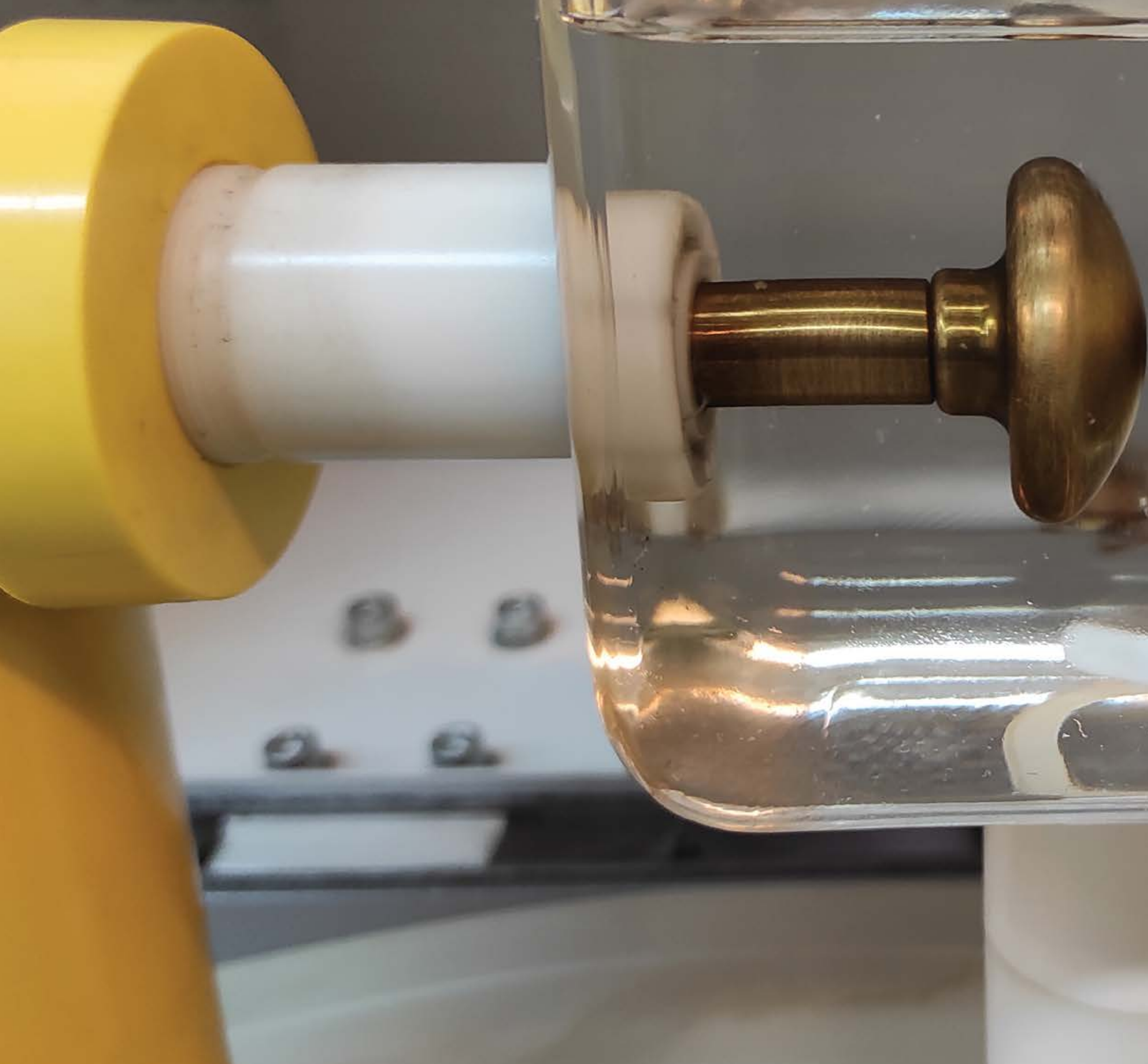
The statistical scatter of breakdown voltages of transformer oil

Part II



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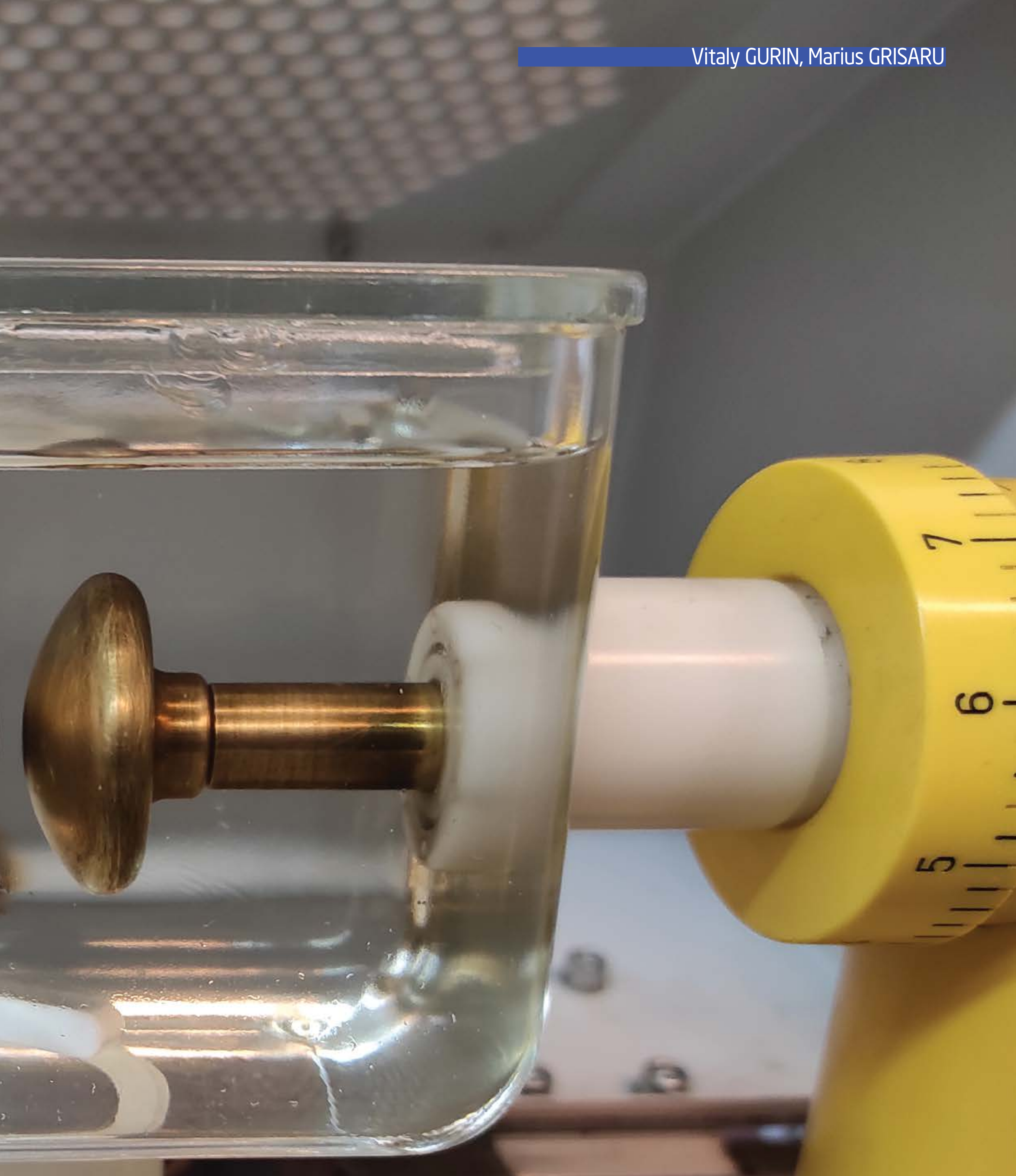


ABSTRACT

The second part of the article is about coefficients of variation (CV%) of breakdown voltage (BDV) of transformer oil and discusses the voltage rise effect and the gap spacing effect. CV% decreases as the rate of voltage rises, but there is insufficient data to quantify this phenomenon. CV% decreases linearly with the logarithm of gap spacing (approximately 3 times per order of magnitude increase in gap).

KEYWORDS:

breakdown voltage, coefficients of variation, gap spacing, IEC, power transformer, size effect, transformer oil, voltage rise effect

Breakdown voltage is the voltage at which the insulating liquid fails and allows electrical discharge or breakdown

4. Breakdown voltage (BDV) and coefficient of variation (CV%) of liquid insulation

Breakdown voltage is the voltage at which the insulating liquid fails and allows electrical discharge or breakdown. BDV is defined as the average breakdown voltage of liquid insulation during several tests according to the standards discussed in Part 1 of the article [1].

The coefficient of variation (CV%) is expressed as:

$CV\% = (\sigma/\mu) \times 100$

where:

- σ is the standard deviation of the breakdown voltages,
- μ is the mean breakdown voltage.

In transformers, the most common insulating liquids are mineral oils, natural esters, and synthetic esters. Each type of liquid has different dielectric properties, resulting in different average breakdown voltages and different variations depending on the influencing factors. The coefficient of variation (CV%) helps to quantify the relative variability or dispersion of breakdown voltage values under different types of liquid and different test conditions. A higher CV% indicates greater variability in breakdown voltage, while a lower CV% suggests a more consistent breakdown characteristic.

5. The voltage rise effect

The rate of change of voltage is the rate at which the voltage increases during the test until breakdown occurs. Each type of fluid has different dielectric properties, resulting in different average breakdown voltages and scatters depending on the rate of change applied. For example, natural esters may exhibit greater variability under voltage due to their molecular structure, while synthetic esters may provide greater consistency in breakdown characteristics.

Let's consider the data we found in the literature on the scatter of transformer oil BDVs.

5.1. Data by Montsinger, 1924

The dependence of the scatter of BDV on the speed of voltage rise was discovered by Montsinger 100 years ago in a more uniform field (distance between 4-in. electrodes 0.375 inches) than is accepted in modern standards. Table 1 is taken from [2] and shows the CV% calculated from Montsinger's data.

As follows from this table, the scatter of BDV doubled when moving from fast (duration full voltage one second) to slow (one kV per 5 seconds) voltage increased.

Considering that CV% is dependent on oil impurities, it may be explained by the fact that increasing the voltage rate has a positive effect on the dielectric strength of the transformer oil since the higher voltage rise rate allows less time for impurities to establish bridges between the electrodes.

Taking into account the above, in order to compare different data, it was necessary to normalize the speed of voltage rise.

The IEC standard speed of uniform voltage rises from zero to the moment of breakdown is 2.0 kV/s ± 0.2 kV/s (according to GOST 2 kV/s ± 20%).

5.2. Data by Gupta and Dias, 2017

In their 2017 report, Indian university scientists Gupta and Dias presented data on the BDV of transformer oil in a standard BAUR tester when changing the rate of rise of voltage **at five points** is varied from 0.5 kV/s to 5 kV/s [3]. At each ramp rate, 10 sets of breakdown voltage are measured. The CV% values we calculated from these data are shown in Fig. 1.

As seen in Fig. 1, at a speed of 1÷3 kV/s it is difficult to determine any trend in the change in CV%, but then CV% logically decreases. Unfortunately, we did not find other initial data on this effect in the literature.

So, as the rate of AC voltage increases, the BDV of the oil increases, and the CV%

The dependence of the scatter of BDV on the speed of voltage rise was discovered by Montsinger 100 years ago in a more uniform field than is accepted in modern standards

Table 1. 60-cycle voltage rise effect acc. to Montsinger. Sample size (the number of breakouts at each speed) N = 16

The speed of voltage rise	Average / kV	CV%
Duration full voltage one second	161.5	6.1
Voltage increased 10-15 kV per second	160.8	7.8
Voltage increased one kV per 5 second	125.1	11.2

decreases. There is currently little data to quantify these phenomena. We also recommend to regularly report the CV% and voltage velocity ramp (if it differs from the standard) along with classic BDV results. This can assist users in determining the causes of failure and considering appropriate oil treatments.

NOTE. Different types of insulating liquids may react differently to voltage stress – see **Annex**.

6. The size effect (gap spacing, electrode area, and stressed oil volume)

Transformer oil breakdown is affected by gap spacing. Transformer designers separate large oil gaps using pressboard baffles to achieve higher dielectric strength. The dimensions of the oil channels between the disks in the windings and between the insulating cylinders of the main insulation of the windings usually range from 1 to 10 ÷ 20 mm, and from the windings to the tank and in the end insulation of the windings up to 40-60 mm and even more. Since experimental studies of oil destruction are often carried out with different geometries, area or volume effects are sometimes used to correlate results.

Therefore, to optimize insulation, it is necessary to study the dependence of CV% on the gap spacing, so and from electrode area, and stressed volume of oil. Regarding the last two dependencies, few people have provided data on CV%.

The first authors we found who had the initial data for calculating the CV% of all three effects were English scientists Nelson et al. and Bell. Half a century ago, in the fundamental works on the study of BDV of transformer oil [4, 5], they provided tabular and graphical initial data, from which we extracted some answers to these questions.

As the rate of AC voltage increases, the BDV of the oil increases, and the CV% decreases, but there is little data to quantify these phenomena

To optimize insulation, it is necessary to study the dependence of CV% on the gap spacing, so and from electrode area, and stressed volume of oil

6.1. Gap spacing effect

An increase in gap spacing naturally causes an increase in BDV (kV) but leads to a decrease in dielectric strength E (kV/mm). This is understandable since a larger gap implies an increase in the population of impurities entering the gap. According to the theory, the average values of BDV and E vary linearly depending on the logarithm of the distance between the gaps [5, 6]. From the point of view of insulation design, we will be interested in how the absolute values of CV% and its speed change. Let's look at the data we collected.

6.1.1. Data by Nelson et al., 1977

Nelson et al. investigated the electrical strength of transformer oil using electrodes with cylindrical geometry of large diameter to obtain almost uniform fields with an electrode area of up to 2 m². Results for the gap spacing effect have been summarized in Table 2 for both 50 Hz (2 kV/s rate of rise) and 1/50 μs impulses at room temperature. The table also shows the CV% values we calculated.

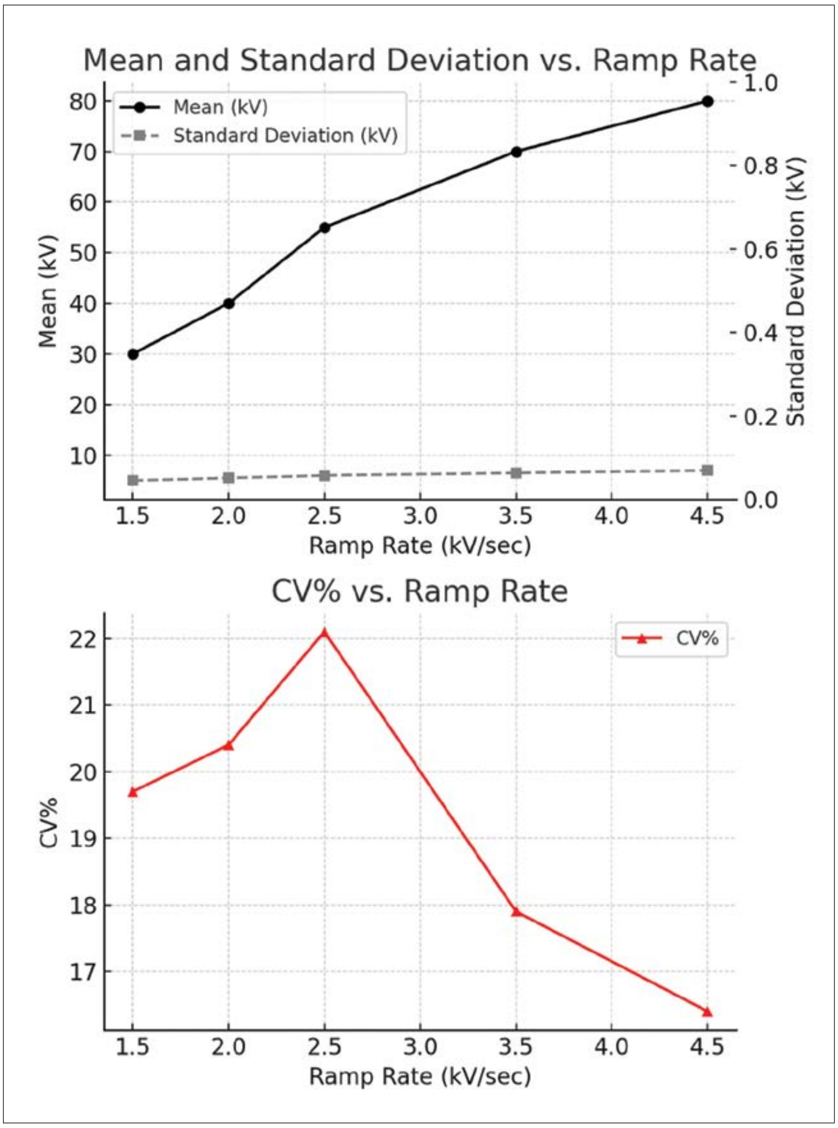


Figure 1. The voltage rise effects acc. to Gupta and Dias

Table 2. Gap spacing effect acc. to Nelson et al. Area is 1.885 m^2. Sample size N = 100 for 50 Hz and about 50 for impulse

Gap / mm	Power frequency		1.2/50 µ impulse	
	E – kV/mm	CV%	E – kV/mm	CV%
21.9	8.6	15.1	18-7	19.6
16-9	8.4	15	20-2	16.4
11-7	8.6	13.1	18-9	10.8
6-8	8.9	8.8	21-7	13.6

While for spheres with a large dose of imagination, one can see a tendency for the CV% to decrease with increasing gap (as with Bell), the opposite can be said for Rogowski electrodes

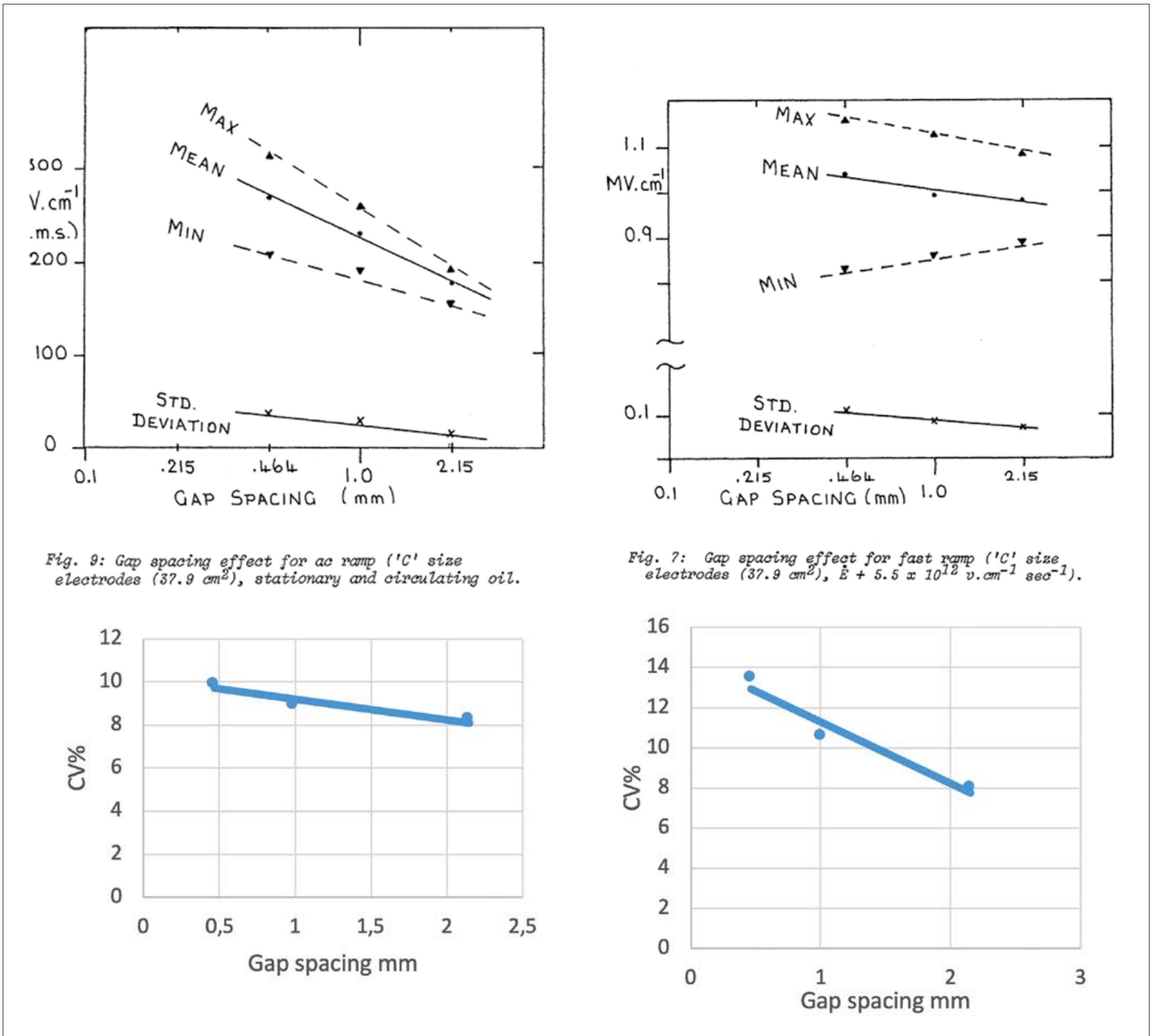


Figure 2. Gap spacing effect acc. to Bell

The nature of the change in the average value and CV% LI BDV (non-uniform electric field!) for various gaps is generally the same as for alternating voltage

The words of the authors *"the electric strength was not independent of gap in the range from 6.8÷21.9 mm"* can also be attributed to CV%.

6.1.2. Data by Bell, 1977

Bell (the University of Newcastle upon Tyne) investigated four gap spacings (0.215, 0.464, 1.0 and 2.15 mm) using a fast ramp (5.5 x 10^{12} V.cm^{-1} sec^{-1}) and an AC ramp (12 kV.cm^{-1} sec^{-1}). The results are shown in Fig. 2. The upper part of the figure is taken from [5], and we created the lower part.

6.1.3. Data by Mohsin et al., 2004

A third of a century later, Indian and Malaysian experts published data on the effect of a gap in the range from 0.2 to 2.0 mm [7]. Spheres with a diameter of 12.5 mm and Rogowski electrodes with a total diameter of 30.0 mm were used as electrodes. The quality of the oil, the procedure for cleaning the cell and electrodes, as well as the method of analyzing the results are the same for all gaps studied.

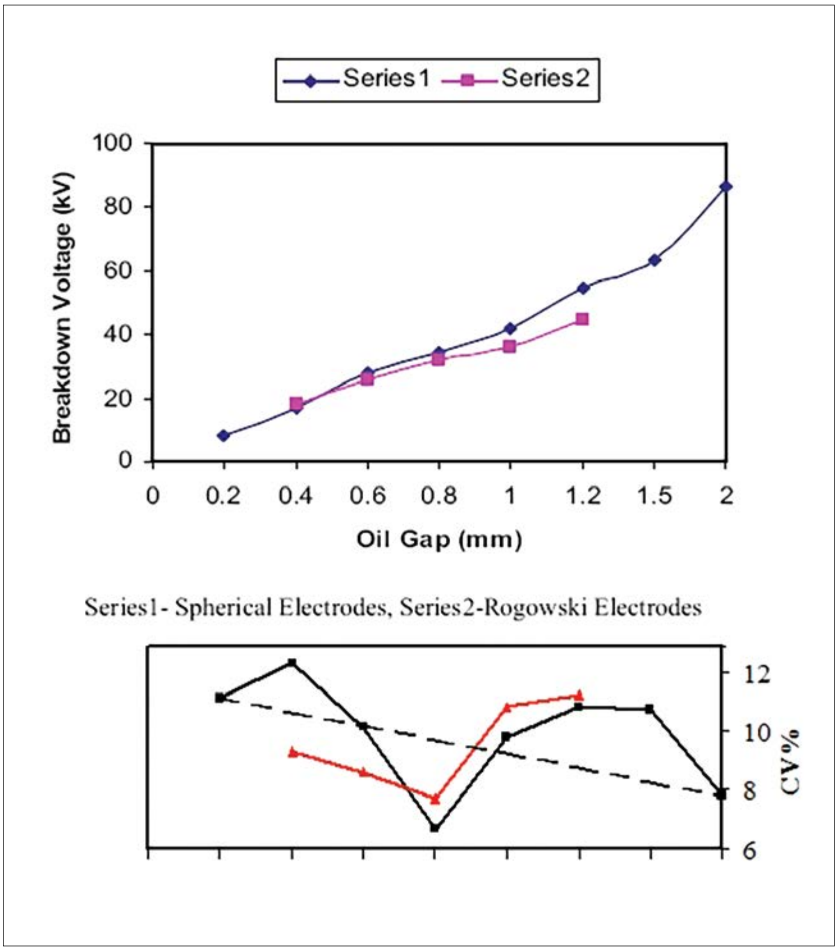
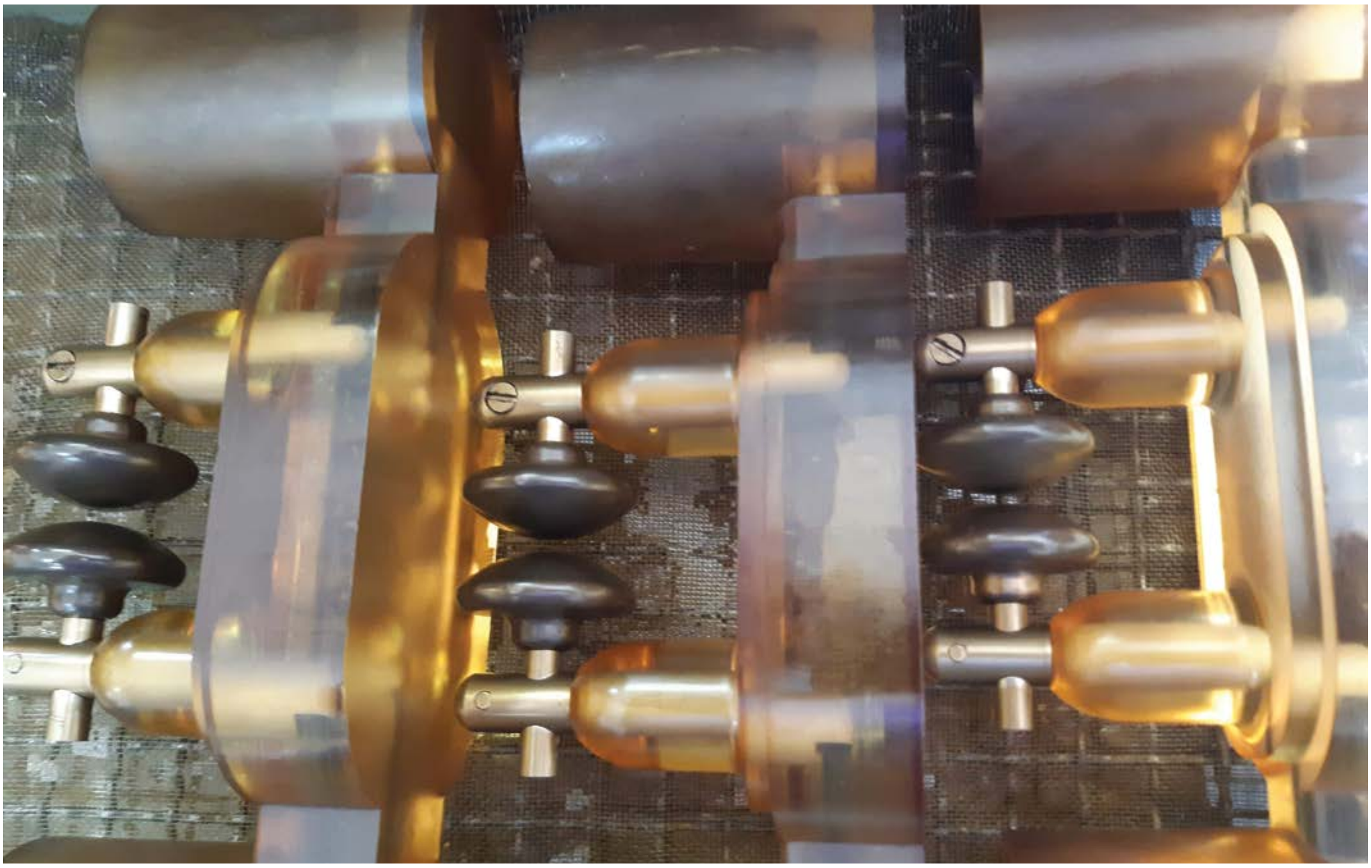


Figure 3. Gap spacing effect acc. to Mohsin et al.

Using the data available in the article, we calculated the CV% and plotted its dependence on the oil gap (Fig. 3). The upper



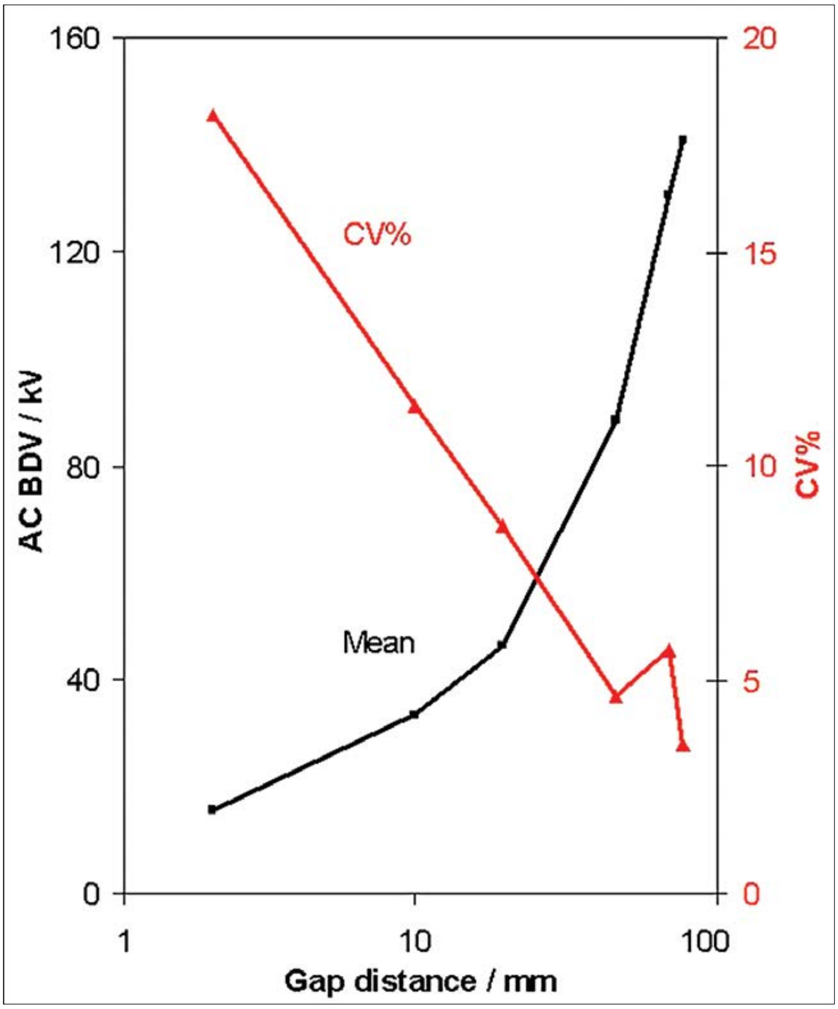


Figure 4. Gap spacing effect acc. to Wang

While for spheres with a large dose of imagination, one can see a tendency for the CV% to decrease with increasing gap (as with Bell), the opposite can be said for Rogowski electrodes

part of Fig. 3 is taken from [7], and the lower part was created by the authors.

As seen in this figure, while for spheres with a large dose of imagination, one can see a tendency for the CV% to decrease with increasing gap (as with Bell), the opposite can be said for Rogowski electrodes. A logical explanation for this could be the "darkening" influence of impurities in the oil.

6.1.4. The gap distances to 85 mm (data by Wang, 2011)

In his dissertation on the study of the breakdown mechanism of ester transformer liquids under AC stress, the author provides data on the BDV of Gemini transformer oil in electrodes needle to sphere with spacing up to 8.5 cm (Table II.26 [8]). The CV% values we calculated are shown in Fig. 4.

As can be seen from this figure, the dependence of CV% on gap distance is an almost ideal (with the exception of one outlier point) straight line.

6.1.5. The lightning impulse breakdown voltage (LI BDV). The gap distances to 50 mm. Data by Hamid et al., 2021

According to IEC 60897, this BDV is defined in a non-uniform electric field (point-to-sphere arrangement) in the range of 10-25 mm. However, Malaysian university experts compared LI BDV of rice bran oil and Hyrax hypertrans transformer oil over a wider range (from 2 to 50 mm) and provided detailed test results [9]. We extracted the data for transformer oil from their publication and plotted Fig. 5.

As can be seen from Fig. 5, the nature of the change in the average value and CV% LI BDV (non-uniform electric field!) for various gaps is generally the same as for alternating voltage: the average value monotonically increases, and CV% decreases, with the exception of an outlier at 30 mm and an incomprehensible slight reduction of 2 mm compared to 4 mm.

6.1.6. The lightning impulse breakdown voltage (LI BDV): Gap distances of 2 ÷ 8 mm (data by Kunikowski et al., 2024)

Polish university scientists from Lodz **[9]** determined LI BDV of synthetic ester, bio-based hydrocarbon and inhibited mineral oil in an original model system with a quasi-uniform electric field distribution equipped with an impregnated pressboard plate placed on the surface of the grounded electrode (Fig. 6). Note that this is the closest imitation of an oil gap in a real transformer from those considered in our review. Four gap sizes were used: 2, 4, 6 and 8 mm.

The values of CV% calculated by us based on the data extracted from graphical constructions by the authors are shown in Fig. 7.

As seen in this figure, the dependence of CV% on gap distance is an almost ideal (with the exception of one outlier point) straight line.

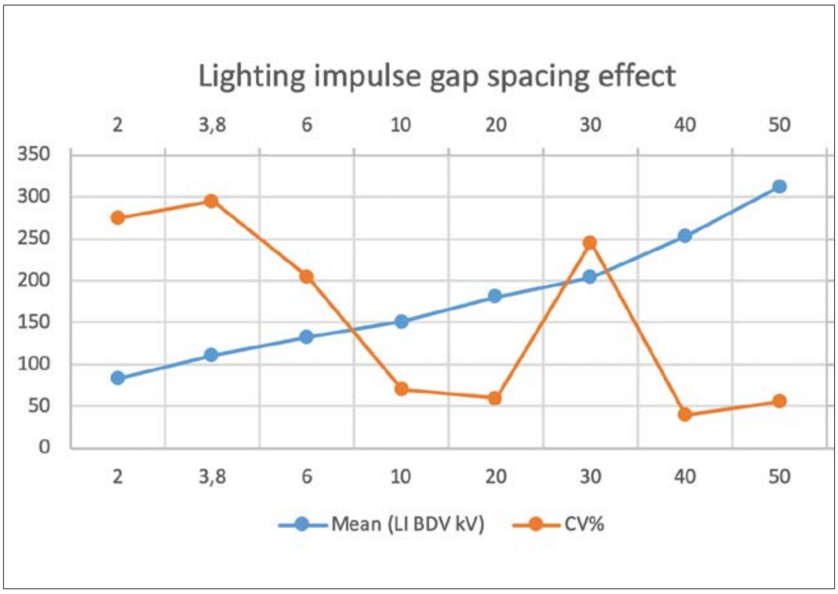


Figure 5. Lighting impulse gap spacing effect acc. to Hamid et al.

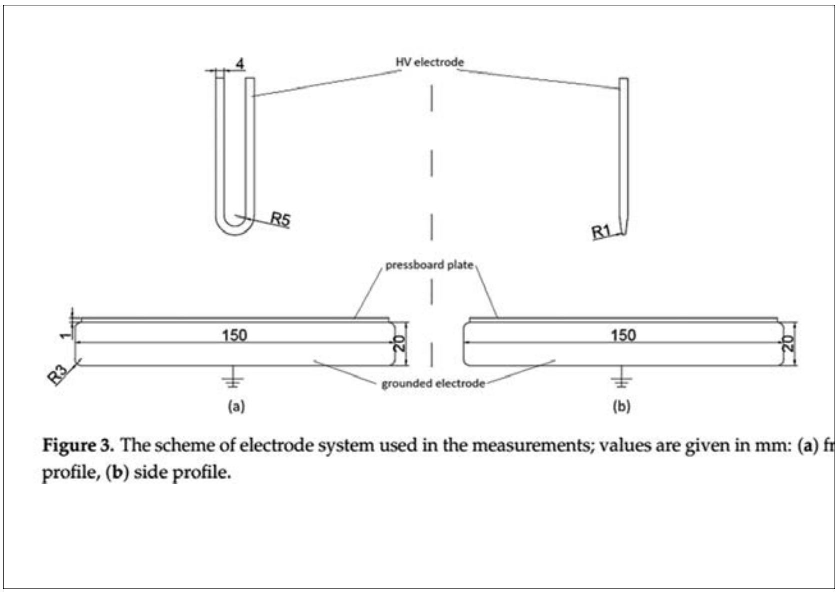


Figure 6. The electrodes in the studies by Kunikowski et al.

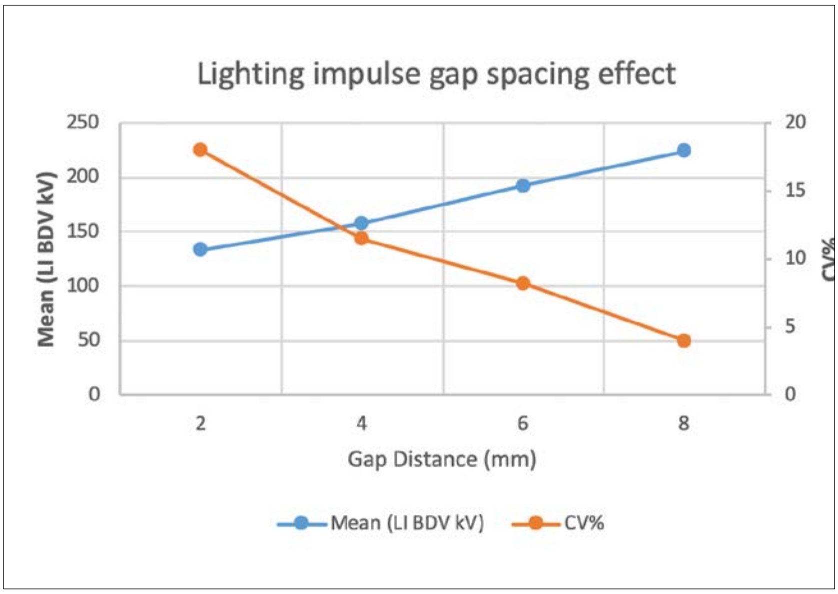


Figure 7. Lighting impulse gap spacing effect acc. to Kunikowski et al.

The nature of the change in the average value and CV% LI BDV (non-uniform electric field!) for various gaps is generally the same as for alternating voltage

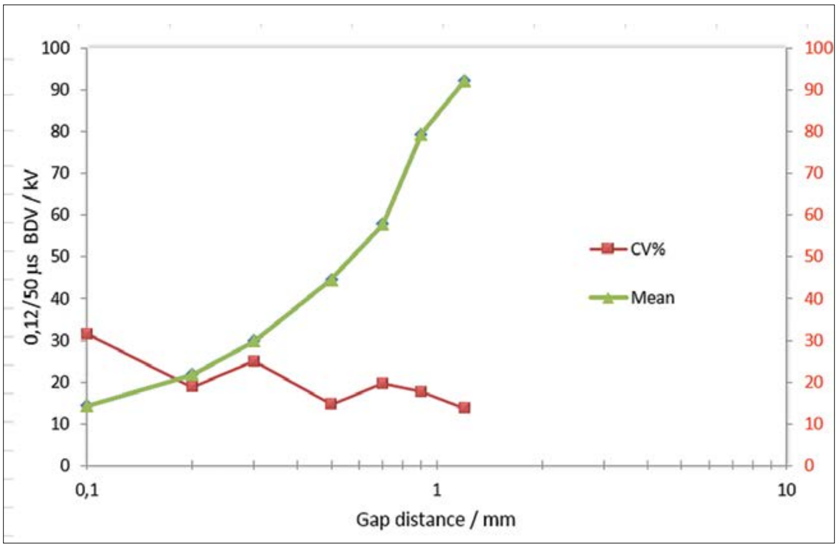


Figure 8. 0.12/50 ms impulse gap spacing effect acc. to Yuan et al.

6.1.7. The steep front impulse breakdown voltage: Gap distances of 0.1 ÷ 1.2 mm (data by Yuan et al., 2017)

Chinese university scientists (Xi'an Jiaotong University) studied transformer oil at pulses of 0.12/50 ms in mushroom-shaped electrodes with a diameter of 30 mm [10]. From the Weibull plots given in their article, we extracted the values of BDV and CV% and plotted Fig. 8.

As seen in this figure, despite the deviations of CV% from the conditionally drawn smoothing falling line, it can be assumed that this line does not contradict the straight line. Note that for the steep front impulse, the CV% decreases by only 2 times when the gap spacing increases by more than an order of magnitude (from 0.1 to 1.2 mm).

To summarize point 6.1, we state that for gap spacing ranging from 0.1 to 85 mm (which generously covers the entire range of distances used in insulating a power transformer) and for voltages from the steep front impulse to AC (which can be considered to cover all types insulation tests) it can be assumed that CV% decreases linearly with the logarithm of the gap distance. In this case, the rate of decrease in CV% is 2÷4 times per order of magnitude increase in the gap.

For gap spacing ranging from 0.1 to 85 mm and for voltages from the steep front impulse to AC, it can be assumed that CV% decreases linearly with the logarithm of the gap distance

Conclusions to Part II

1. CV% serves as a valuable indicator for assessing the stability and predictability of transformer oil and other insulating fluids under electrical stress. Studying and understanding the dependencies of CV% on the factors that affect it is important for the optimal design of internal insulation and maintenance of power equipment of power systems with reliable insulation characteristics.

2. As the rate of AC voltage, the BDV of the oil increases and the CV% decreases. There is currently little data to quantify these phenomena. We recommend regularly reporting the CV% and voltage velocity ramp (if it differs from the standard) along with classic BDV results.

3. For gaps ranging from 0.1 to 85 mm (which completely covers the entire range of distances used in power transformer insulation) and for voltages from steep edge to AC (i.e. for all types of insulation tests), the CV% can be considered to decrease linearly with the logarithm of the gap (on average about 3 times with an increase in the gap by 10 times).

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Annex: Liquid type vs. CV%

As shown in the article, the voltage rise effect in transformer oil is attributed mainly to impurities present, and it should be noted that other effects may be present in different insulating liquids, correlated to polarization effects of different pure liquids starting for less polar structure of paraffin and gas to liquids oils up to much polar esters. The molecular structure of the fluid may be the main reason for differences in CV%. The Vaan Der Walls intermolecular forces and strengths of dipole momentum determine the response factor of each molecule to react to the transients of the voltage ramp. Liquid viscosity affects the mobility of those nonpolar to slightly polar molecules; therefore, temperature also affects measurements. Those phenomena occur besides the solubility influence on CV% of BDV.

Having analyzed the literature data, we can come to the following preliminary comparative conclusions for the three most common liquids:

Mineral oils: Typically exhibit moderate breakdown voltages and moderate CV%. They are relatively stable but may have different CV% at higher ramp rates due to their dependence on temperature and aging.

Natural esters: These liquids are less flammable but with higher pour points may show different CV% due to greater variability in their dielectric strength, especially under different ramp rates or moisture content.

Synthetic esters: Often show lower CV% due to their consistency and higher resistance to breakdown. They provide stable dielectric performance across varying voltage ramp rates.

These subjects will be discussed in the next part of the study.

Authors

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.

Marius Grisaru holds an MSc in Electro-Analytical Chemistry from the Israel Institute of Technology. He has almost 30 years of intense experience in almost all transformer oil test chains, from planning, sampling, and diagnosis to recommendations and treatments, mainly in Israel but also in other parts of the world. He is responsible for establishing test strategies and procedures and creating acceptance criteria for insulating liquids and materials based on current standardization and field experience. In addition, he trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE, and a former member of ASTM. He is also the author and co-author of many papers, CIGRE brochures, and presentations at prestigious international conferences on insulation oil tests, focusing on DGA, analytical chemistry of insulating oil, and advantageous maintenance policy for oil and new transformers.