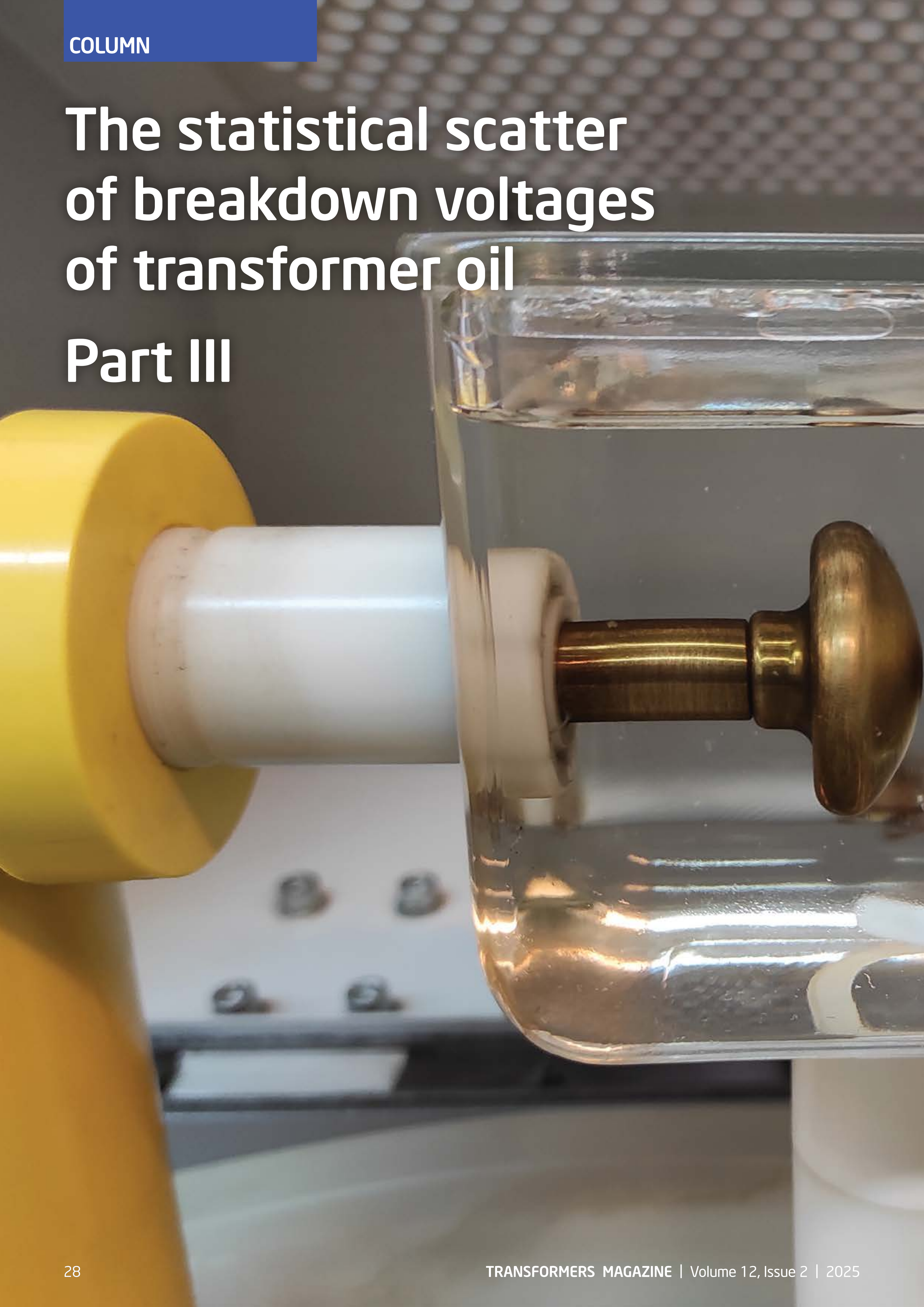
The statistical scatter of breakdown voltages of transformer oil

Part III



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The primary purpose of the earliest insulating liquid tests was to predict transformer failures due to liquid breakdown voltage

ABSTRACT

The third part of the article about coefficients of variation (CV%) of breakdown voltage (BDV) of transformer oil discusses area effect and volume effect. Apparently, BDV decreases linearly with area on a logarithmic scale, but this does not apply to CV%. There is currently little data to make any quantitative recommendations. With an increase in the stressed oil volume by orders of magnitude, CV% decreases several times, but this estimate requires verification.

KEYWORDS:

area effect, breakdown voltage, coefficients of variation, electric strength, transformer oil, stressed oil volume

Standard deviation (σ) measures the dispersion or spread of breakdown voltage (BDV) values around the mean (average) value

1. Introduction

As noted in the previous part of the article, the area effect and volume effect are components of the size effect [1].

First, let's take a short historical journey. The primary purpose of the earliest insulating liquid tests was to predict transformer failures due to liquid breakdown voltage. This was particularly important in the early 20th century when these critical liquid tests were first introduced. However, it is even more important today, as transformer sizes have been significantly reduced compared to the past, while voltage stress has increased considerably.

This means that a smaller electrode area and a reduced stressed liquid volume must now withstand much higher electrical stress. As a result, research into these parameters has become less theoretical and more practical, requiring transformer designers to better understand the effects of both the applied voltage surface area and the reduction of stressed volume.

2. Standard deviation (σ) and coefficient of variation (CV%)

Recall that the main parameters for assessing the scatter breakdown voltage are the following:

- *Standard deviation (σ)*

Standard deviation (σ) measures the dispersion or spread of breakdown voltage (BDV) values around the mean (average) value. It quantifies how much BDV values deviate from the mean in a dataset.

Mathematically, the standard deviation is given by:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

Where:

• xi = Individual BDV measurement
• μ = Mean BDV value
• N = Number of measurements

The coefficient of variation (CV%) is a normalized measure of dispersion that expresses the standard deviation as a percentage of the mean BDV

- *Coefficient of variation (CV%)*

The coefficient of variation (CV%) is a normalized measure of dispersion that expresses the standard deviation as a percentage of the mean BDV. It helps compare BDV variations across different experimental setups or conditions.

CV% is calculated as:

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

Where:

• σ = Standard deviation of BDV
• μ = Mean BDV value

Table 1 shows the differences between standard deviation and CV%.

Let us formulate *practical conclusions for BDV measurements:*

- Standard deviation is useful when absolute BDV stability is required, such as in designing transformer insulation with fixed breakdown limits.
- CV% is better suited for comparing BDV variability across different stressed volumes and electrode configurations.
- BDV testing should report both Standard Deviation and CV% to provide a complete statistical description of breakdown characteristics.
- CV% is a better metric for large-scale transformer oil testing since it accounts for different oil conditions and electrode sizes.

Additionally, the coefficient of variation (CV%) for breakdown voltage has be-

Table 1

Aspect	Standard deviation (σ)	Coefficient of variation (CV%)
Definition	Measures the absolute variation in BDV values	Measures relative variation as a percentage of the mean BDV
Unit Dependence	Expressed in BDV measurement units (e.g., kV)	Dimensionless percentage
Interpretation	Indicates absolute scatter in BDV measurements	Allows comparison between datasets with different BDV magnitudes
Comparison across tests	It is not suitable for comparing BDV distributions with different means	It is better for comparing different BDV datasets
Application	Useful when absolute voltage variation is critical	Used when relative variation is more important than absolute values

come critical, not just because standard measurement procedures require greater accuracy but, more importantly, because it is highly relevant to transformer operation. Breakdown of the liquid matrix and potential transformer failure occurs at the lower extremes of the BDV distribution. Therefore, transformer designers must know this probability for a given geometric configuration and stress design to ensure reliable transformer performance.

The CV% for breakdown voltage has become critical, not just because standard measurement procedures require greater accuracy but, more importantly, because it's high relevance to transformer operation

This study is devoted to the study of literature data on area effect and volume effect, from which data could be extracted for calculating CV%.

3. Area effect

3.1. Data by Weber and Endicott, 1956

Three quarters of a century ago, Weber and Endicott (General Electric Co.) discovered a nonlinear relationship between the dielectric strength of transformer oil and the area of the electrodes [2]. The dependence extracted from their classic work and the CV% we calculated are shown in Fig. 1. As can be seen from the figure, dielectric strength decreases almost linearly with the logarithm of the electrode area, but no pattern is visible in the change in CV%.

Fifteen years later, Dr. Nelson (University of London), in collaboration with Dr. Salvage (Heriot-Watt University, Scotland) and Mr. Sharpley (Parsons Peebles Ltd, Scotland), conducted what has become a classic study of the electric strength of transformer oil for large electrode areas [3].

3.2. Data by Nelson et al., 1971

The authors give the electrical strength for an area in the range of 0.07 ÷ 1.885 m^2 (Table 2). The table also shows the CV% values we calculated. To cite the authors' words, "*the change in strength with electrode area conformed approximately to the logarithmic law predicted by Weber and Endicott*" are confirmed by a comparative analysis of the table's first, second and fourth columns. However, the changes in CV% do not show any patterns, just like in the Weber and Endicott data.

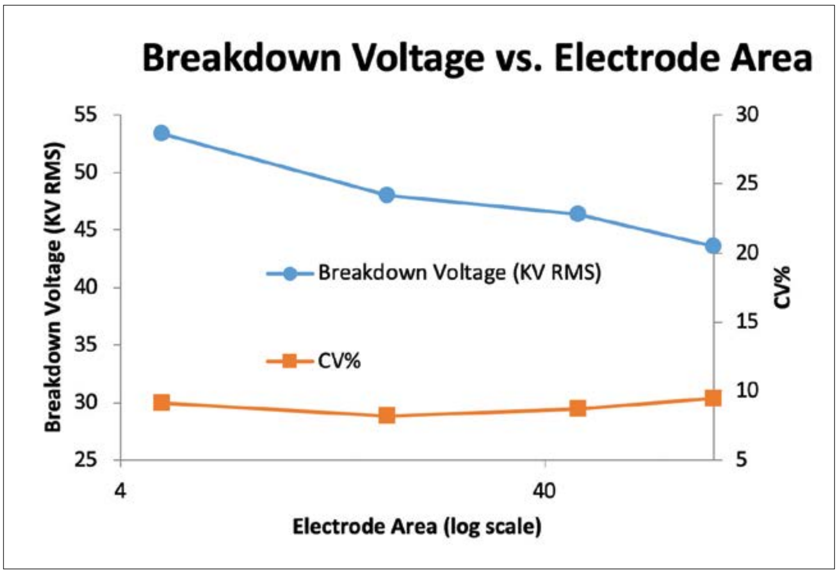


Figure 1. Area effect, according to Weber and Endicott

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

Area / m2	Power frequency		1.2/50 μs impulse	
	E – kV/mm	CV%	E – kV/mm	CV%
1-885	8-9	8.8	21-7	13.6
0-631	9 0	17.1	23-6	14.6
0-211	9-9	14.9	24-9	17.9
0 070	10-3	10.8	28.0	16
0 070	12.0	10	32-0	14.1

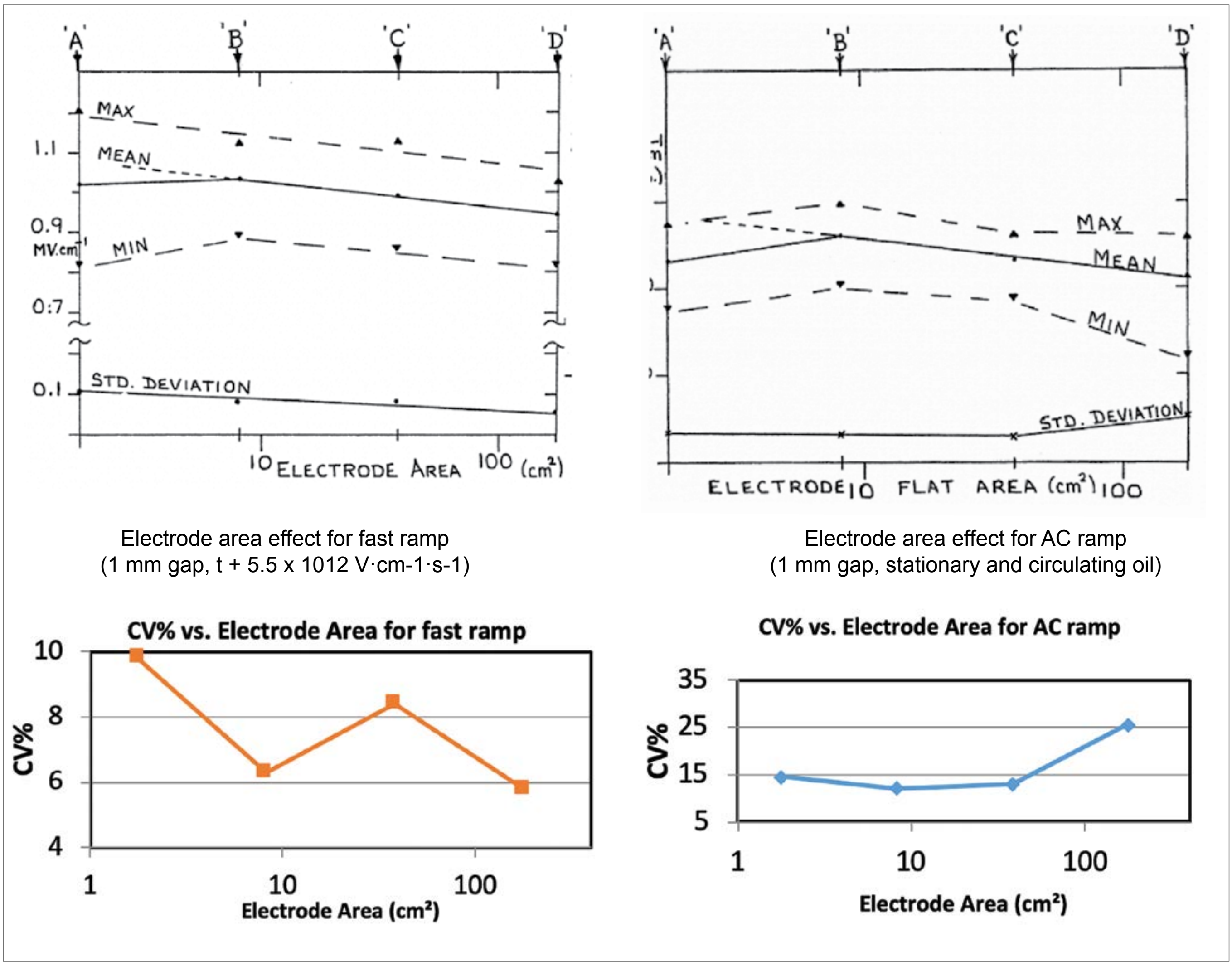


Figure 2. Area influence on different measurements, according to Bell

In 2022, Markovic et al. concluded that for the mushroom electrodes, the electrical strength and CV% decrease with the logarithm of the area practically in a straight line

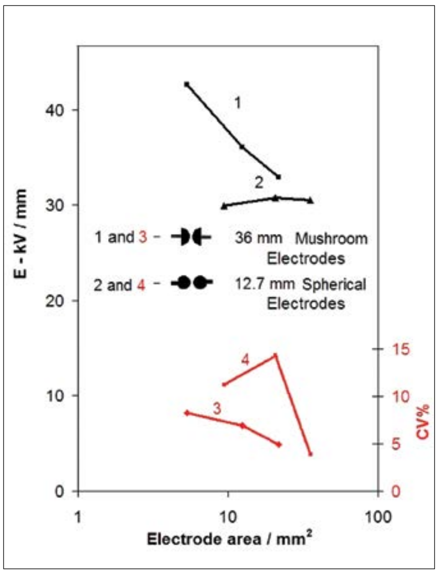


Figure 3. Area effect, according to Markovic et al.

3.3. Data by Bell, 1977

Bell (University of Newcastle upon Tyne, England) investigated four electrode areas (1.77, 8.19, 37.9 and 177 cm²) using a fast ramp (5.5 x 10^{12} V·cm^{-1}·s^{-1}) and an AC ramp (12 kV·cm^{-1}·s^{-1}). The results are shown in Fig. 2. The upper part of the figure is taken from [4], the lower part was created by us.

It should be pointed out that Bell defined area (and volume) on the basis of the electrode flat area and not according to the "90 per cent field area" or "breakdown site area", as used by some researchers.

As seen in Fig. 2, for the fast ramp case, there is a weak tendency towards a decrease in both E and CV%. However, in the case of the AC ramp, the dependence on the area is not visible for both values.

3.4. Data by Markovic et al., 2022

Croatian specialists' (Končar Distribution & Special Transformers) tests were performed with the Megger OTS100AF oil testing device [5]. The transformer oil used was Ergon's Hyvolt III mineral oil. Two types of electrodes (indicated in Fig. 3) and three area sizes were used.

For mushroom electrodes, the electrical strength and CV% decrease with the logarithm of the area (5.3, 12.5 and 21.7 mm²) practically in a straight line (curves

In data by Nelson et al., E decreases quite well linearly on a logarithmic scale depending on the volume of oil for both AC and impulses, but the CV% in both cases are randomly scattered

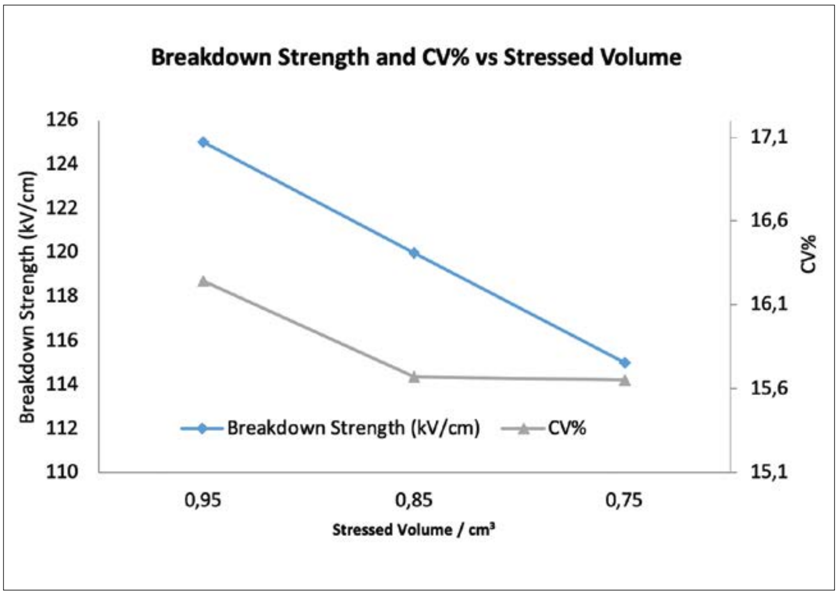


Figure 4. Breakdown strength and CV% vs stressed volume (Table V of Wilson [6])

1 and 3). For spherical electrodes with an area of 9.4, 20.6 and 35.4 mm^2, no patterns are observed (curves 2 and 4).

To summarize point 3, we state that the area effect is much less pronounced than the cap spacing effect described in the previous part of the article [1]. It can be assumed that the BDV decreases linearly with the area on a logarithmic scale. According to the theory, the scatter of the BDV for this effect is determined by the condition and cleanliness of the electrode surface. However, in the areas of internal insulation that interest us, there are no electrodes that are not covered with insulation (we do not consider tap changers). Thus, at present, there is little data on the area effect in the literature, and it is not yet possible to give any quantitative recommendations to designers on optimal insulation.

4. Volume effect

4.1. Data by Wilson, 1953

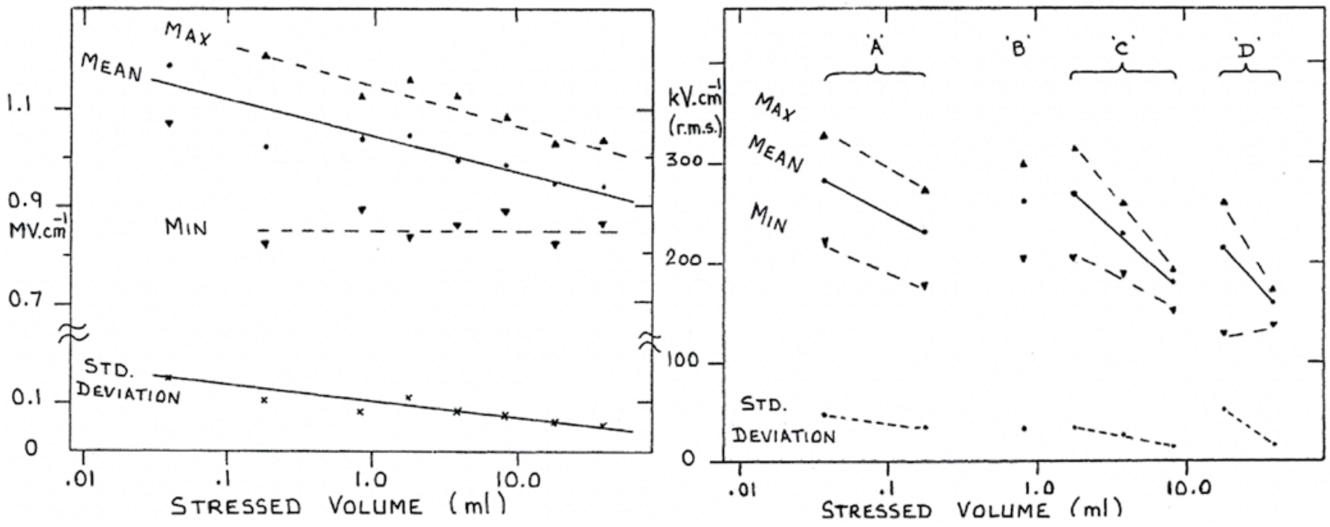
The first person to notice this effect was Wilson (General Electric) back in 1953. In his now classic work [6], he proposed the theory that the primary factor, which determines the unit dielectric strength of commercial oil of controlled quality around electrodes of different geometries,

In 1953, Wilson proposed a volume of the oil under stress to be the primary factor which determines the unit dielectric strength of commercial oil of controlled quality around electrodes of different geometries

Table 3. Volume effect, according to Nelson et al. Sample size N = 100 for 50 Hz and about 50 for impulse

Volume / m3	Power frequency		1.2/50 µs impulse	
	E – kV/mm	CV%	E – kV/mm	CV%
0.041	8,6	15,1	18,7	13.6
0.032	8,4	15,0	20,2	14.6
0.022	8,6	13,1	18,9	17.9
0.013	8,9	8,8	21,7	16
0.0073	9,0	17,1	23,6	14.1
0.0024	9,9	14,9	24,9	17.9
0.0008	10,3	10,8	28,0	16
0.0004	12,0	10,0	32,0	14.1

In data by Nelson et al., E decreases quite well linearly on a logarithmic scale depending on the volume of oil for both AC and impulses, but the CV% in both cases are randomly scattered



Volume effect for fast ramp (E + 5.5 × 10^{12} V·cm⁻¹·s⁻¹)

Volume effect for AC ramp (stationary and circulating oil), 4 electrodes areas, A, B, C, D

Str. volume / relative units	CV%
17	12.3
33	10.4
51	7.6
59	10.6
67	7.9
76	7.4
83	6.3
93	6

CV%			
16.5			
14.9			
	13.1		
		13.2	
		11.3	
		8	
			24.1
			10.7

Figure 5. Volume effect on breakdown voltage, standard deviation, and CV% according to Bell

is the volume of that oil under stress. The reason is basically statistical. For small volumes of oil, such as test cups, statistical variations are large, and unit dielectric strengths are high. For large volumes at high spacing, such as in large power equipment, lower unit dielectric strengths must be recognized, but statistical reliability and reproducibility are greatly improved.

Wilson's paper, unfortunately, contains only one case where data could be extracted to calculate the CV%. We present it in Fig. 4.

As seen in Fig. 4, with an increase in volume by 1.8 times (from 0.74 to 1.33 cm^3), E clearly linearly decreases on a logarithmic scale by only 1.09 times, and CV%, if we conditionally draw a straight line by only 1.04 times.

In 1969, Palmer and Sharpley confirm that electrode shape influences breakdown by modifying stressed volume rather than directly affecting BDV

4.2. Data by Nelson et al., 1971

The data extracted from [2] are presented in Table 3.

TThe data from this table were also plotted on graphs. It turned out that E decreases quite well linearly on a logarithmic scale depending on the volume of oil for both AC and impulses, but the CV% in both cases are randomly scattered.

4.3. Data by Bell, 1971

The data extracted from [4] are shown in Fig. 5.

As can be seen from the left part of Fig. 5, for a fast ramp with an increase in stressed

volume by almost three orders of magnitude, CV% decreases by two times. For the AC ramp (right part of the figure), the stressed volume of oil (segments A, B, C) increases on average by 4 times, and CV% decreases by 2.5 times.

5. Data by Palmer and Sharpley, 1969

Palmer and Sharpley, contemporaries of Nelson and Bell, published an equally important article [7], which presents the results of electrical-strength tests on transformer oil, alone and in combination with solid insulation, under various conditions. The article presents the dependencies of the electrical strength of transformer oil in a uniform field (industrial frequency voltage and pulse voltage) for large volumes of oil (more than 10^3 cm^3). The authors' main conclusions follow.

5.1. Breakdown of voltage and electrode area

• Electrode area has a weaker effect on BDV than stressed volume.

• For polished aluminium/steel disc electrodes, BDV decreases as electrode diameter increases, but this effect is less significant than volume dependency.

• Figures 8 and 9 in [7] confirm that electrode shape influences breakdown by modifying stressed volume rather than directly affecting BDV.

5.2. Breakdown voltage and stressed oil volume

- Breakdown voltage decreases significantly as stressed oil volume increases, following a logarithmic trend.
- BDV is primarily controlled by stressed volume rather than electrode area.
- In nonuniform fields, BDV can be predicted using the failure-stress/volume characteristic of oil in uniform fields

5.3. Coefficient of variation (CV%) and stressed oil volume

- CV% remains nearly constant (~10-11%) for all tested oil volumes.
- Despite BDV decreasing, the distribution of breakdown voltages follows a normal (Gaussian) distribution, not an extreme-value distribution.
- Figure 6 in [7] shows that breakdown

voltage distributions remain stable regardless of stressed volume.

6. Differences between Palmer and Sharpley [7] and previous papers [2-6]

6.1. Breakdown voltage (BDV)

- Palmer and Sharpley (1969): BDV is primarily controlled by stressed volume and follows a logarithmic trend.
- Wilson (1953) and Bell (1977): BDV decreases with stressed volume, but the relationship is sometimes modelled as power-law rather than logarithmic.
- Nelson et al. (1971): Found that BDV is influenced more by large-scale electrode configurations, but Palmer emphasizes stressed volume instead.

6.2. Coefficient of variation (CV%)

- Palmer and Sharpley (1969): CV% remains stable (~10-11%) across different stressed volumes, indicating a normal distribution.
- Bell (1977): Observed that CV% decreases significantly with increasing stressed volume, particularly for fast ramp conditions.
- Markovic et al. (2022): Found electrode shape influences CV%, whereas Palmer and Sharpley suggest stressed volume is the dominant factor.

6.3. Electrode area

- Palmer and Sharpley (1969): Electrode area has a weaker effect than stressed volume, with BDV decreasing slightly for larger electrodes.
- Nelson et al. (1971): Stressed volume and electrode area effects were nearly equal, contradicting Palmer's emphasis on volume.
- Bell (1977): Found that electrode area influences breakdown when combined with high oil circulation, whereas Palmer only analyzed stationary oil.

For large transformers, predicting breakdown strength requires volume-based models rather than electrode-based models

Parameter	Effect of Increasing Electrode Area	Effect of Increasing Stressed Volume
Breakdown Voltage (BDV)	Decreases, but the effect is weaker	Decreases significantly (logarithmic relationship)
CV%	Minimal influence compared to the stressed volume	Remains relatively constant (~10-11%)

7. Summary table of the studies reviewed

Aspect	Marković et al. (2014)	Palmer and Sharpley (1969)	Bell (1977)	Nelson et al. (1971)	Weber and Endicott (1956)	Wilson (1953)
BDV vs. Stressed Volume	Decreases significantly (FEM-confirmed)	Logarithmic decrease	Nonlinear decrease	Influenced by both volume and electrode area	Weak-link failure model	Decreases but slower trend
BDV vs. Electrode Area	Weaker effect than volume	Minimal effect	Nonlinear decrease with area	Area and volume effects are nearly equal	Larger area increases breakdown probability	Minimal impact compared to volume
CV% vs. Stressed Volume	Slight increase in variation	Stable (~10-11%)	Decreases significantly	Fluctuates, no clear trend	Follows extremal distribution	No significant trend was observed
CV% vs. Electrode Area	No clear trend	No trend observed	Decreases with area	Minor variations, no consistent trend	Weaker electrodes show more variability	No observed correlation
Application	Useful when absolute voltage variation is critical	Used when relative variation is more important than absolute values	Useful when absolute voltage variation is critical	Used when relative variation is more important than absolute values	Useful when absolute voltage variation is critical	Used when relative variation is more important than absolute values

Dielectric strength decreases almost linearly with the logarithm of the electrode area, but no pattern is visible in the change in CV%

8. Practical implications for transformer design

- Insulation systems should prioritize controlling stressed volume over electrode size.
- Transformer oil testing should focus on stressed volume effects rather than electrode area effects alone.
- For large transformers, predicting breakdown strength requires volume-based models rather than electrode-based models.
- Since CV% remains stable across stressed volumes, transformer reliability predictions can assume consistent statistical distributions.

Conclusion

1. Marković et al. (2014) confirm BDV trends using FEM modelling, supporting Palmer and Sharpley (1969) on volume effects. Their findings differ from Bell (1977), who emphasized electrode area effects. Nelson et al. (1971) viewed volume and area effects as nearly equal. Weber and Endicott (1956) proposed a weakest-link failure model, and Wilson (1953) found no strong correlations for CV% but confirmed BDV reduction with volume.
2. The area effect is much weaker than the cap saving effect. Apparently, the BDV decreases linearly with the area on a logarithmic scale, but we did not find any patterns in the dependence of CV%. At present, there is little data on the area effect, and it is not yet possible to give any quantitative recommendations to designers of optimal insulation.
3. With an increase in the stressed oil volume by orders of magnitude, the CV% decreases several times, but this assessment requires verification.

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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.