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STATISTICAL AND NUMERICAL ANALYSIS OF TRANSFORMER OIL AC BREAKDOWN

SUMMARY

Transformer oil AC breakdown research is an important part of transformer insulation design. Research presented in this paper consists of statistical and numerical analysis of breakdown data measured in portable oil tester. Statistical analysis is done by modeling measured data as a random process with Gaussian and Weibull probability function. Numerical analysis uses statistical data for calculation of stressed oil volume, stressed electrode area and safety factors of “cumulative stress” method. Both statistical and numerical analysis showed how breakdown withstand depends on different variables and why they are important in measurement interpretation.

Key words: oil breakdown, Gaussian distribution, Weibull distribution, FEM, stressed oil volume, stressed electrode area, “cumulative stress” method

1. INTRODUCTION

Aim of this paper is to statistically and numerically compare three methods which describe AC breakdown of transformer oil: stressed oil volume (SOV), stressed electrode area (SEA) and cumulative stress method [1 – 6].

Experimental part consists of three different test variables: electrode type, electrode distance and transformer oil treatment. Tests are performed with Megger OTS100AF oil testing device, with oil breakdown range up to 100 kV. Transformer oil in all experiments was Ergon’s Hyvolt III mineral oil.

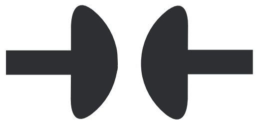
Numerical part is done with *Infolytica ElecNet* software and custom written VBA scripts.

Statistical analysis was influenced by work done by Martin and Wang in 2008 [7].

2. TRANSFORMER OIL TESTING

Table I shows different values of test variables.

Table I - Test variables names and abbreviations

Test Variable	Value	Abbreviation
Electrode type	 36 mm Mushroom Electrodes	A
	 12.7 mm Spherical Electrodes	B
Electrode distance	1 mm	1
	2 mm	2
	3 mm	3
Transformer oil treatment	Mineral oil degassed	D
	Mineral oil non-degassed	N

This makes a total sum of twelve measurement sets. Each set is coded according to variable abbreviations. For example, test with "B" type of electrodes, electrode distance of "1 mm" and "Degassed" transformer mineral oil is abbreviated "B1D". For each measurement set, a number of 40 breakdown voltages are documented, with 1 minute pause between breakdowns (no stir).

2.1. Statistical analysis

Visualization and analysis of acquired data was done with the help of the *Wolfram Mathematica 10.0* and *Microsoft Excel 2010*. Figure 1 shows histogram plots, with estimated censored Weibull distribution (continuous line) and Gaussian distribution (dashed line).

Weibull probability [8] density function $P(x)$ is defined for $x \in [0, \infty)$ with parameters α and β as:

$$P(x) = \frac{\alpha}{\beta}\left(\frac{\alpha}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{1}$$

Gaussian probability [9] density function $P(x)$ is defined for $x \in (-\infty, \infty)$ by μ and σ as follows:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2}$$

Table II shows statistic parameters of these two distributions (α, β and μ, σ), and also goodness-of-fit (GOF), as well as percentiles P_1 and P_{50} for both parametric and non-parametric evaluation of the data. For Gaussian distribution 50th percentile equals mean value ($P_{50} \equiv \mu$).

Table II - Statistical evaluation of measured data

	Weibull distribution					Gaussian distribution					Non-parametric	
	GOF	α	β	P_1 [kV]	P_{50} [kV]	*GOF*	μ	σ	P_1 [kV]	P_{50} [kV]	P_1 [kV]	P_{50} [kV]
B1N	0.91	11.58	39.42	26.50	38.20	0.72	37.70	3.89	28.64	37.70	30.40	38.20
B2N	0.75	17.02	68.31	52.13	66.85	0.83	66.27	4.44	55.94	66.27	55.90	66.40
B3N	0.69	15.46	94.13	69.90	91.93	0.15	90.71	8.19	71.65	90.71	57.10	93.10
B1D	0.80	13.59	43.58	31.06	42.42	0.96	42.00	3.43	34.01	42.00	34.10	42.00
B2D	0.86	16.68	72.45	54.99	70.87	0.95	70.26	4.83	59.03	70.26	57.00	70.00
B3D	0.10	18.05	98.30	76.18	96.32	0.35	94.76	4.65	83.93	94.76	83.40	94.40
A1N	0.71	10.87	32.94	21.58	31.85	0.76	31.53	3.12	24.28	31.53	24.70	32.20
A2N	0.92	13.36	60.15	42.64	58.53	1.00	57.95	4.88	46.59	57.95	45.10	57.80
A3N	0.16	6.13	74.28	35.06	69.96	0.30	69.40	10.75	44.40	69.40	48.50	65.90
A1D	0.98	13.11	37.43	26.35	36.40	0.38	35.94	4.01	26.62	35.94	17.70	36.40
A2D	0.64	9.48	73.94	45.50	71.13	0.20	70.03	10.31	46.04	70.03	34.90	71.20
A3D	0	1.54	311.09	15.71	245.23	0	97.84	3.79	89.03	97.84	85.30	100.00

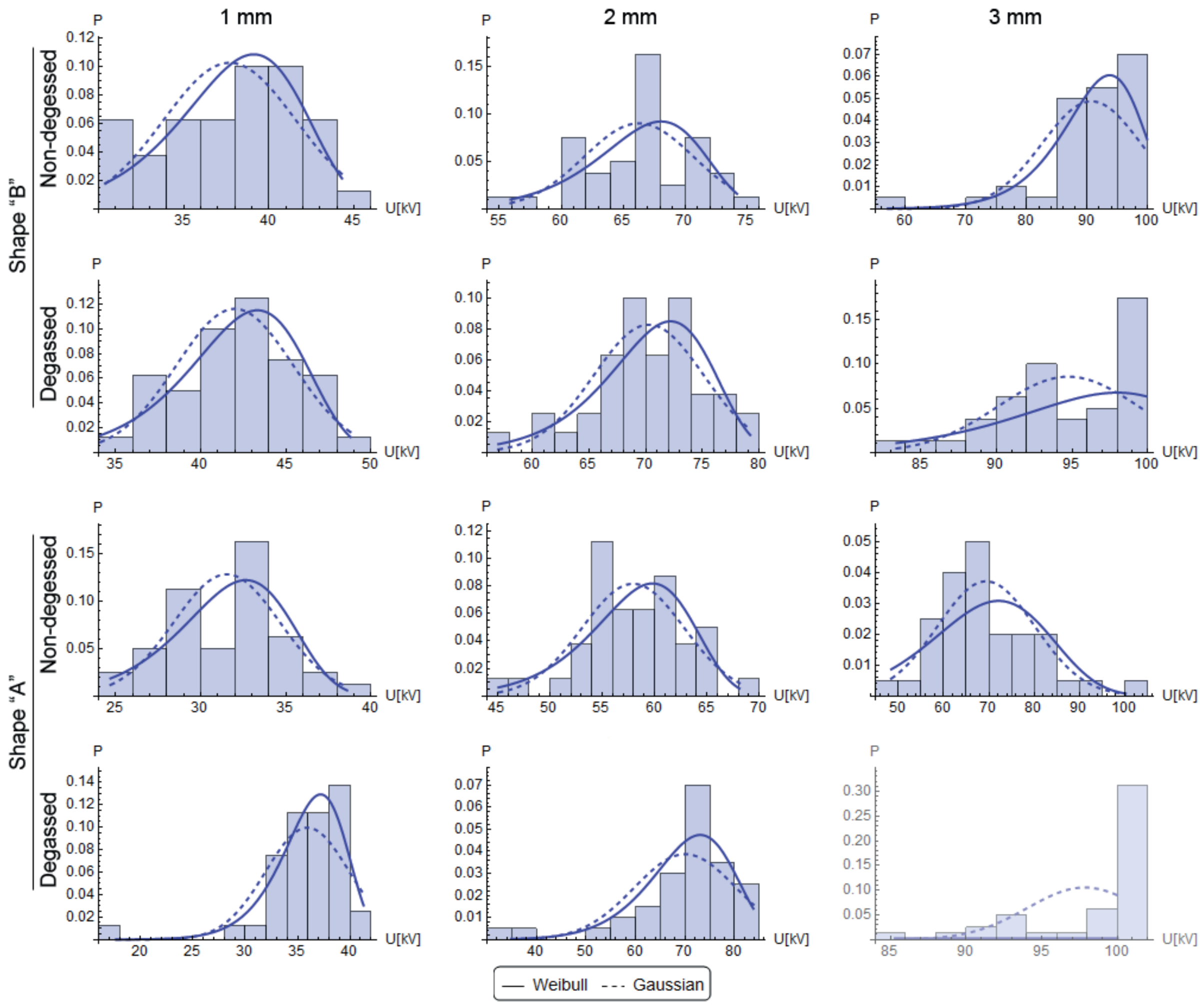


Figure 1 – Histogram plot of measured data

Figure 2 shows both first and fiftieth percentile for Weibull, Gaussian and non-parametric distribution of acquired voltage breakdown data.

GOF values for Weibull and Gaussian distribution are shown on Figure 3. They represent measure of the deviation of a sample from expectation.

Table III shows percent of breakdowns (per test set) that did not occur.

All voltage breakdown values are shown on Figure 4. It contains four graphs that show forty breakdown values for one, two and three millimeters, depending on electrode shape and oil treatment.

Figure 5 shows Gaussian parameters μ and σ from Table II normalized to 1 mm (i.e. average breakdown field between electrodes), according to Eq. (3).

$$\overline{E} = \frac{\overline{U}}{d} = \frac{\mu \pm \sigma}{d} \tag{3}$$

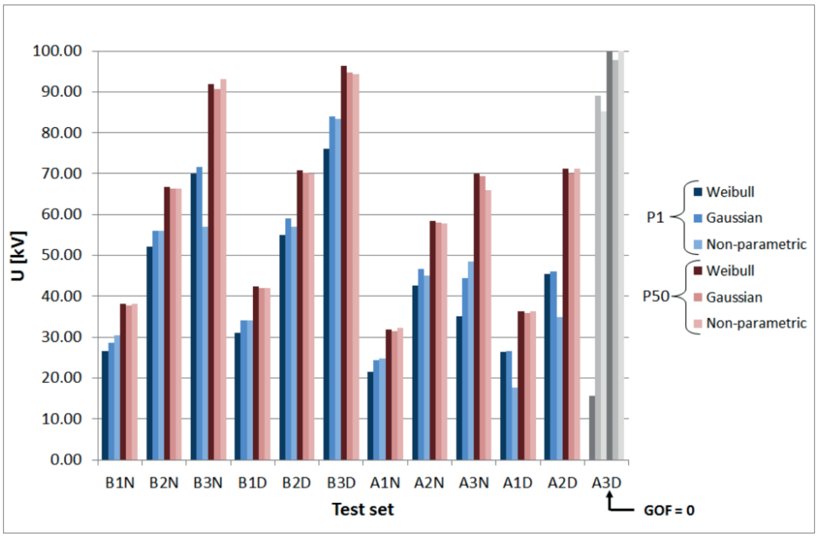


Figure 2 – First (P_1) and fiftieth (P_{50}) percentile for three distributions from Table II

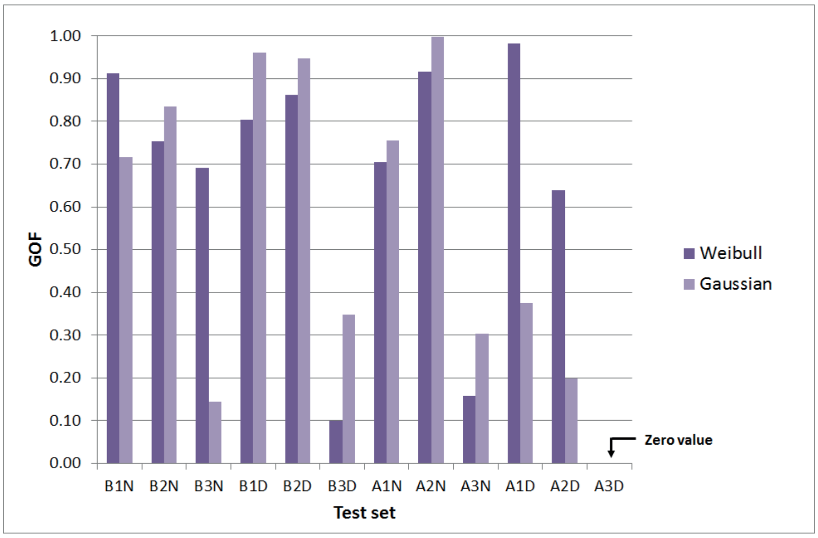


Figure 3 – Goodness-of-fit for parametric distributions in Table II

Table III - Percent of measurement in which breakdown did not occur

	"No-breakdown" rate [%]
B3N	7.5%
B3D	30.0%
A3N	2.5%
A3D	65.0%

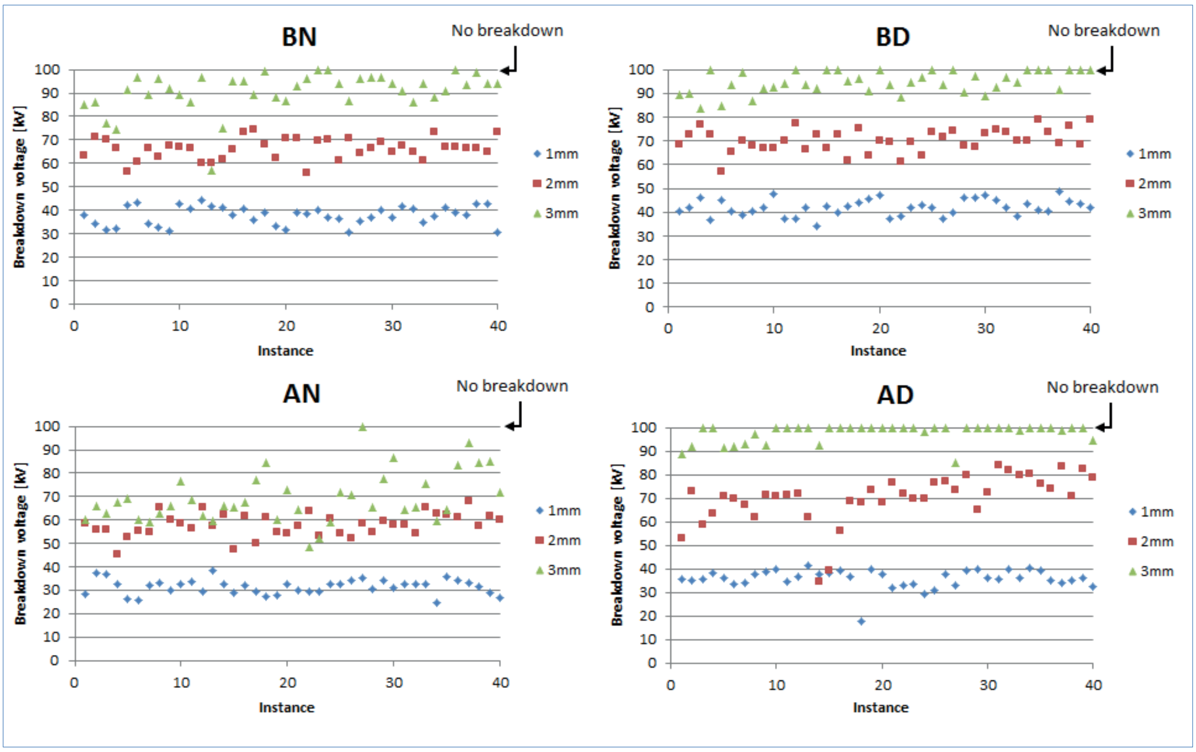


Figure 4 - Dot plot of measured breakdown data

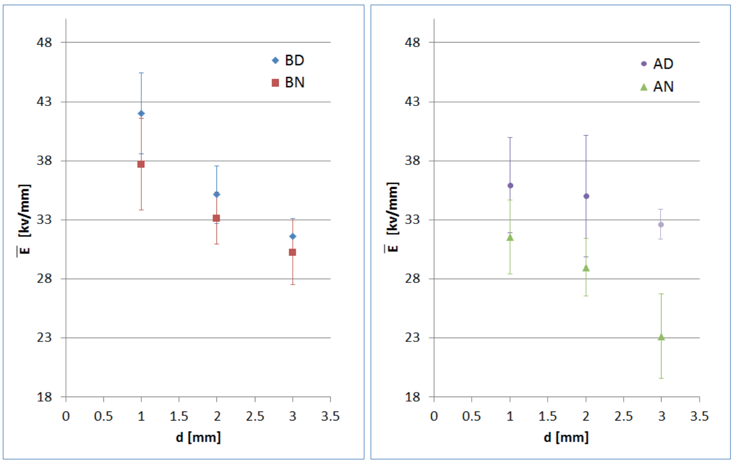


Figure 5 – Value of $\overline{E}$ according to Eq. (3) for 1, 2 and 3 mm distance

From previous figures and tables, the following observations can be made:

a) P_{50} varies less than P_1 across distributions for all measurements (Figure 2)

b) σ increases with electrode distance (Table II)

c) GOF has lowest values for 3 mm distances (Figure 3)

d) $\overline{E}$ decreases with electrode distance (Figure 5)

Measurements taken on 3 mm electrode distance could have lowest GOF values because of greater dispersion of data (i.e. higher σ) or a fact that certain percent of breakdowns did not occur for this distance (Table III). For instance, A3D measurement has the highest rate of non-occurring breakdowns (65%) and zero GOF value (Figure 3). To highlight this, all results referring to this measurement were faded.

It was expected that the censored Weibull distribution would give overall better GOF values for 3 mm distance than Gaussian distribution, since Gaussian distribution does not support data censoring. However, this is true only for B3N measurement. Looking at Figure 3, GOF values presumably do not follow any pattern either for Weibull or Gaussian distribution, thus a noteworthy conclusion based on significance of only one of the parametric distributions cannot be made (the higher the GOF, the more significant distribution is; however, in this circumstance, a statement that one distribution is "better" than other cannot be made, since GOF is inconsistent for both distributions).

Results have also confirmed that degassed oil has higher breakdown values than non-degassed oil. However, an investigation to which extent this relates to moisture content was not made, since authors weren't able to control the absolute moisture content of oil samples. Therefore, rather than choosing continuous variable of "moisture content", research was simplified by choosing discrete (or binary, to be exact) variable of oil "treatment", which was able to have only two conditions:

a) "Degassed" – meaning it had been filtered and dried.

b) "Non-degassed" – meaning it had been taken out of the storage tank without any treatment.

It has been assumed that all samples of degassed oil for "A" and "B" electrodes (in measurements A1D, A2D, A3D and B1D, B2D, B3D) have "equal" moisture content, since they passed same standard process of drying and filtering, although oil samples were not drawn from the same oil "population" (they were sampled at different time with four weeks' time span). In other words, difference between moisture content for electrodes "A" (4 ppm) and electrodes "B" (5 ppm) had been neglected, although moisture for "A" electrodes was 20 % lower. This cannot be said for non-degassed measurements, since their moisture content differed significantly. This withdraws a fact that only AD and BD measurements can be compared regarding electrode shape, which will be done in next part after numerical calculation.

3. NUMERICAL CALCULATION

Two-dimensional (2D) axisymmetric FEM model (Figure 6) is used to calculate stressed oil volume (SOV), stressed electrode area (SEA) and safety factors (q) of "cumulative stress" method for each of twelve testing sets.

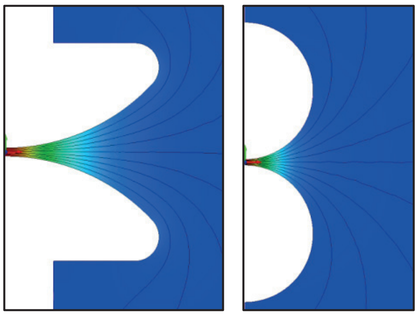


Figure 6 - 2D axisymmetric FEM model for electrodes type "A" and "B"

3.1. Stressed oil volume

Stressed oil volume is equal to "region in which calculated electric stress values are between the maximum value and 90% of the maximum value" [10]. For a case of mushroom electrodes, it has been assumed that 90% of maximum electric stress is within their spherical part. Considering this, SOV for both sphere and mushroom electrodes is calculated according to the formulas:

$$SOV = V_2 - V_1 - V_3 \tag{4}$$

$$V_i = \pi \int_{z_1}^{z_2} r^2 dz \quad i = [1,2,3] \tag{5}$$

where:

SOV – stressed oil volume

V_i – volumes of rotational bodies, created by rotation of curves C_1, C_2 and C_3 around z axis [12]

Figure 7 shows curves C_1 and C_3 defined with circle arcs formed by electrodes in a cross section plane, while curve C_2 is the result of a contour plot of $0.9 \cdot |E|_{\max}$, where $|E|_{\max}$ is maximum electric field in solved model [10].

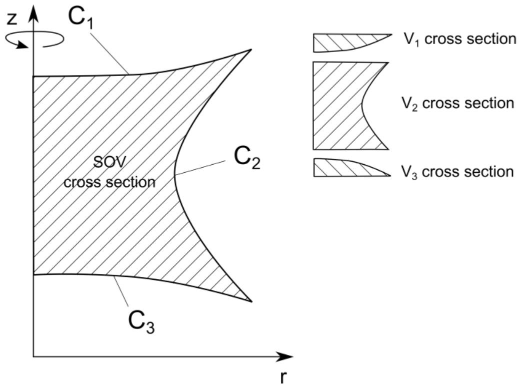


Figure 7 - Cross section of a stressed volume between electrodes

3.2. Stressed electrode area

Stressed electrode area for one electrode is calculated according to equation (6) for a sphere cap shown on Figure 8.

$$SEA = 2\pi Rh \tag{6}$$

where:

SEA – stressed electrode area
R – electrode radius
h – height of a sphere cap obtained from geometry of curve C_1 or C_3 on Figure 7

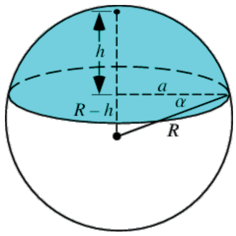


Figure 8 - Area of a sphere cap [11]

3.3. "Cumulative stress" method

Safety factor q of one streamline is calculated [6], [10] according to Eq. (7) and (8).

$$q = \frac{E_{pd}(x)}{E_{av}(x)} \tag{7}$$

where: E_{pd} is low probability PD/breakdown and
E_{av} is calculated according to:

$$E_{av}(x) = \frac{1}{x}\int_0^x E(x)dx \tag{8}$$

where: q – safety factor value
E_{pd} – low probability PD/breakdown
E_{av} – average field along streamline
$E(x)$ – electric field stress (numerically calculated)

3.4. Choosing FEM model boundary value

To calculate electric stress in kV/mm between electrodes, boundary values (namely electrode voltage in kV) should be applied to 2D axisymmetric model. This poses a question which of the measured results should be applied.

In insulation design practice, it is common to use P_1 voltage breakdown value of Weibull distribution, but with additional safety margins [6], [7]. In case of measurements provided in this paper, it seems that number of breakdowns is insufficient to compensate scattering of measurements, especially for the 3 mm case. Thus, although parametric fit of first percentile of Weibull distribution should represent 1 % probability that breakdown will occur, the significance of these results provided in Table II is doubtful. However, since the primary aim of this paper is not investigation of oil breakdown criteria, the question of threshold determination is left for future research.

Regarding FEM model boundary values, authors made a decision that one of the electrodes should have fiftieth percentile of Gaussian distribution (U_1=P_{50}), while the other electrode consequentially has U_2=0 kV.

The first reason for this decision was that Gaussian P_{50} is used in standardized oil testing according to IEC 60156 [13], even though it does not have a practical meaning in insulation design.

The second reason was that the Gaussian P_{50} does not differ significantly from Weibull P_{50} and even non-parametric P_{50}, which was a sort of counterweight to GOF inconsistency seen on Figure 3.

3.5. Numerical results

Gaussian P_{50} values from Table II are inserted into FEM model, and calculated results are presented in Table IV.

Table IV- Results of numerical calculation

	B1N	B2N	B3N	B1D	B2D	B3D
$\|E\|_{max}$ [kV/mm]	38.2	34.0	31.5	42.6	36.1	32.9
SOV [mm^3]	6.9	26.3	54.9	6.9	25.8	54.6
SEA [mm^2]	5.4	12.7	21.7	5.3	12.5	21.7
q_{min}	0.363	0.368	0.357	0.411	0.436	0.432
	A1N	A2N	A3N	A1D	A2D	A3D
$\|E\|_{max}$ [kV/mm]	32.1	29.9	24.1	29.9	30.2	30.5
SOV [mm^3]	13	47.5	104.6	13	47.5	104.6
SEA [mm^2]	9.4	20.6	35.4	9.4	20.6	35.4
q_{min}	0.438	0.422	0.472	0.590	0.524	0.467

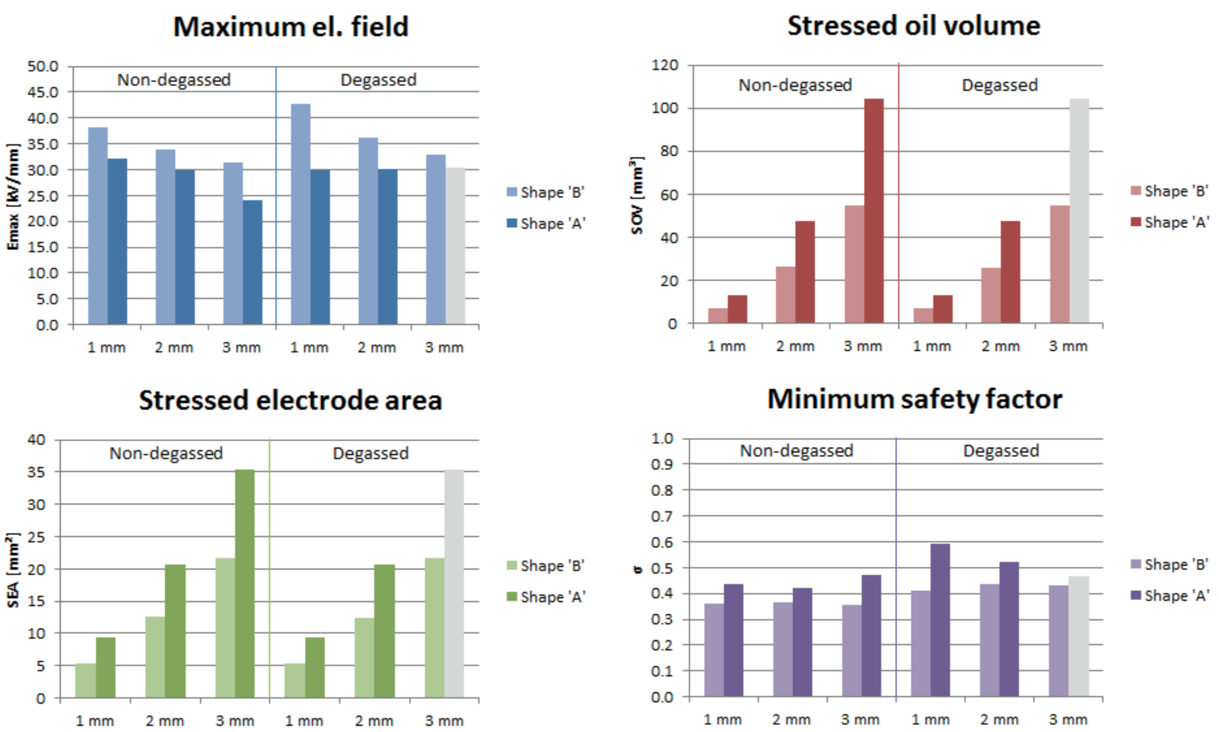


Figure 9 – Visualization of results from Table IV

From the results above, the following observations can be made:

a) $|E|_{max}$ is greater for “B” electrodes
b) $|E|_{max}$ decreases with electrode distance for “B” electrodes
c) SOV and SEA depend solely on electrode geometry (shape and distance)
d) SOV and SEA values are higher for “A” electrodes
e) SOV and SEA increase with electrode distance
f) Safety factors have values less than one (q < 1)
g) Safety factors values are higher for “A” electrodes

It would be expected that by having smaller radius, “B” electrodes should have withstood smaller voltage because of the higher electric stress. However, Figure 5 showed that “B” electrodes, having higher value of $\overline{E}$, withstood higher voltage.

Indeed, the results have confirmed that “with the increase in stressed volume, the dielectric strength of the insulation system reduces. If the electrode radius is increased, the stress values reduce; but at the same time the stressed oil volume (between maximum value and 90% of maximum value) increases reducing withstand”, as states in [10], page 342. Same thing applies with stressed electrode area, as authors showed in [2].

Regarding “cumulative stress” method, safety factors values are as expected (q < 1), since values taken for their configuration (Eq. (7) and (8)) are defined by low probability (first percentile or lower) PD/breakdown, while for this particular case they were calculated with fiftieth percentile. Although electrodes “A” showed higher safety factor values (meaning that the withstand voltage should also be relatively higher than for “B” electrodes), it should be noted that the method itself depends on field homogeneity, which was not discussed in this paper.

4. CONCLUSION

Paper has considered statistical and numerical analysis of transformer oil AC breakdown. By using twelve different measurement sets, authors have presented how breakdown voltage depends on electrode distance, electrode shape and transformer oil treatment. Stressed oil volume, stressed electrode area and safety factors of “cumulative stress” method were calculated using 2D FEM model, confirming that by increasing SOV and SEA, breakdown withstand of transformer oil decreases.

Any future research that considers oil breakdown measurement should presume large number of repetitive tests, especially for large electrode distances, for which dispersion of data rises. It should be taken into account that in the case of a research which includes devastative measurements (such as solid insulation breakdown research), expenditures (such as time and material) could easily reach very high cost levels.

Authors believe that any oil breakdown measurement represented in kV/mm, aside from oil properties, should also have a note regarding electrode distance and electrode shape, since the breakdown results themselves do not describe completely the oil ability to withstand electrical breakdown. In addition, this means that oil breakdown results should not be compared between different electrode geometries. Lacking of electrode geometry information (or international standard) by which transformer oil is to be tested, could be misleading in customer inquiries. For example, if a customer requests only oil breakdown withstand values without proper definition of testing equipment setup, a transformer manufacturer could give valid test results according to test setup that suits his interests (instead of ‘mushroom’ electrodes with 2.5 mm distance, he could use ‘spherical’ electrodes on 1 mm distance and get higher kV/mm breakdown values).

For a final note, both statistical and numerical analysis have proven to be useful in description of oil breakdown, and will be used for future research as well.

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