# ELECTRODE AREA EFFECT ON DIELECTRIC BREAKDOWN STRENGTHS OF MINERAL OIL AND ESTERS

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**Abstract**: With the rising interests in applying esters to large power transformers, it is important for the insulation designers to understand the breakdown strengths of the esters. The breakdown strengths of transformer liquids are generally regarded to follow the Weibull distribution. They are usually measured by small scale tests, and extrapolated to full scale following parallel/series breakdown probability models. This paper clarifies the electrode area effect using well processed transformer liquids, including a mineral oil, a synthetic ester and a natural ester. It is found that esters are more sensitive to the area effect than mineral oil. Due to the narrow distribution of the breakdown voltage, the shape parameter of mineral oil is larger than those of esters, which explains the better performance of mineral oil than esters when stressed under electrodes of large surface areas.

## 1 INTRODUCTION

Insulating oils are used as one of the main insulation materials in power transformers and are used in large volume, usually tens of tons. To secure their optimum utilization, an understanding of the breakdown strengths of the liquids in transformer full scale is of great importance. However, it is neither economical nor necessary to carry out such a test. A reasonable estimation of the breakdown strength of transformer liquid in full scale can be obtained by extrapolation from a series of small scale tests following parallel/series breakdown probability models, which represents the area effect or the volume effect.

It is well known that the AC breakdown strength of mineral oil is decreased with the increase of the electrode surface area or the liquid volume subjected to high electric field stresses [1, 2]. Thus, the area effect or the volume effect should be considered in the practical design of the electrical insulation. Since the area effect is closely related to the contaminations in the transformer liquids, the liquid qualities should also be considered [3]. The weakest links in the contaminated liquids will reduce their breakdown strengths and influence the breakdown strength distributions, thus influencing the area effect.

With rising interest in applying synthetic ester and natural ester in large power transformers, the influence of electrode area on the breakdown strengths of esters should be discussed. Since the physical and chemical properties of esters are different from mineral oil [4], it is expected that there are some differences between their a breakdown strengths when they are stressed under electrode with large surface area.

The purpose of this paper is to comparatively study the area effects on the breakdown strengths of a mineral oil, a synthetic ester and a natural ester under uniform AC field. Seven types of electrodes with effective stressed areas (ESA) between 2.2 $mm^2$ to 17700 $mm^2$ are used. At the same time, the 2-parameters Weibull distribution and parallel breakdown probability model were also applied to analyze the area effect.

## 2 THEORATICAL ANALYSIS OF AREA EFFECT USING WEIBULL DISTRIBUTION

The Weibull distribution is a general purpose reliability distribution used to model the material strengths, or times to failure. It was found that Weibull distribution can be used to fit the breakdown voltage distributions of the insulating liquids much better than other distributions [5]. Using Weibull distribution, the area effect can be theoretically modelled for the use of extrapolation of the breakdown strengths of transformer liquid under large electrodes [6].

Supposing the ESA of an electrode is $S$, the breakdown voltage of insulating liquid stressed between a pair of such electrodes should follow the Weibull distribution as shown in (1).

$$P(E) = 1 - e^{-(\frac{E}{\alpha})^{\beta}} \quad (1)$$

Where $P(E)$ is the failure rate of the test liquid at the applied voltage of $E$. $\alpha$ is the scale parameter, indicating the breakdown voltage at a failure rate of 63%. $\beta$ is the shape parameter, measuring the dispersion of the breakdown voltage distribution.

From weakest link theory and the parallel breakdown probability model [7], $S$ can be regarded as $n$ pieces of basic element $S_0$

connected in parallel. The breakdown voltage of liquids stressed under electrode $S_0$ should also follow Weibull distribution as shown in (2).

$$P_i(E) = 1 - e^{-(\frac{E}{\alpha_i})^{\beta_i}} \tag{2}$$

Since $n$ pieces of basic element $S_0$ were connected in parallel, the breakdown probability of $P$ and $P_i$ follows:

$$1 - P = \prod_i^n (1 - P_i) \tag{3}$$

$$\ln(1 - P) = \sum_i^n \ln(1 - P_i) \tag{4}$$

The $S_0$ is the basic element of electrode $S$, and the applied voltage on each element is the same. Thus $P_i$ is the same for all the basic elements and (4) can be written as:

$$(\frac{E}{\alpha})^{\beta} = \sum_i^n (\frac{E}{\alpha_i})^{\beta_i} = \frac{S}{S_0}(\frac{E}{\alpha_i})^{\beta_i} \tag{5}$$

Solve this equation, we have:

$$\beta = \beta_i \tag{6}$$

$$\alpha = \alpha_i \left(\frac{S}{S_0}\right)^{-\frac{1}{\beta}} \tag{7}$$

Equation (6) indicates that the shape parameter of the breakdown voltage distributions is independent of the electrode *ESA*. From (7), we have:

$$\log(\alpha) = -\frac{1}{\beta}\log(S) + \left(\frac{1}{\beta}\log(S_0) + \log(\alpha_i)\right) \tag{8}$$

The $S_0$, $\alpha_i$ and $\beta$ are the area, scale parameter and shape parameter of the basic electrode element, which can be regarded as constants. Thus, (8) can be written as (9), in which $\alpha$ and $\beta$ are scale and shape parameters of the breakdown voltage distribution under electrode $S$, and $k$ is a constant determined by the liquid.

$$\log(\alpha) = -\frac{1}{\beta}\log(S) + k \tag{9}$$

$$\log(\alpha) = a - b \cdot \log(S) \tag{10}$$

Equation (9) can be further written as (10), in which $a$, $b$ are constants depending on the type of insulating liquid. Since $\alpha$ is the breakdown voltage at a failure rate of 63%, (10) shows the area effect on the breakdown voltage of an insulating liquid. Three conclusions can be obtained from the analysis:

- There is a linear relationship between the logarithmic scale parameter $\alpha$ and the logarithmic electrode *ESA*.
- Comparison of (9) and (10) shows that the reduction rate $b$ of the scale parameter is in reverse relationship with the shape parameter $\beta$. This indicates the breakdown voltage will reduced more significantly with the increase of electrode ESA if the breakdown voltage distributes wider.
- The shape parameter $\beta$ of the breakdown voltage distribution is independent of the ESA of the electrode, if parallel breakdown probability model is ideally followed.

## 3 EXPERIMENTAL DESCRIPTIONS

### 3.1 Oil samples and preparations

Three transformer liquids were investigated in this paper, which are Gemini X produced by Nynas as the mineral oil, Midel 7131 produced by M&I Materials as the synthetic ester, and FR3 produced by Cooper Power Systems as the natural ester.

In order to comparatively study the electrode area effects on the AC breakdown voltages of various transformer liquids, the qualities of the liquids should be controlled to the same level. Otherwise the number of weak-links on unit area for various transformer liquids will be different, and thus it will be difficult to compare the area effect. To control their qualities, the transformer liquid samples were processed before the tests. At first, the liquids were filtered through 0.2 μm membrane filter units. Then, the purified samples were degassed and dehydrated in a vacuum oven at less than 5 mbar and 80 °C for 48 hours. After that, the samples were given a further 24 hours to cool down to ambient temperature under vacuum conditions. To confirm their qualities, the liquid samples were checked before the experiments. It was found that the particle contents (>5μm) in the samples are less than 500 per 100 ml. The water contents of the samples were in the range of 3-10% RH. Therefore, it is regarded that the qualities of the processed liquid samples are in the same level.

### 3.2 Experimental Setup

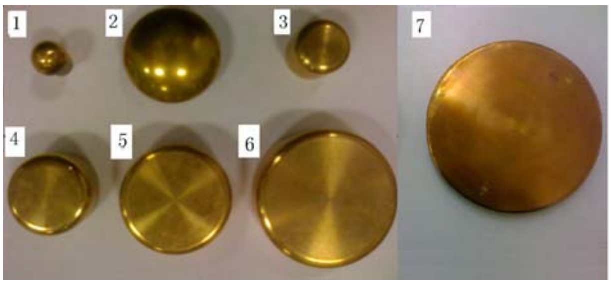



**Figure 1:** Electrodes used for breakdown voltage measurements

Figure 1 shows seven types of electrodes employed for the breakdown voltage measurement in the tests. Electrode 1 is a sphere type electrode with a diameter of 12.5 mm, and electrode 2 is a VDE type electrode with a diameter of 35 mm. Electrodes 3 to 7 are circular, flat electrodes with different diameters, whose edges are curved away with a radius of 1 mm. Table 1 lists the diameters of the electrodes and their corresponding effective stressed areas (*ESA*). The *ESA* is the electrode area which is stressed under electric field larger than 90 % value of the maximum electric field. It is found that the breakdown strength of a transformer liquid depends on the *ESA* rather than the total electrode area [6]. To confirm the field distributions, the field calculation shows that the electric field near the electrode edge does not affect the uniform field between the flat portions of the electrodes.

**Table 1:** Shape configurations for electrodes used in breakdown voltage measurements

| Electrode number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Shape | sphere | VDE | flat | flat | flat | flat | flat |
| Diameter (mm) | 12.5 | 35 | 20 | 30 | 40 | 50 | 150 |
| Effective stressed area ($mm^2$) | 2.17 | 5.22 | 283 | 660 | 1194 | 1885 | 17671 |

For electrode 1 to 6, the AC breakdown voltages of the processed liquids were measured by a Baur DPA75 tester. The current sensor in the tester is set to trip within 10 µs after the breakdown current reaches 4 mA [8], which is found to be suitable to both avoid a false trip and protect the quality of the liquid samples from deteriorating. Since electrode 7 is too large to fit to the DPA 75, the breakdown voltage is measured using a different setup described as follows. The AC voltage was provided by a single phase transformer up to 75 kV. A 500 kΩ resistor was connected between the high voltage supply and the test container to limit the current when a breakdown occurs. It was found that there is little reduction of the breakdown strengths with the increase of the gap distance for clean transformer liquids [3, 9]. Since the qualities of transformer liquids used in this paper are well controlled, the gap distance between parallel electrodes is set at 1 mm.

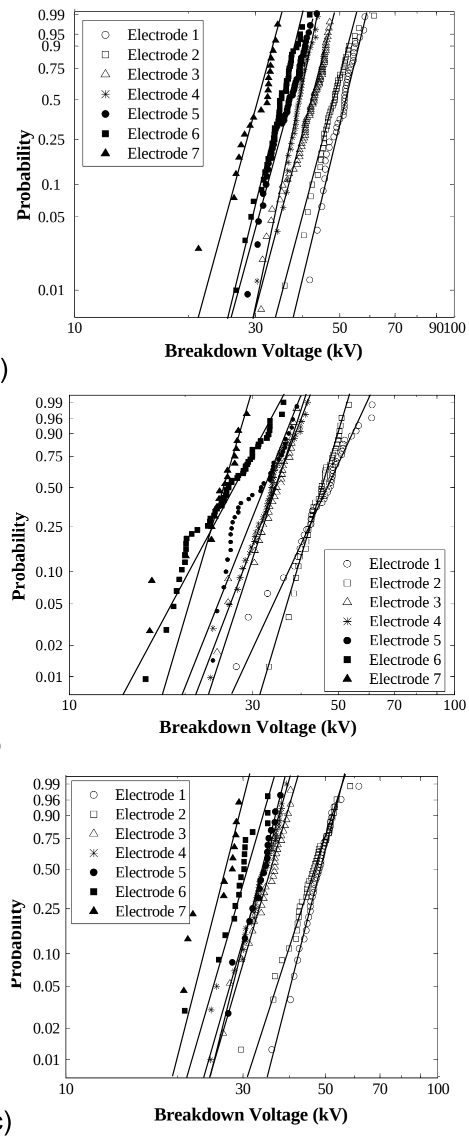
### 3.3 Experimental Procedure

In the tests, the testing electrodes were fitted into the test container filled by Geimini X, Midel 7131 and FR3, respectively. The AC voltage was applied on the liquid samples, and increased from 0 kV at a speed of 0.5 kV/s until a breakdown occurs. To obtain accurate results, at least 40 breakdown voltages were measured for each setup using electrode 1 to 6. For electrode 7, since the released energy by each breakdown is quite large, no more than 20 breakdown voltages were measured for each setup to reduce the deteriorations.

It should be noted that since the esters used in the tests are more viscous than mineral oil, the gaseous by-products of breakdowns take relatively longer time to be expelled from the esters than mineral oil, Thus, our tests followed the recommendations by the IEEE C57.174 that extra standing time was given after pouring the liquid sample into the test cell and before the start of the tests. For electrode 1 to 6, the time interval between two successive breakdowns was increased from 1 minute (required in the ASTM D1816) to at least 5 minutes. For electrode 7, the time interval is increased to at lest 15 minutes. At the same time, an electromagnetic stir was working continuously to assist the expelling of the gaseous by-products.

## 4 RESTULS AND DISCUSSIONS

Figure 2 shows the Weibull plots of the AC breakdown voltages of transformer liquids for various electrodes. The Weibull plots of both mineral oil and esters give generally straight lines, which indicate that the Weibull distribution can be applied to fit the breakdown voltage of both mineral oil and esters.




(a) (b) (c)

**Figure** 2: Weibull plots of breakdown voltage distributions for various electrodes, (a) Gemini X, (b) Midel 7131, (c) FR3

Table 2 lists the Weibull scale parameters ($\alpha$) and shape parameters ($\beta$) estimated from the Weibull plots of the breakdown voltages for various electrode area conditions. The results indicate that the scale parameters of all the liquids are decreased with the increase of the electrode *ESA*, which shows the electrode area effect. The relationship between the scale parameter and *ESA* are plotted in Figure 3. The solid lines are the fitted curve of the scale parameters by least square method. The results confirm the conclusion from the theoretical analysis that the logarithmic scale parameter ($\alpha$) reduces linearly with the increase of the logarithmic electrode *ESA*.

**Table 2:** Weibull parameters of breakdown voltage distributions of transformer liquids for various electrodes

| Electrode | Gemini X | | Midel 7131 | | FR3 | |
|---|---|---|---|---|---|---|
| | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ |
| 1 | 52.4 | 15.2 | 49.1 | 7.19 | 49.3 | 12.9 |
| 2 | 50.3 | 13.7 | 47.4 | 10.4 | 49.1 | 10.6 |
| 3 | 43.6 | 14.4 | 35.0 | 9.22 | 36.9 | 13.0 |
| 4 | 40.0 | 17.9 | 35.6 | 12.1 | 35.3 | 13.0 |
| 5 | 38.1 | 12.6 | 33.1 | 7.72 | 34.8 | 15.6 |
| 6 | 36.3 | 13.5 | 28.1 | 6.02 | 31.3 | 10.2 |
| 7 | 31.8 | 12.5 | 25.7 | 10.0 | 27.5 | 12.2 |

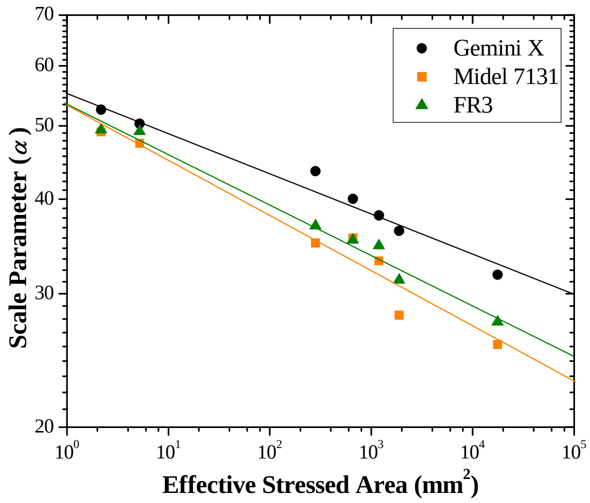



**Figure 3:** Experimental shape parameters as a function of electrode areas for transformer liquids

Table 2 also shows that the shape parameters of a test liquid are not the same under different electrode areas. Table 3 lists the calculated average values and standard deviations of the shape parameters for transformer liquids from the experiment results. It is clearly seen that the shape parameters vary within a range. Generally speaking, the shape parameters of Gemini X are larger than those of Midel 7131 and FR3. This indicates that the breakdown voltages of Gemini X distribute narrower than Midel 7131 and FR3. Similar results were also obtained in [5]. Consequently, the breakdown voltage of Midel 7131 and FR3 is reduced more significantly with the increase of electrode ESA than that of Gemini X. This is generally in line with the previous theoretical analysis of an idealized model.

**Table 3:** Calculation of average values, standard deviations and 90% confident intervals of the shape parameters for various transformer liquids

| Liquids | $\beta$ | | |
|---|---|---|---|
| | average | Standard deviation | 90% confident interval |
| Gemini X | 14.3 | 1.9 | [11.2, 17.3] |
| Midel 7131 | 9.0 | 2.1 | [5.5, 12.4] |
| FR3 | 12.5 | 1.8 | [9.5, 15.5] |

From Figure 3, the area effect equations for transformer liquids can be derived. Table 4 lists the parameters *a* and *b* used in the equations, and (11) shows the area effect equations. This equation can be used to extrapolate the scale parameters of transformer liquids stressed under electrodes with large *ESA*.

**Table 4:** Calculated *a* and *b* values used in the area effect equations for transformer liquids

| Liquids | *a* | *b* |
|---|---|---|
| Gemini X | 1.7391±0.0096 | 0.0508±0.0034 |
| Midel 7131 | 1.7195±0.0140 | 0.0697±0.0056 |
| FR3 | 7.7274±0.0140 | 0.0666±0.0055 |

$$\begin{cases} \log(a_{\mathrm{GeminiX}}) = 1.7391 - 0.0508 \cdot \log(S) \\ \log(a_{\mathrm{Midel7131}}) = 1.7195 - 0.0697 \cdot \log(S) \\ \log(a_{FR3}) = 1.7274 - 0.0666 \cdot \log(S) \end{cases} \quad (11)$$

Therefore, the breakdown voltage distribution of a clean transformer liquid can be derived by putting the scale parameter extrapolated from (11) and the average shape parameter listed in Table 3 back into (1). Equation (12) shows the breakdown voltage distribution for Gemini X, Midel 7131 and FR3 respectively when they are stressed under electrode *S*. In this equation, the unit of electrode area *S* is *mm*$^2$, and the unit for applied voltage *E* is *kV per mm*. Based on (12), the breakdown voltage at specified probability can be obtained.

$$\begin{cases} P_{\mathrm{GeminiX}}(E) = 1 - \exp\left(-S^{0.73}\left(\dfrac{E}{54.8}\right)^{14.3}\right) \\ P_{\mathrm{Midel7131}}(E) = 1 - \exp\left(-S^{0.63}\left(\dfrac{E}{52.4}\right)^{9.0}\right) \\ P_{\mathrm{FR3}}(E) = 1 - \exp\left(-S^{0.83}\left(\dfrac{E}{53.4}\right)^{12.5}\right) \end{cases} \quad (12)$$

## 5 APPLICATION OF AREA EFFECT EQUATIONS

Assuming a large electrode with 1 $m^2$ *ESA*, the average value of the breakdown voltage at low probabilities (10% and 1%) of transformer liquids can be calculated using (12). The calculation results are listed in Table 5. Furthermore if we consider the statistical natural of shape parameter, the 90% confident interval of the shape parameter (Table 3) can be used to calculate the breakdown voltage distribution. Thus the 90% confident interval of the breakdown voltages at low probabilities for transformer liquids can be obtained and also listed in Table 5. It can be seen that the breakdown voltage of esters at lower probability are much smaller than that of mineral oil when a large electrode is used.

**Table 5:** Calculation of average value and 90% confident interval of breakdown voltage at low probabilities

| Liquids | average | 90% confident interval |
|---|---|---|
| *Breakdown Voltage at 10% Probability* | | |
| Gemini X | 23.2 | [22.2, 23.8] |
| Midel 7131 | 15.6 | [13.2, 16.7] |
| FR3 | 16.8 | [16.8, 18.4] |
| *Withstand Voltage at 1% Probability* | | |
| Gemini X | 19.6 | [18.0, 20.8] |
| Midel 7131 | 11.9 | [8.7, 13.8] |
| FR3 | 14.7 | [13.1, 15.8] |

It should be noted that the breakdown voltages of transformer liquids are closely related to the qualities of the test liquids [10]. The transformer liquids used in this paper were well processed, thus most of the contaminations in the bulk liquids were removed. For contaminated transformer liquids, lower breakdown voltages will be expected.

## 6 CONCLUSIONS

It is concluded that the breakdown strengths of the transformer liquids are significantly reduced with the increase of the electrode ESA. The reduction of the breakdown strengths of esters with increased electrode ESA is more significant than that of mineral oil, due to their wider breakdown voltage distributions than that of mineral oil.

Although the manufacturers have reported similar breakdown strengths of esters to that of mineral oil based on small scale tests [8], the area effect should be taken into consideration during the insulation design for power transformers. The large surface areas of the conductive components in power transformers indicate that the breakdown strengths of esters might be smaller than that of mineral oil.

## 7 ACKNOWLEDGMENTS

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