled transformers is not expected in the near future.

In order to take the first timid step toward statistical methods, we not only recall the origins and trace the accumulation of knowledge about VTC insulation of power transformers but also try to extract from experimental data statistical param-

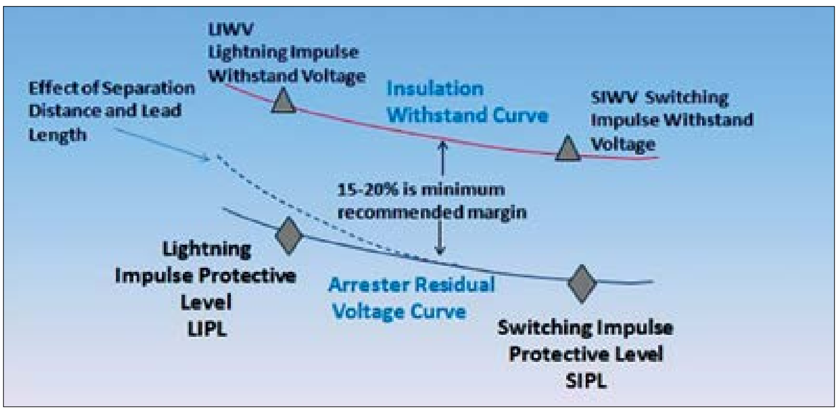

Figure 1. Explanation of margin in the coordination of insulation of modern HV power transformers

eters of the scattering of breakdown voltages and PD inception voltages (number of experimental points, average values, coefficients of variations and distribution laws). The accumulation of such data is necessary both for future statistical coordination and optimization of the internal insulation of transformers.

We focus on original tabular and graphical material from primary sources and pay less attention to formulae derived as a result of experiments (and then included in special programs for calculating insulation). Rarely do authors provide statistics or primary tabular data of interest to us from which it is possible to calculate scattering parameters. Sometimes primary data are plotted graphically. In these cases, we write out numerical data from the graphs. Despite the mistakes of the authors in plotting data and despite our mistakes in extracting figures from graphs, it can be assumed that our coefficients of variation approximately reflect the objective picture of experimental data scattering. In this case, we will focus on scattering corresponding to LI, SI and one-minute voltages because the insulation of modern transformers is designed according to these test voltages.

Let's start our review from the good old days of typewriters and slide rules when basic data on the VTC of transformer insulation were recorded. In some cases, data have not lost their significance over time. Let us first consider experimental data on VTC using the example of the three oldest and largest manufacturers of power transformers - General Electric Company, Westinghouse Corporation and Soviet transformers engineering, accumulated over almost 100 years of research.

When a transformer fails an insulation test, it is usually due to puncture of solid insulation, creepage over solid insulation, rupture of oil or puncture of solid insulation and oil in series (Montsinger, 1924)

Let us first consider experimental data on VTC using the example of the three oldest and largest manufacturers of power transformers

2. General Electric Company data

2.1. Work by Montsinger, 1924 [4]

When a transformer fails an insulation test, it is usually due to one or more of the following causes: puncture of solid insulation, creepage over solid insulation, rupture of oil or puncture of solid insulation and oil in series. The above four failure causes were studied by Montsinger of Transformer Engineering Dept., GE, in determining (1) dielectric strength vs. time of voltage application and (2) dielectric strength vs. frequency. Montsinger calls dielectric strength vs. time of voltage application in this paper "strength-time curve".

Montsinger gives a strength-time curve for: one layer of 2.37 mm oil-treated pressboard in oil at 25°C; one layer of 2.37 mm oil-treated pressboard in oil at 75°C; 76 mm black varnished bond paper, total thickness per layer 127 mm. 2 layers under No. 10 transil oil at room temperature, 50 mm (2-in.) electrodes; 305mm black varnished cambric, 2 layers under oil at room temperature, 50 mm (2-in.) diam. electrodes; 305 mm black varnished cambric; No. 10 transil oil at 25°C, two 10 cm (4-in.) diam. round edge electrodes spaced 9.5 mm (0.375 in.) apart; 60 and 200-cycle at one layer 2.37 mm (0.0935-in.) oil-treated pressboard', in oil at 25°C, two 100 mm (4-in.) diam. electrodes; 2.37 mm (0.0935-in.) oil-treated pressboard, in oil at 100°C, two 100 mm (4-in.) diam. electrodes; 420-cycle at 2.37 mm (0.0935-in.) oil-treated pressboard, in oil at 100°C, two 100 mm (4-in.) diam. electrodes; 60 and 420-cycle at 7 layers 305 mm black varnished cambric in oil at 100°C.

All Montsinger force-time curves gradually decrease over time. An example is shown in Fig. 2. We do not present the rest of the curves so as not to overload the article with information that is unimportant.

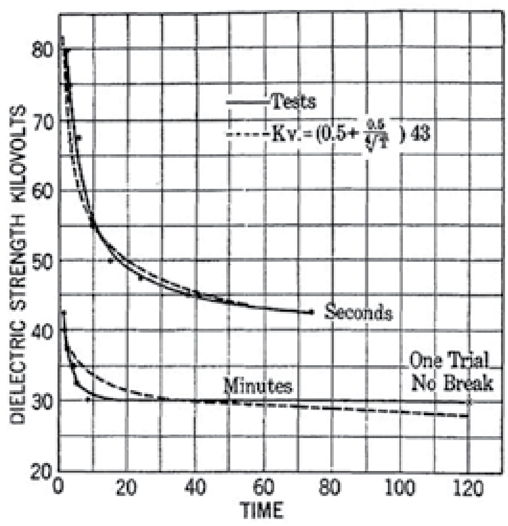

Fig. 3—60-Cycle Strength-Time Curve

One layer of 0.0935-in. oil-treated pressboard in oil at 25 deg. cent. Each point average of 10 tests. Time for voltage to build up (approx. 1 sec.) included 2-in. diam. electrodes

Figure 2. Example of a strength-time curve by Montsinger-1924 = *Fig. 3 p. 340 Montsinger-1924 [4]*

TABLE III.
EFFECT OF TIME OF VOLTAGE APPLICATION ON RUPTURE STRENGTH OF NO. 10 TRANSIL OIL

Sine wave, 60-cycle voltage—distance between 4-in. electrodes 0.375 inches. Dielectric strength of oil 25 to 30 kv. tested with one inch disks 0.1 in. apart

Duration Full Voltage Approx. one second	Voltage Increased 10 to 15 kv. per second	Voltage Increased one kv. per 5 seconds
165	164	119
165	144	109
155	170	134
150	132	136
160	168	125
150	166	135
170	174	117
160	170	94
165	165	133
170	172	140
165	150	137
135	140	110
172	168	128
165	162	130
170	158	123
167	170	141
Average 163 kv. Per cent 130	160 kv. 128	125 kv. 100

At this point the dielectric strength of the oil was unavoidably lowered with sand to put out a fire.

120	108	78
110	122	89
118	88	86
100	110	92
125	98	80
130	118	83
125	95	91
110	100	92
95	138	97
140	145	96
134	118	108
110	138	94
Average 126 kv. Per cent 127.5	115 kv. 116.5	99 kv. 100

Figure 3. Table III from Montsinger's article, 1924 = *Table III p. 342 Montsinger-1924 [4]*

Of particular interest to us is the fact that Montsinger gives 6 samples of initial data on the breakdown voltages of transformer oil (Fig. 3). Based on these data, we calculated the first 100-year-old scatter statistics (Table 1).

The scattering in the upper part of the table is within CV% = (6.1~11.2)%; the average value is 8.4%. The illogical increase in CV% with increasing time from 6.1 to 11.2% can only be explained by the statistical nature of oil breakdown. Yet 1.5 times greater scattering in the lower part (the average value is 11.5 + 16.1 + 9.1/3 = 12.2%) is due to the same reason as the decrease in breakdown voltages - a stronger influence of impurities in the oil.

2.2. Work by Clark, 1925 [5]

Clark, a physicist in another division of General Electric, was researching the dielectric strength of fibrous insulation (oil paper, varnished insulation, mica) almost simultaneously with Montsinger. He obtained dependences in time and also approximated monotonically decreasing curves, which he called the time-voltage relation. Figure 4 shows one example of the 15 curves shown in his article. We do not present the remaining curves so as not to overload the article with information.

2.3. Volt-time curve by Montsinger, 1935

The subsequent decade of research on samples and models of transformer insulation at GE led to new knowledge. Experimental dependences of breakdown strength over

Table 1. Scatter statistics of 60-cycle breakdown voltage at a distance between 4-in. electrodes 0.375 inches. Dielectric strength of oil 25 to 30 kV, tested with one-inch disks 0.1 in. apart (calculated from Montsinger data - see Fig. 3)

Top of the Montsinger table			
Number of points / N	16	16	16
Average / kV	161.5	160.8	125.1
Coefficient of variation CV%	6.1	7.8	11.2
Lower part of the Montsinger table			
Number of points / N	12	12	12
Average / kV	118.1	114.8	90.5*
Coefficient of variation CV%	11.5	16.1	9.1

* In Montsinger erroneously indicated 99 kV

Clark, a physicist in another division of General Electric, was researching the dielectric strength of fibrous insulation (oil paper, varnished insulation, mica) almost simultaneously with Montsinger

time are summarized in the now classic curve published by Montsinger in 1935, which he called the volt-time curve (Fig. 5). Blume {2] states: «*So far as is known, the curve … was the first complete volt-time curve obtained on insulation in America*».

2.4. Montsinger volt-time curve, 1951

In the second edition of Blume [6], Montsinger gave a new volt-time curve for the "solid insulation - oil duct - solid insulation" series in addition to the curve of Fig. 5 above. This emulates the main insulation of a transformer (Fig. 6). The new curve has the same peculiar shape as in Fig. 5 (and many similar curves for solid insulation published by Montsinger in 1933 and 1935).

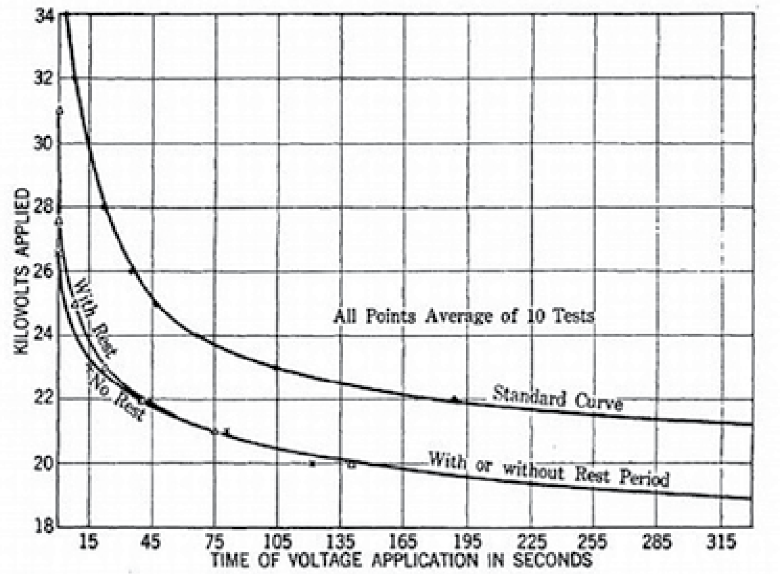

FIG. 4—EFFECT OF A PREVIOUSLY APPLIED VOLTAGE ON THE TIME-VOLTAGE RELATION

Insulation—9 Layers Oil Treated Kraft Paper (0.003 in.)
Test Voltage—60-cycle
Test Medium—Transil Oil at Room Temperature
Electrodes—1 ½-in. Brass with 3/64-in. Edge Radius
"Standard Curve"—Original Curve for Insulation
"No Rest"—Relation obtained, after Application of 22 kv. for 2½ min. without an Intervening Rest Period
"With Rest"—Relation obtained after Application of 22 kv. for 2½ min. followed by a Rest Period of 5 min.

Figure 4. The time-voltage relation of 9 layers of oil-treated kraft paper 0.003 in. acc. to Clark [5]. *= Fig. 4 Clark [5]*

Experimental dependences of breakdown strength over time are summarized in the now classic curve published by Montsinger in 1935, which he called the volt-time curve

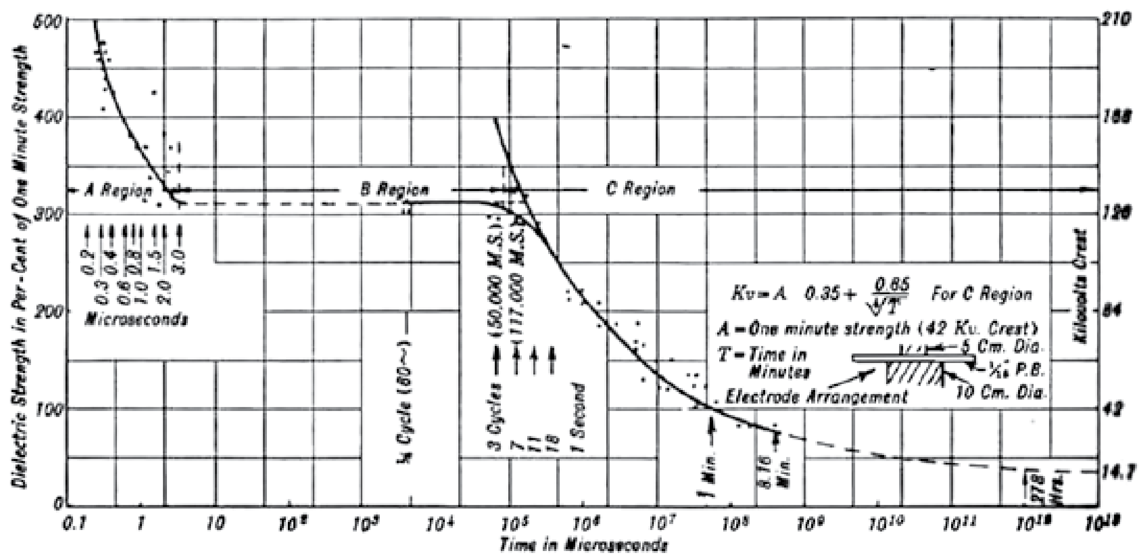

Figure 5. Volt-time curve of breakdown of 1/16" oil-treated pressboard in oil at a temperature of 25°C for electrode arrangement (see insert sketch). Breakdowns in Region A occurred on the crest or front of the wave *= Fig. 14 p. 472 Blume-1938 [2]*

Montsinger gave a curve for a pure oil ¼-inch gap also having a similar peculiar shape by which he emphasized that this form of volt-time curve is objective for all types of transformer insulation

In addition, Montsinger gave a curve for a pure oil ¼-inch gap (obtained by Bellaschi - see Section 3.2 below) also having a similar peculiar shape. Thus, he emphasized that this form of volt-time curve is objective for all types of transformer insulation.

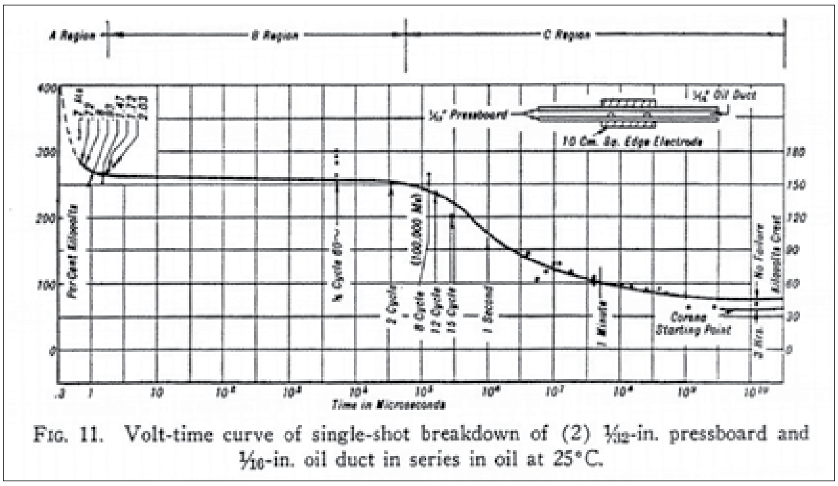

Figure 6. Volt-time curve of single-shot breakdown of (2) 1/32-in. pressboard and 1/16-in. oil duct in series in oil at 25ºC = *Fig. 11 p. 421 Blume-1951 [6]*

3. Westinghouse Electric Company data

The early work of Westinghouse specialists coincides in time with GE's. Results differ little from the work of GE specialists.

3.1. Works by Vogel, 1924 [7] and 1933 [8]

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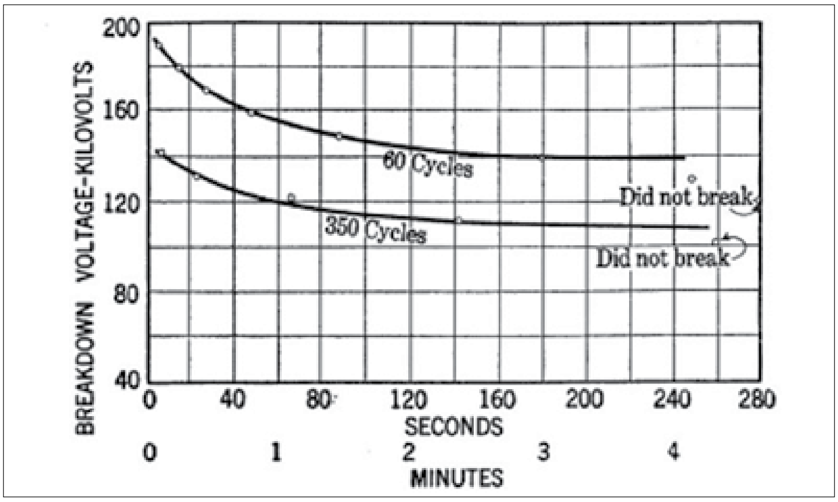


Figure 7. Time-Voltage Curve at 60 and 350 Cycles according to Vogel-1924 [7]. = *Fig.25 Vogel-1924 [7]* 3 sheets 1/8 in. oil-impregnated fullerboard with alternative 1/8-in. oil ducts at 25°C

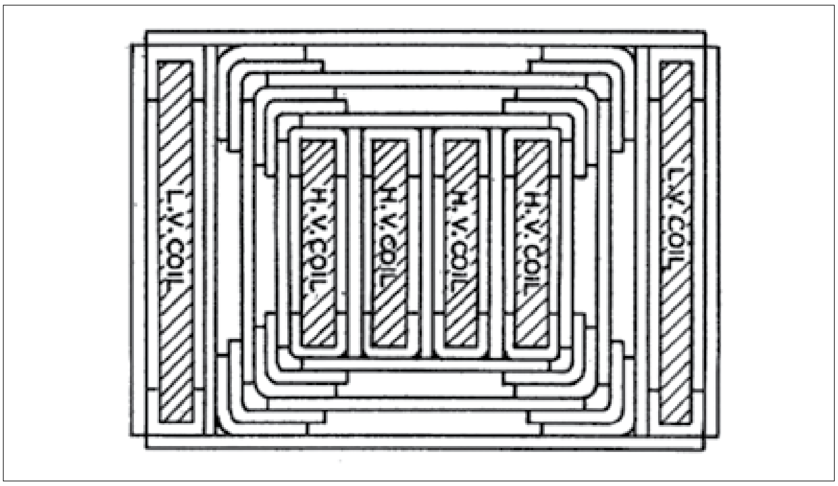


Figure 8. View of a shell-type transformer insulation in iron opening model [8] = *Fig. 1 Vogel-1933 [8]* High-voltage and low-voltage coils are shaded.

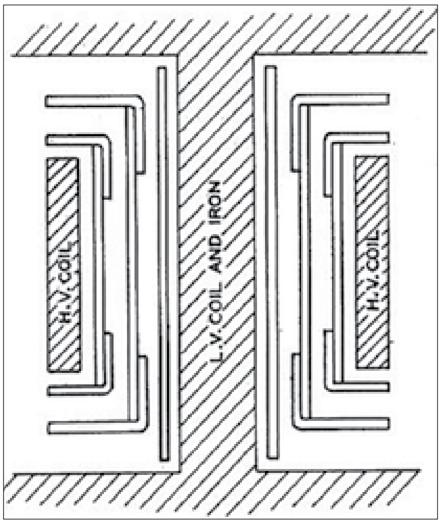


Figure 9. View of core type transformer insulation model [8] = *Fig. 2 Vogel-1933 [8]* The low-voltage coil and iron are represented as one piece

Vogel also gives a graph and states that impulse breakdown voltage does not depend on impulse polarity or time within 2-13 μs

of induced voltage during transformer testing. Results gave some of the first dependencies of strength over time (for example, Fig. 7). In total, the author gives 25 curves. We do not present the rest of the curves so as not to overload the article with information. Curves constructed from single points fall monotonically similar to those of Clarke and Montsinger. The author calls them Time-Voltage Curves. From them, it is impossible to extract information of interest to us about the scattering of breakdown voltages.

The same author published tables of breakdown voltages (Figs. 10 and 11) in 1933 [8]. Other, more complex models of main transformer insulation were studied (Figs. 8 and 9). Statistics calculated from these tables are shown in the first two rows of Table 2.

Vogel also gives a graph (Fig. 12) and states that impulse breakdown voltage does not depend on impulse polarity or time within 2-13 μs. By extracting and processing data from this graph, we obtain the statistics shown in the last row of Table 2.

From Table 2 it follows that the average coefficient of variation for AC ((4.9 + 5.7) / 2 = 5.3) is 1.3 times less than for LI (6.8).

TABLE I—TESTS ON SHELL TYPE INSULATION MODELS
60 CYCLE—70 DEG C OIL

Model	Voltage held 1 min—kv rms	Voltage at failure—kv rms
15	280	290
16	300	310
17	290	300
18	270	280
20	260	270
	280	290
Average	280	290

Figure 10. Table I from Vogel's article, 1933 = *Table I p. 411 Vogel- 1933 [8]*

TABLE II—TESTS ON CORE TYPE INSULATION MODELS
60 CYCLE—70 DEG C OIL

Model	Voltage held 1 min—kv rms	Voltage at failure—kv rms
3	300	310
4	270	280
7	300	310
8	320	330
9	280	290
10	310	320
11	300	310
12	320	330
Average	300	310

Figure 11. Table II from Vogel's article, 1933 = *Table II p. 412 Vogel-1933 [8]*

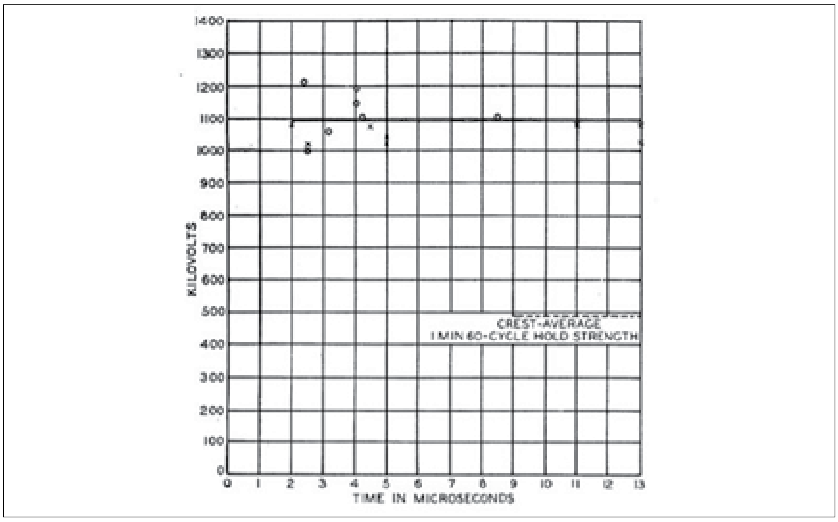


Figure 12. Surge voltage strength of interleaved barrier for both positive (X) and negative (O) waves according to Vogel-1933 [8] = *Fig.9 p. 414 Vogel-1933 [8]*

Table 2. Voltage at failure - statistics according to Figs. 10, 11 and 12 (Vogel-1933) [8]

Models	Test	N	Average / kV	CV%
Shell type insulation models, 700C oil	60 cycle	6	290	4.9
Core type insulation models, 700C oil	60 cycle	8	310	5.7
Interleaved barrier	LI	15	1088	6.8

Bellaschi and Teague from Westinghouse published a paper in 1937 where they demonstrated voltage-time breakdown curves for transformer oil

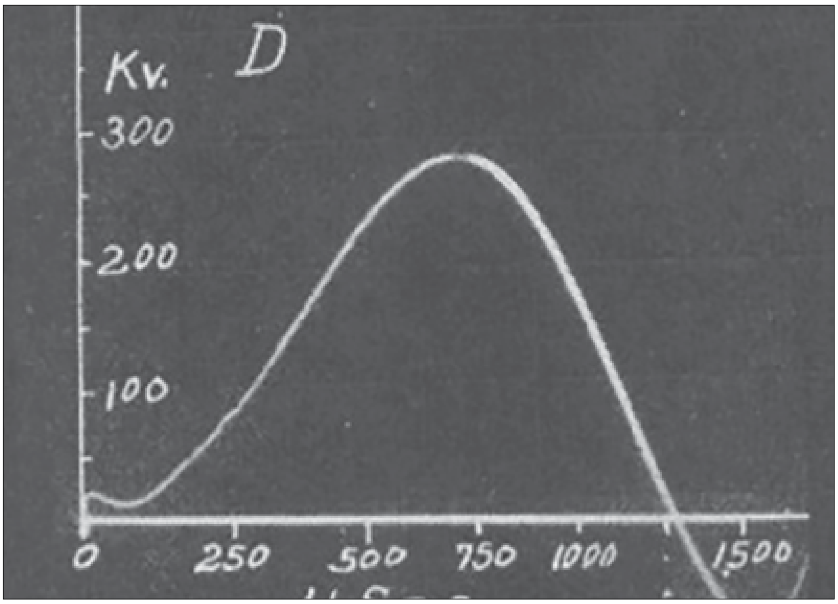


Figure 13. Switching impulse used by Bellaschi & Teague [9] = *from Fig. 8 Bellaschi & Teague [9]*

3.2. Voltage-time breakdown curves by Bellaschi, 1937

Bellaschi (research and development engineer), and Teague (engineer) from Westinghouse published a paper in 1937 which was recommended by AIEE committees on electrophysics and electrical machinery [9]. Their paper demonstrated voltage-time breakdown curves for transformer oil, 0.25-inch, 0.5-inch, 1.0-inch spacing, as well as voltage-time breakdown and corona-time curves for 0.056-inch and 0.125-inch oil-impregnated fullerboard tested in transformer oil.

Bellaschi's curves are similar to Montsinger's voltage-time curve. But they have two significant differences: 1) on voltage-time breakdown curves of Bellaschi & Teague,

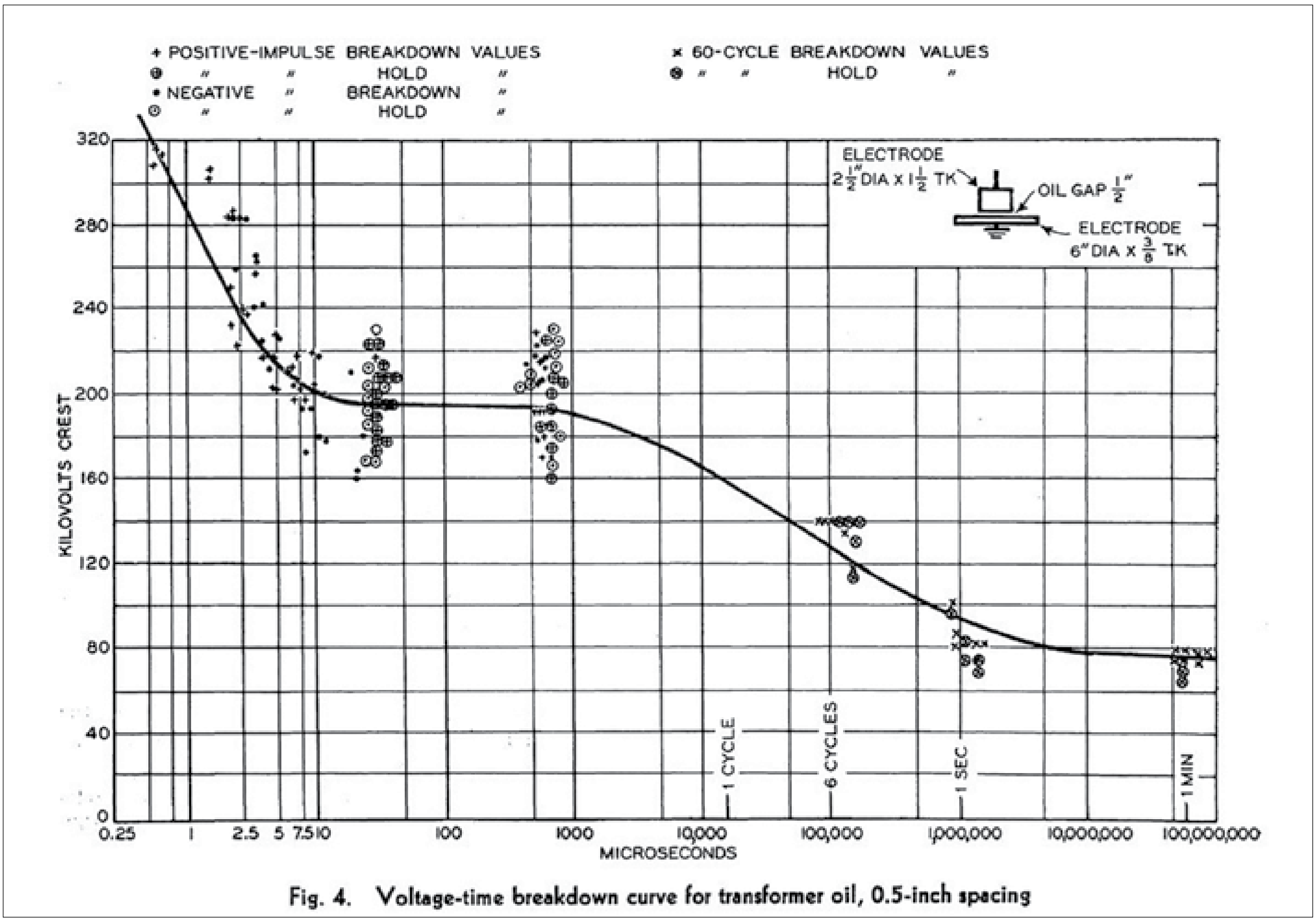


Figure 14. Voltage-time breakdown curve for transformer oil, 12.7 mm (0.5-inch) spacing according to Bellaschi & Teague [9] = *Fig.4 Bellaschi & Teague [9]*

there is no dotted part (as in Montsinger) since the authors used the SI test for the first time in practice (Fig. 13); this impulse is not much different from the standardized one in present day; 2) Bellaschi & Teague recorded "corona" (PD) for the first time in the world in the study of dielectric strength.

The scattering of breakdown voltages of LI and SI of oil-impregnated fullerboard is about one and one-half times lower than for transformer oil

Two of the five curves obtained by Bellaschi & Teague also reflect the results of LI tests and AC 60-cycle tests (6-cycle, one-second, one-minute), see Figs. 14 and 15. The remaining three curves demonstrate scattering.

All five Bellaschi & Teague figures show experimental breakdown voltage points. We extract LI, SI, and one-minute tests and calculate the scatter statistics shown in Tables 3a and 3b.

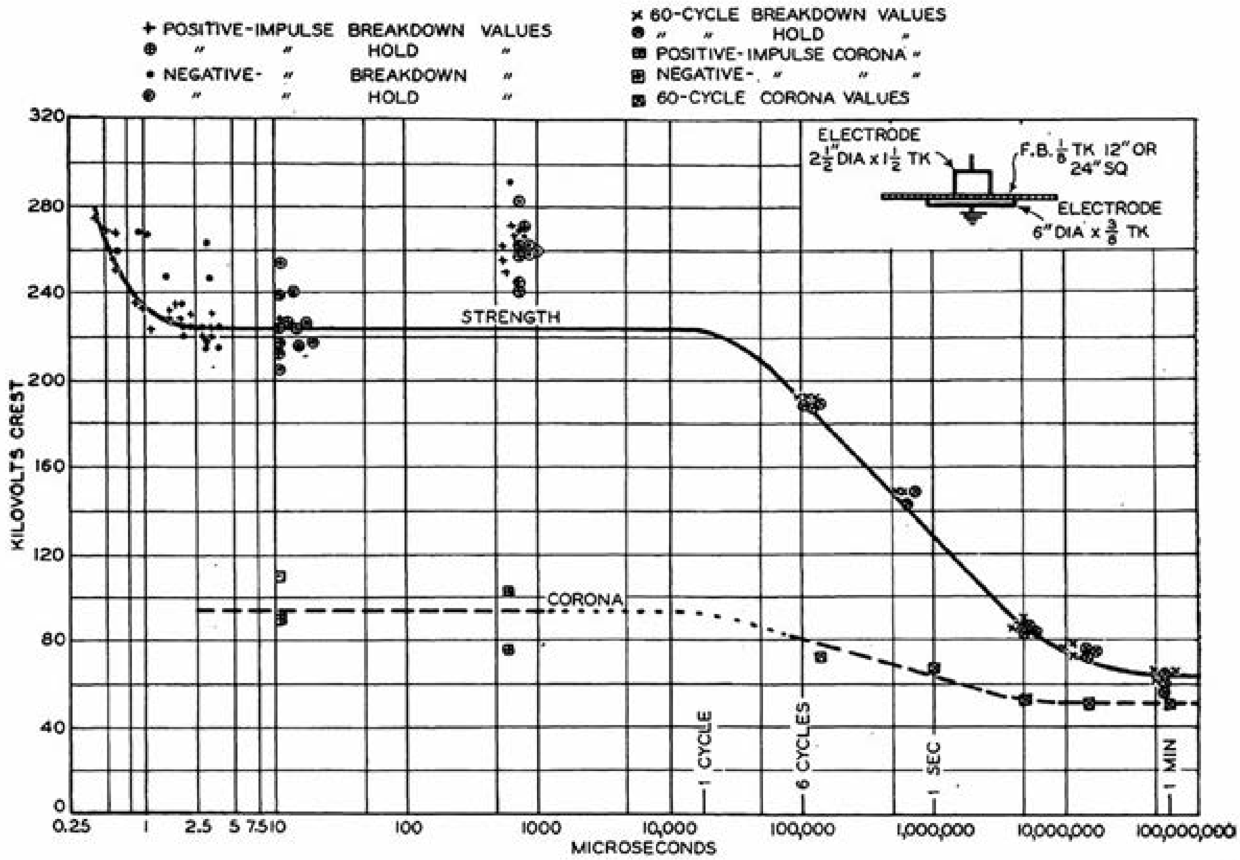


Fig. 7. Voltage-time breakdown and corona-time curves for 0.125-inch oil-impregnated fullerboard tested in transformer oil

Figure 15. Voltage-time breakdown and corona-time curves for 0.125-inch oil-impregnated fullerboard tested in transformer oil according to [9] = *Fig. 7 Bellaschi & Teague [9]*

Table 3a. Coefficients of variation for breakdown voltage of transformer oil according to Bellaschi & Teague. *N* is the number of points in the sample.

Test name	LI	SI	1 min
Statistics	CV% / N	CV% / N	CV% / N
Transformer oil, 0.25-inch spacing	-	9.2/21	3.9/9
Transformer oil, 0.5-inch spacing	9.9/29	9.9/34	6.3/9
Transformer oil, 1.0-inch spacing	4.1/4	7.8/13	2.2/6
Average CV%	7.0	9.0	4.1
Weighted average CV%	9.2	9.3	4.4

Table 3b. Coefficients of variation for breakdown voltage of oil-impregnated fullerboard according to Bellaschi & Teague. *N* is the number of sample points.

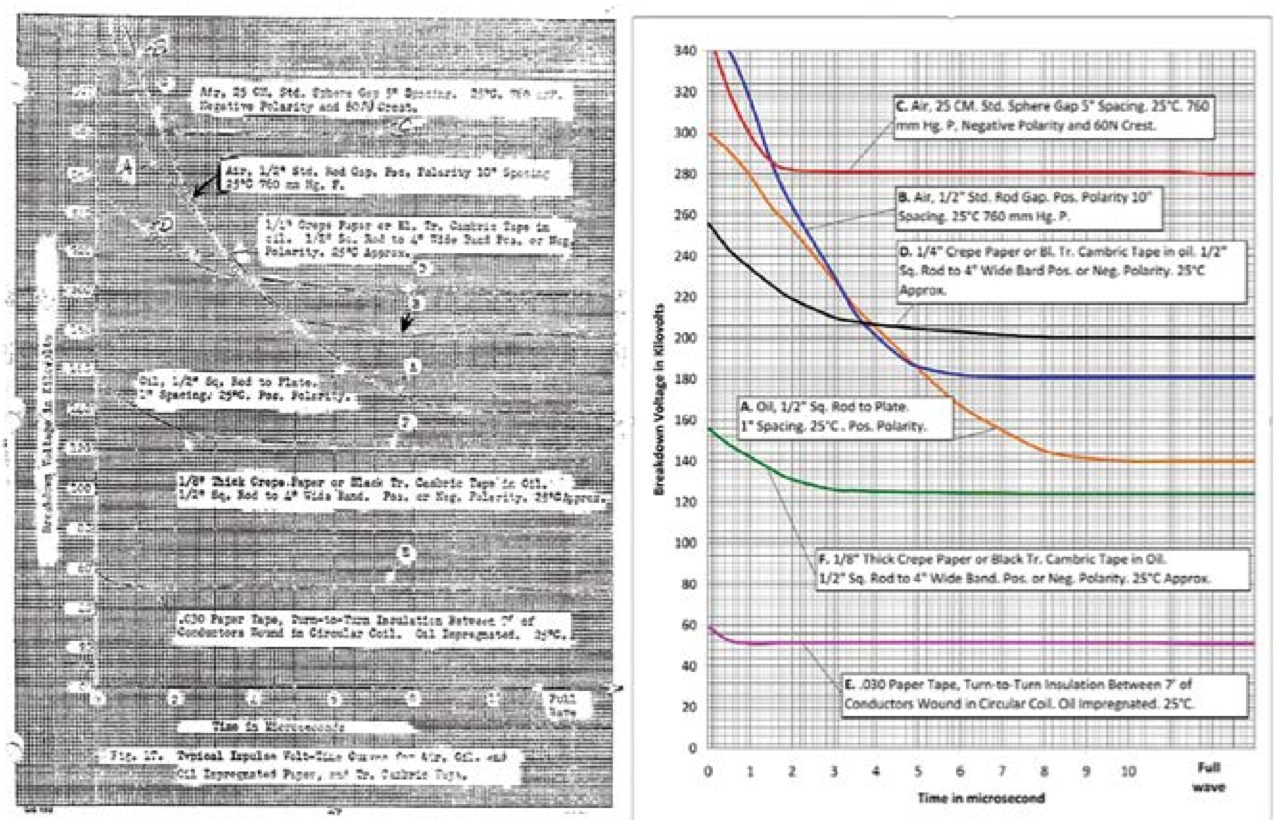
Test name	LI	SI	1 min
Statistics	CV% / N	CV% / N	CV% / N
0.056-inch oil-impregnated fullerboard tested in transformer oil	-	3.9/12	4.1/6
0.125-inch oil-impregnated fullerboard tested in transformer oil	5.9/12	9.7/18	9.5/7
Average CV%	5.9	6.8	6.8
Weighted average CV%	5.9	7.4	7.0

Analyzing Tables 3a and 3b, we note that the scattering of breakdown voltages of LI and SI of oil-impregnated fullerboard is about one and one-half times lower than for transformer oil, and the SI scattering is possibly the largest for both types of transformer insulation.

3.3. Westinghouse Lectures on the basics of transformers [10]

In 1966, Westinghouse gave its staff a series of lectures on transformer basics. We briefly repeat information on the dependence of insulation breakdown over time, which is contained in the lecture on transformer insulation.

Since energy is required to break down insulation, a time element is introduced. The withstand voltage of most insulating materials is inversely related to time. Some materials have a very high breakdown for short "impulse" times of a few microseconds as compared to that for longer durations of minutes or hours. Short-time failures may be caused by disruptive factors only, whereas long-time failures may involve thermal degradation, electrolytic ionization or corona effects. Corona effects may lead to damage by producing nitrous oxide or from rapid oxidation by ozone. Since the cause of failure may be complex, there is a wide difference in the behavior of various dielectric materials. Many attempts have been made to express the volt-time relation mathematically, but due to difficulty in covering all variables, most formulae require real-time informa-



a) original b) revised

Figure 16. Typical Impulse Volt-Time Curve for Air, Oil and Oil Impregnated Paper, and Tr. Cambric Tape [10] = *Fig.17 of Lectures [10]*

tion on all variables, but they only hold for specific conditions.

For impulse voltages, some materials have a considerably higher strength for short flashover times than for long flashover times; other materials show essentially no increase. In Fig. 16, the impulse volt-time curve for typical materials is given. Curve A is for one one-inch (2.5 cm) oil gap between a one-half-inch square rod with square ends and a smooth plate. Curve B is for a ten-inch (25 cm) gap in air between two one-half-inch square rods mounted horizontally. Curve C is for a 10 in (25 cm) sphere) the gap in the air set for 75 five-inch spacing. Curve D is for 1/4 inch (6 mm) thick oil-impregnated paper tape or 1/4" varnished cambric tape on a half-inch rod tested between the rod and a four-inch-wide metal band. Curve E is for 762 mm thick oil-impregnated paper turn-to-turn insulation. Note that the 762 mm thick paper and the sphere gap have flat volt-time characteristics. The rod gap in air and the 1/4 inch (6 mm) thick paper both have some turnup for short times, showing that the shape of the electrodes and the material effect time to flashover.

A great deal of experimental impulse strength data and one-minute sixty-cycle strength data were available for various materials. However, very little information was available in the time range from an impulse to one minute. A few years ago, tests were conducted in our own laboratories to obtain data on transformer oil and oil-impregnated pressboard to extend volt-time curves from an impulse to the one-minute time range. Typical volt-time curves for 1/8-inch (3 mm) thick pressboard and 1/2-inch (12.5 mm) oil duct between a 2 1/2-inch (63.5 mm) diameter square edge disc and a smooth plate are given in Fig. 17. It will be noted that both the oil and the pressboard have about the same strength in the switching surge range of 1000 or so microseconds as full cycle waves. Hence, if a transformer is insulated for full wave impulses, it probably will also be adequate for switching surges.

The following approximate "finger-tip" data are given for convenience. A comparison of this data to experimental information in the curves shows that such data must be used cautiously and judiciously.

Note that Fig. 16 given in a 1966 lecture, is a compilation of two Bellaschi & Teague figures (see Figs. 14 and 15), confirming the fundamental importance of the Bellaschi & Teague work done almost 30 years earlier.

Time	Dielectric Strength in Terms of the One-Minute Strength, Rms
2 Microseconds (crest)	$2.2 \times \sqrt{2}$
1 Second	1.5
1 Minute	1.0
Continuously	0.6 to 0.9 (common value = 2/3)

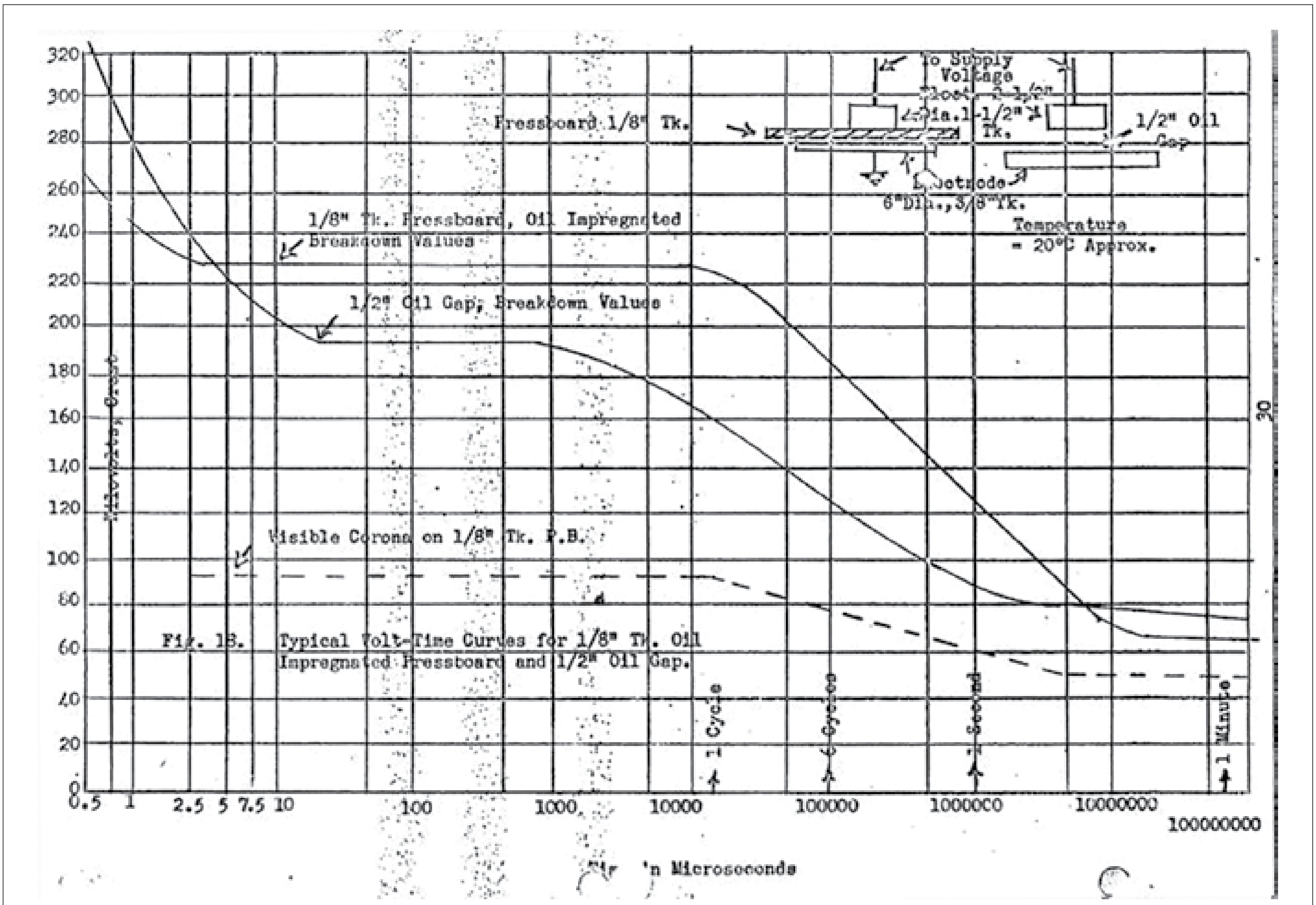


Figure 17. Typical Volt-Time Curve for 1/8-inch (3mm) Tr. Oil Impregnated Pressboard and 1/2 inch (12.5mm) Oil Gap [10] *= Fig.18 of Lectures [10]*

4. Conclusion to Part I

1. A very peculiar form of the dependences of dielectric strength of transformer insulation on time was discovered by Montsinger and confirmed by Bellaschi. It has not been challenged for 90 years, although it was significantly refined in further studies. The phrase coined by Montsinger (volt-time curve) is the most common one in English-language literature.

2. Bellaschi laid the foundation for that set of tests in 1937. Thirty-five years later, it was adopted and is still preserved in the standards as a routine for EHV transformers.

3. Mathematical expressions for the volt-time relationship are only valid for very limited conditions due to the difficulty of covering all variables.

4. Insulation strength at AC operating voltages is 0.6-0.9 times the strength at one-minute voltage.

5. More recent information from the specialists of GE and Westinghouse about VTC and the scattering of insulation strength is not available in public literature. Apparently, this information is proprietary.

6. Information about the scattering of breakdown voltages was extracted from the early work of GE and Westinghouse specialists (Tables 1, 2, 3a and 3b) and is sent to our data box. This will be analyzed in the last part of the article. Let us note initially that no difference was found in the spread of values for oil, solid insulation samples and transformer insulation models. Surprisingly, the highest CV% occurs for CI. The smallest value of CV% for one-minute voltage is 1.3 times less than for LI.

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