01 Jan 1984

STATISTICAL ANALYSIS OF BREAKDOWN IN TRANSFORMER OIL.

J. Derald Morgan
Missouri University of Science and Technology

M. A. Abdellah

Frank Ferracane

Recommended Citation

J. D. Morgan et al., "STATISTICAL ANALYSIS OF BREAKDOWN IN TRANSFORMER OIL.," *Conference Record of IEEE International Symposium on Electrical Insulation*, pp. 288 - 290, Institute of Electrical and Electronics Engineers, Jan 1984.
The definitive version is available at https://doi.org/10.1109/eic.1984.7465200

Conference Record of 1984 IEEE International Symposium on Electrical Insulation, Montreal, June 11-13, 1984

STATISTICAL ANALYSIS OF BREAKDOWN IN TRANSFORMER OIL

J.D. Morgan, Senior Member, IEEE
M.A. Abdellah, Student Member, IEEE
Electrical Engineering Department
University of Missouri-Rolla
Rolla, MO 65401

and

Frank Ferracane
Illinois Power and Light
Decatur, IL 62525

Abstract - The statistics of breakdown for transformer oil in a uniform field gap is an important design consideration. The theoretical probability distribution which closely fits the experimental data under 60 Hz ac voltage, positive and negative lightning impulses and positive and negative switching surges is evaluated and a statistical distribution is suggested.

INTRODUCTION

Breakdown characteristics of insulating liquid is a subject of extensive study. Determination of the intrinsic breakdown voltage of a liquid has been the goal of many investigations. The breakdown of an insulating liquid is controlled by external factors, for instance, gap configuration, voltage waveform, oil quality and impurities.

A statistical study of breakdown is useful in evaluating the properties of liquids. The question of which particular theoretical statistical distribution represents the properties of liquids has not yet been satisfactorily determined. The most suitable criterion for the choice of a distribution is the closeness of the statistical fit to experimental observations [1]. Utilizing this assumption some investigators assumed that a normal distribution represented their data and rejected other statistical distributions (2,3,4). Others assumed that a distribution of the smallest values type I or Weibull distribution which is a particular case of an extreme distribution would best fit observations (5,6,7,8). Most of the published data is on breakdown statistics of transformer oil at power frequency. Limited data is published at other voltage waveforms such as lightning and switching surge impulse voltages. Since these waveforms frequently occur due to both lightning and circuit switching, it is necessary to study the nature of oil breakdown statistics under these waveforms in both uniform and nonuniform field gaps.

The statistics of breakdowns in transformer oil for uniform field gaps stressed by impulse voltages has been extensively studied by the authors. The polarity effects of both the lightning and switching impulses have been observed. The one minute ac breakdown probability distribution is included in this paper for comparison with other findings.

Experimental Arrangement

The electrodes used in this investigation were 46 mm diameter uniform field brass electrodes, set at a 1.25 mm gap. They were mounted vertically in a two liter plexiglass container. The electrodes were polished and buffed to a mirror finish before each set of experiments. Commercial transformer oil (Shell diala AX) was used. The oil was dehydrated with molecular sieves, filtered through a sintered glass filter of 0.2 μm pore size and degassed by placing the oil under a 10^{-2} torr vacuum for more than eight hours, the oil was changed after each breakdown.

Positive and negative lightning and switching surge impulses as well as 60 Hz ac voltages were used. The 1.5/50 μs and the 160/1800 μs impulse waveforms were obtained from a Hipotronics five stage, 500 kV, 2.5 kJ Marx generator. The 60 Hz ac voltage was obtained from a Biddle 100 kV, 15 kVA corona free transformer.

Impulse voltages were measured using a Tektronix storage scope model #7613. The peak voltage at breakdown and time to breakdown were recorded. AC voltages were measured using a Hipotronics 100 kV capacitor divider in conjunction with a peak voltmeter. The scope was calibrated against a sphere gap and the peak voltmeter calibrated against an electrostatic voltmeter. The accuracy of ac voltage measurements was estimated to be ± 0.5% and impulse voltages within the 3% accuracy of the sphere gap calibration method of IEEE #4.

Experiment Design:

A voltage level V_0 was selected at which the 0.001 fractile of the distribution of breakdown was expected. 10 tests were applied with 30 second intervals between any two tests. Another 10 tests were applied at a voltage level $V_0 + \Delta V$, where ΔV is a constant step increase of voltage. This process continued until the first breakdown occurred at a voltage level $V_k = V_0 + k\Delta V$ and at a test number m out of 10. K was chosen to be 6 to 8 voltage levels and ΔV = 5 kV. If this procedure is repeated N times and if n_i is the number of failures or breakdowns at a voltage level V_i, then it is possible to find the probability of failure on the next voltage application by equation

$$P(V_i) = \frac{n_i}{10(N - \sum_{k=1}^{i} n_k) + \sum_{j=1}^{n_i} (m_j+1)} \qquad (1)$$

where m_j is the number of tests passed before failure.

For ac tests the one minute breakdown voltage was found as follows, the voltage was increased from zero at a rate of 2 kV/sec. to a voltage level V_0. If no breakdown occurs within one minute the voltage was increased one step ΔV where ΔV = 3 kV. The process was continued until the first breakdown. This process is repeated 50 times (N = 50). The probability of failure on next voltage V_i, where $V_i = V_0 + i\Delta V$, may be given by (2)

$$P(V_i) = \frac{n_i}{(N - \sum_{j=1}^{i-1} n_j)} \qquad (2)$$

CH1964-6/84/0000-288 $01.00 C 1984 IEEE

Results and Discussions:

The distribution of breakdown calculated using equations 1 and 2 are plotted using a Weibull distribution as shown in Figures 1 to 3 for ac, lighting impulses and switching surges respectively. A regression straight line approximation appears to fit the data closely. This leads us to assume that the breakdown probability distribution for transformer oil follows an extreme value distribution of the smallest values of which the Weibull distribution is a particular case. However, this assumption should be taken carefully as the straight line approximation is a subjective matter. Two people looking at the same plot might arrive at different conclusions. The larger the number of samples and the greater the divergence from the assumed model, the easier it will be to detect a true, as opposed to a random departure.

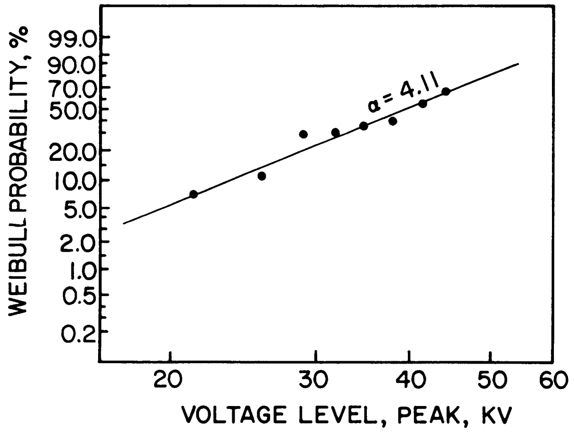

Fig. 1. Weibull Plot of AC Breakdown

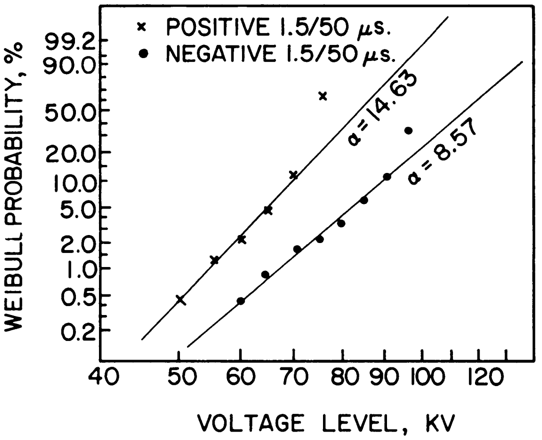

Fig. 2. Weibull Plot of Lighting Breakdown

The two parameter Weibull distribution as a function of the voltage level V_i is given by

$$p(V_i,\alpha,\beta) = 1 - \exp\left[-\left(\frac{V_i}{\beta}\right)^{\alpha}\right] \qquad (3)$$

where α and β are the shape and scale parameters respectively. The mean voltage of the Weibull distribution having the parameters α and β may be obtained by evaluating the integral

$$\bar{V} = \int_0^{\infty} V\left(\frac{1}{\beta}\right)^{\alpha} \alpha V^{\alpha-1} e^{-\left(\frac{V}{\beta}\right)^{\alpha}} dV \qquad (4)$$

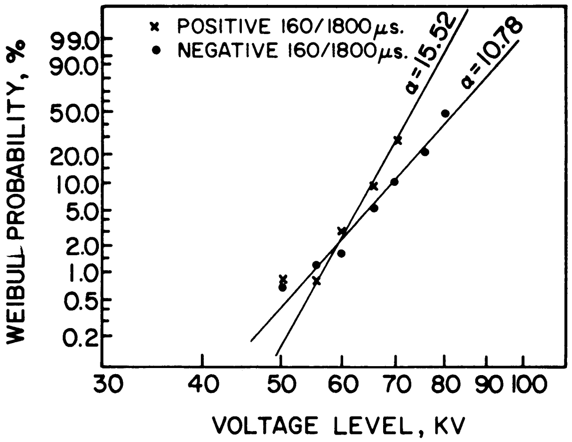

Fig. 3. Weibull Plot of Switching Impulse Breakdown

$$\bar{V} = \left(\frac{1}{\beta}\right)^{-\frac{1}{\alpha}} \int_0^{\infty} V^{\frac{1}{\alpha}} e^{-V} dV \qquad (5)$$

Recognizing the integral as $\Gamma\left(1+\frac{1}{\alpha}\right)$, then the mean voltage $\bar{V}$ is given by

$$\bar{V} = \left(\frac{1}{\alpha}\right)^{-\frac{1}{\alpha}} \Gamma\left(1+\frac{1}{\alpha}\right) \qquad (6)$$

and the standard deviation

$$\sigma = \left(\frac{1}{\beta}\right)^{-\frac{1}{\alpha}} \Gamma\left(1+\frac{1}{\alpha}\right) \sqrt{\frac{\Gamma\left(1+\frac{2}{\alpha}\right)}{\left[\Gamma\left(1+\frac{1}{\alpha}\right)\right]^2} - 1}$$

$$\sigma = \bar{V} \sqrt{\frac{\Gamma\left(1+\frac{2}{\alpha}\right)}{\left[\Gamma\left(1+\frac{1}{\alpha}\right)\right]^2} - 1}$$

The parameters α and β of the Weibull distribution can be obtained from the slope of the plotted straight line and $\beta = e^{-a/\alpha}$ where a is the intercept of the straight line plotted on a Weibull distribution chart.

The one minute results of the 60 Hz ac voltage are replotted in log-normal distribution paper. As shown in Figure 4, the test results can be approximated by a straight line. In the same figure, the ac test results

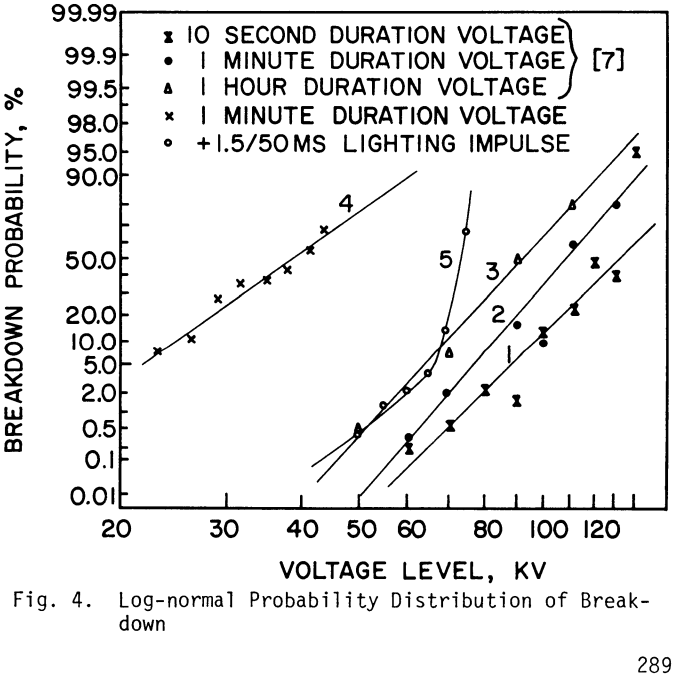

Fig. 4. Log-normal Probability Distribution of Breakdown

for the 10 second, 1 minute and 1 hour performance of a uniform field oil gap, which have been assumed to follow the Weibull distribution [7,8], are replotted in a log-normal distribution. As shown in Figure 4 these results can be approximated by the straight lines 1, 2 and 3. The results suggest that both the normal distribution and the extreme distribution of the smallest value should be considered when the breakdown distribution of oil under power frequency is analyzed statistically. It was assumed [5,6] that if the breakdown could only be attributed to the weakest link in the insulation then the breakdown would most probably follow the extreme distribution of the smallest values for which a Weibull distribution is a particular case. If the influence of the experimental conditions exceed that of the weakest point, the breakdown will follow a Gaussian distribution [2,3]. The experimental results in this study suggest that both the weakest link breakdown and the experimental conditions influence the results and it is not easy to separate their effects. However, from a theoretical point of view the extreme distribution is more likely.

Figures 2 and 3 show the results under lightning and switching impulses of both polarities. Before assuming that the extreme distribution fits the oil breakdown distribution more closely than the Gaussian distribution the data of reference [3] was replotted which followed the normal distribution. This is shown in Figure 5. Comparing Figure 5 with Figure 3 in reference [3], it is seen that the Weibul distribution is a closer approximation to the experimental data than the normal distribution in spite of the limited number of experimental points. Figure 6 is a replot of Figure 3 of reference [2]. The authors of reference [2] rejected the extreme distribution because of the results plotted in Figure 3 of their paper. Figure 6 shows that the Weibul distribution which is a particular case of an extreme distribution is a good approximation to the results of reference [2] using 1/5 μsec. impulses.

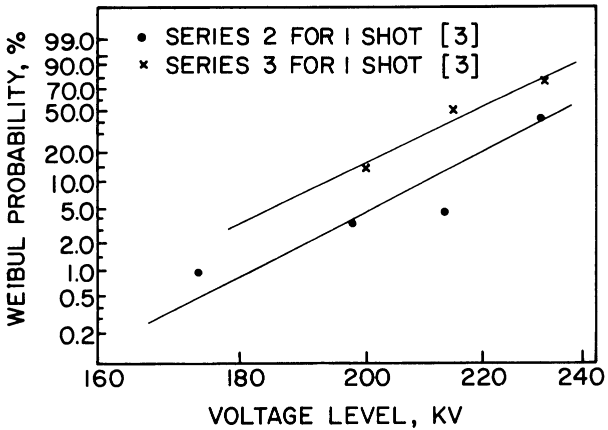

Fig. 5. Weibull Plot of the Breakdown Statistics [3]

The results of the positive lighting impulse is replotted in Figure 4. It can be seen that it is difficult to represent this data by a single straight line. Therefore it can be assumed that the weakest points in the insulation exceed the influence of the experimental conditions.

From this investigation, two conclusions can be drawn.

1. For power frequency (60 Hz), the oil breakdown distribution follows the extreme as well as the normal distribution.

2. For impulse voltages the breakdown distribution is more likely extreme in nature.

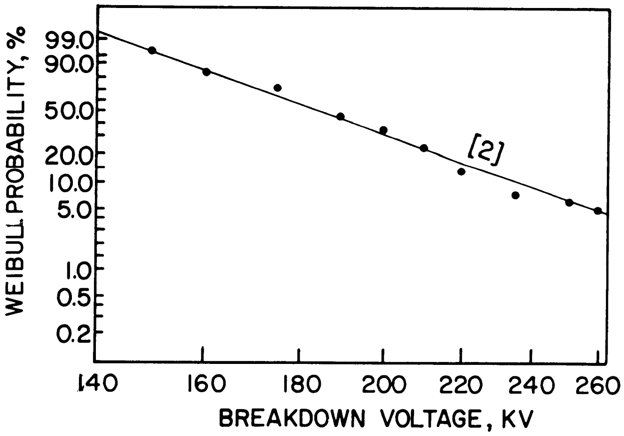

Fig. 6. Weibull Plot of Breakdown Distribution [2]

REFERENCES

[1] G.J. Hahn and S.S. Shapiro, "Statistical Models In Engineering", Book, John Wiley & Sons, Inc. 1967.

[2] T.H. Sie and O. Wohlfahrt, "Transference of Test Results from Experiments on Small Models to n Times Larger Test Objects With Insulation Under Oil", AIEE, Vol. 81, pt. III, pp. 601-608, 1962.

[3] T.H. Sie and O. Wohlfahrt, "Contribution to the Measurement of the Impulse Withstand Voltage of Oil-Paper-Insulation Systems", Vol. PAS-88 No. 6, pp. 862-868, 1969.

[4] S. Palmer and W.A. Sharpley, "Electric Strength of Transformer Insulation", Proc. IEEE, Vol. 116, No. 12, pp. 2029-2037, 1969.

[5] K.H. Weber and H.S. Endicott, "Area Effect and Its Extremal Basis for the Electric Breakdown of Transformer Oil", AIEE Transactions, Vol. 75, pt. III, pp. 371-381, 1956.

[6] H.S. Endicott and K.H. Weber, "Electrode Area Effect For the Impulse Breakdown of Transformer Oil", AIEE Transactions, Vol. 76, pt. III, pp. 393-399, 1957.

[7] M. Ikeda and S. Menju, "Breakdown Probability Distribution and Equiprobabilistics V-T Characteristics of Transformer Oil", Vol. PAS-98, No. 6, pp. 1430-1437, 1979.

[8] M. Ikeda and T. Inoue, "Statistical Approach To Breakdown Stress of Transformer Insulation", Third Inter. Symp. on High Voltage Engineering, Paper #23.18, Milan, 1979.