Mixed Weibull Distribution Model of DC Dielectric Breakdowns with Dual Defect Modes

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I. Introduction

DC voltage step-up to breakdown tests in several polymeric insulators have shown many transient non-shorting arcs—termed pre-arcs—prior to final dielectric breakdown. An average of 17 pre-arcs were observed per breakdown test. Pre-arc distributions as an efficient proxy for breakdown could lead to accelerated and more effective DC dielectric testing.

We compare the cumulative distributions of pre-arcs and breakdowns from parallel plate breakdown tests in low-density polyethylene (LDPE) to determine if the distribution of pre-breakdown arc is correlated with the distribution of DC breakdown field strength. Fig. 1 shows ammeter data from 5 step up tests in LDPE. Measurements with fast oscilloscopes (inset Fig. 1) suggest higher-amplitude pre-arcs as seen in the ammeter are multiple low-amplitude fast pre-arcs integrated over the ammeter’s data response time.

Possible reasons why DC pre-arcing is not widely reported. Our tests included:

- Use of slower ramp rate (20 V/3.5 s)
- dC/dt than the ASTM standard
- Ammonia sensitive to 100 mA
- Reduced electrode spacing
- Large flat electrodes
- Beveled electrode edges

II. Quantile-Quantile Plots

The empirical cumulative distribution (ECD)

\[ F_n(x) = \frac{1}{n} \sum_{i=1}^{n} I(x_i \leq x) \]

where

\[ I(x_i \leq x) = \begin{cases} 1 & \text{if } x_i \leq x \\ 0 & \text{otherwise} \end{cases} \]

Fig. 2 shows the ECD for LDPE of 88 breakdowns and 25,568 quantized pre-arcs. Although with 17x the signal to noise ratio the distributions look similar, the ECD plot does not directly address whether the two ECDs are related.

Quantile-Quantile (Q-Q) plots allow direct non-parameterized comparison of cumulative distributions of data and/or functions. The (x, y) values of a Q-Q plot are the x values of two ECDs at specified quantiles, \( F_n(x) \). Interpolation may be needed to compensate for measurements at different quantiles.

Q-Q plots that lie on the line y = x indicate identical ECDs.
Other linear Q-Q plots indicate a scaled relationship between two ECDs.
Q-Q plots that deviate from a line indicate that the ECDs are not related.

III. Comparison of Distributions

Fig. 3 shows the Q-Q plot for the ECDs of breakdowns and pre-arcing in LDPE. The quantities of the much denser pre-arcing distribution were interpolated to match those of the 88 breakdowns. The linear fit of Q-Q plot show that the distributions are clearly related.

The insets of Fig. 2 and Fig. 3 show the result of plotting using the normalized electric field for each event type. In both plots we see that the similarity between the two ECDs increases. This shift in electric field is attributed to the difficulty in accurately counting frequent high field pre-arcing events as breakdown begins to occur.

By contrast, observe the Q-Q plot comparing test chamber pressure and measured sample thickness (Fig. 4) which confirms there is no relationship between these two independent variables.

IV. Conclusions

Q-Q analysis shows that the distribution of pre-arcing events as a function of applied field is strongly correlated with the distribution of breakdown events in LDPE. Pre-arcing as proxy for DC dielectric breakdown testing of could expedite the characterization and selection of insulating materials for HVDC, high voltage switching, spacecraft charging, electronics, and other applications.

To corroborate this correlation observed in LDPE, similar tests are in progress for polyimide, polypropylene and SiO₂ (borosilicate glass).

Recoverable low-energy defects on the order of kT have been suggested as a plausible mechanism for the relationship between pre-arcing and breakdown. As an arc begins, thermal energy released to the surrounding medium may anneal the defects required for runaway breakdown.

References