DRY-BAND DISCHARGES ON SILICONE RUBBER INSULATION

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Abstract: Clean-fog solid-layer tests have been performed on a silicone-rubber suspension insulator of 11kV rating. The artificial pollution layer and the cold-fog conditions are shown to reduce significantly the flashover voltage, sometimes down to 40% of its normal value. This reduction of flashover voltage is similar to that of polluted ceramic insulators, where it is usually ascribed to the formation of dry bands on the conductive surface, resulting in partial arc breakdown and ultimately flashover. In these new tests, the presence of dry bands could be deduced not only from pre-flashover discharge events, but their structure was also directly observed. This has been made possible by the use of both infrared and visible recording of the test insulator during fog tests, combined with current and voltage data logging. In a parallel investigation of rectangular textured samples which were vacuum-cast from the same material and tested using an inclined-plane procedure, a stable, controlled dry band could be established on the polluted surface. When discharge inception occurred across the band, these discharges resulted in a fall, rather than an increase, of the leakage current. Such reproducible dry band breakdown provided an opportunity to characterize experimentally their electrical properties.

1 INTRODUCTION

This paper first presents examples of observations of clean-fog tests on an artificially polluted 11kV silicone-rubber insulator, where the tests were monitored both for the visual development of pre-flashover phenomena and the surface heating process: secondly, similar observations of a textured sample of the same material were made during inclined-plane tests. Both procedures showed dry-band development on the polluted silicone-rubber surface.

A recently proposed model [1] represents the dry-band discharge as a streamer-spark structure, in contrast to the standard model of an arc-like interdependence of current and voltage. These two models are tested against the new data for textured samples, and the discharge is shown to have streamer characteristics, at least in its early development. The similarity to the dry-band formation on the shank regions of shedded insulators in the clean-fog tests, indicates the possibility of design improvements.

2 CLEAN-FOG TESTS

2.1 Test Arrangement

A modified version of the IEC-60507 Solid Layer Method [2] was used to test a silicone-rubber composite insulator of 11kV nominal voltage and a creepage length of 375mm [Figure 1]. This was vacuum cast in the laboratory from Dow Corning HV 1540/10P. A pollution suspension of conductivity 11.2 S/m, consisting of tap water, kaolin and sodium chloride was applied directly to the insulator. Because the hydrophobic properties of silicone rubber normally inhibit the formation of a uniform pollution layer, the addition to the pollution suspension of a non-ionic wetting agent, Trixton-100 (as used in inclined plane tests), enabled nominally uniform pollution to be achieved. Extension of the drying time after application of the pollution can, if required, allow some hydrophobic recovery to take place.

Figure 1: Silicone-rubber insulator tested in the fog chamber.

The insulator was suspended in a fog chamber of dimensions 2 x 2 x 3m, which was fitted with spray nozzles delivering 3l/h at 2.4bar, and connected to a 100kV, 50Hz transformer of short-circuit rating 6A. An open window to the chamber enabled the
test to be recorded using both a FLIR A320 infrared camera and a Sony Handycam.

Data acquisition of the test voltage and the leakage current were achieved with National Instruments LabVIEW software enabling the capture of 200 samples/cycle for post-processing.

### 2.2 Fog Chamber Results

The dry pollution was exposed to the fog for a pre-wetting period before a high voltage was applied. After 15-25 minutes, a low-voltage test (<1kV) showed that the leakage resistance was stable at a value in the range 2 to 5 MΩ. However, application of a test voltage >3kV caused the leakage current to fall significantly. This increase of the leakage resistance to a range 20 to 25 MΩ was shown by the infrared camera to be often associated with the formation of a dry band on the shank immediately below an insulator shed. Further dry band development developed with increasing voltage, and partial arc discharges became frequent. Figure 2(a) shows discharges recorded by camcorder at a voltage of 25.3kV. These were transient events of short duration, and little was visible between events. The infrared record also recorded the discharges, but in addition revealed the presence of dry bands. Figure 2(b) shows dry bands on all three sections of the insulator shank immediately before the partial arcs of Figure 2(a). The surface temperature profile along the length of the insulator shows that the dry band regions can be as much as 8°C above the ambient 17°C. Each dry band was found to develop, change form and fade over lifetimes of minutes. Even after flashover at 29.1kV (Figure 3), the pre-flashover temperature profiles persisted for some time. A final low-voltage measurement after a similar test showed that the overall leakage resistance between discharges had increased during the 38-minute high-voltage test to a value of around 100 MΩ.

![Figure 2a: Insulator dimensions and partial arcs at 25.3kV (video frame)](image)

![Figure 2b: Dry bands and temperature profile on insulator at 25.3 kV.](image)
After removal of high voltage, the continued application of the fog rewetted the pollution layer, and after a 15-minute period the initial leakage resistance was gradually restored to a value of 5 MΩ.

The role of dry band formation in the flashover process is clear from these observations. Local breakdown was often confined to these narrow regions but the discharge could also connect adjacent dry bands and could propagate significant distances along the insulator at voltages well below the flashover level. It is obviously useful to examine more closely the properties of individual dry-band breakdown. This has been found to be possible from data obtained (Section 3) from inclined-plane tests on textured silicone rubber samples.

3 INCLINED-PLANE TESTS

3.1 Dry-Band Formation

A stable, controlled dry band has been produced in standard IEC 60587 3.5kVrms inclined-plane tests on silicone-rubber samples with a textured surface [3]. Discharge inception occurred across this band as shown in Figure 4(a), and it was notable that such discharges resulted in a fall, rather than an increase, of the leakage current in the pollution layer. A transition to a higher current arc phase was thus inhibited, compared with non-textured samples, for which stable dry bands did not form.

The IR record and accompanying temperature profile in Figures 4(b) and 4(c) show obvious similarities to those of the insulator fog tests, but the heavier pollution level of the inclined-plane test resulted in higher surface temperatures. This reproducible dry band formation enabled the electrical properties of the discharges to be quantified.

The dry band, made visible by the set of parallel bridging streamers, traversed the length of the sample and was frequently followed by a period of arcing at the lower electrode. The traverse was associated with, but was slower than, the rate of flow of pollutant across the inclined plane.

Data logging showed that the leakage current exhibited a characteristic shape; This is shown in the typical 50Hz total-current record (Figure 5) persisting in this case over a time of 8.5s between instants A and E, which were associated with the initiation and traverse time of the dry band from the high-voltage electrode to the ground electrode.
The lower current during the later period F was that of the subsequent electrode arc before it self-extinguished and a new cycle began. Of particular interest is the modulation of the current decay in the period AE, with the larger current peaks such as B and D, alternating with the smaller current peaks such as C. Simultaneous observations of the dry band discharge activity and the leakage current showed clearly that the lower currents occurred during active discharges in the dry band, and the larger currents coincided with the intervals when no discharges were seen. Such intervals arose from the periodic, temporary re-wetting of the dry band by the flowing pollutant.

The nature of the current modulation importantly implies that the discharge channel conductance was lower than the pollution layer conductance.

For the pollution layer without discharges, the layer-current decay corresponding with the maxima in Figure 4 is approximated by

\[ i_L(t) = 32.5 \exp \left[ -0.075t \right] \text{ mA} \]  

(1)

The current minima coinciding with dry-band discharges also decay during the traverse:

\[ i_D(t) = 26.6 \exp \left[ -0.08t \right] \text{ mA} \]  

(2)

3.2 Contaminant Layer Conductance

The decay of current in eq. (1) is the result of a falling conductance \( G_L(t) \) of the contaminant layer during the traverse of the dry band. This fall is attributed to evaporation of the layer caused by the ohmic heating revealed by the infrared records [3]. If we assume that the rate of evaporation, and thus the rate of fall of layer conductance, is proportional to the power loss, then

\[ \frac{dG_L(t)}{dt} \propto -U^2 G_L(t) \]  

(3)

which would indicate

\[ G_L(t) = G_L(0) \exp \left[ -kU^2 t \right] \]  

(4)

This is consistent with the observed exponential decay of leakage current in the contaminant layer. At the test voltage of 3.5kVrms, the measured leakage current gives an initial layer conductance of about 6.6µS which decays to about half-value in 8s.

3.3 Discharge Conductance

The ratio of the leakage current during dry-band discharges are present to that when no dry band is formed is

\[ \frac{i_D(t)}{i_L(t)} = 0.82 \exp \left[ -5 \times 10^{-3} t \right] \]  

(5)

This ratio is, therefore, almost constant at about 0.8 over the observation period of 8s, so that the combined conductance \( G_{DL} \) of the dry-band discharges \( G_D \) in series with that of the contamination layer \( G_L \) is lower than that of the layer alone, and falls from 5.4µS to 2.7µS during this time. From these measurements, we obtain the initial conductance \( G_D(t=0) \) of the discharges across the dry band to be 28µS, falling to 14µS after 8s. If several discharges bridge the dry band, these values will be the sum of individual discharge conductances.

4 DISCHARGE MODELLING

4.1 Discharge Voltage Gradient

The voltage \( U_D \) across the dry band when bridged by the discharges is

\[ U_D = U G_L / (G_L + G_D) = 0.2 U = 700 \text{V rms} \]  

(6)

Since dry-band discharges for the 4mm Texture \( \gamma \) [3] tended to align with the intersecting edges of the square-intersection pattern (Figure 4), the approximate discharge path length corresponds with the length of an intersection:

\[ \text{Discharge path} = \pi \times (\text{protuberance diameter}) / 2 \sqrt{2} \]

\[ = 4.44 \text{mm} \]  

(7)

This indicates a peak voltage gradient across the discharge of \( \sqrt{2}(700)/4.44 \approx 223 \text{V/mm} \), which is significantly larger than the peak gradient of about 100V/mm across the 50mm leakage path of the pollution layer, and causes the observed fall of leakage current during dry-band discharges.

4.2 Comparison with streamer-spark model

The measured 700V voltage fall indicated in eq.(6) is in good agreement with that predicted by the streamer-spark model of dry-band breakdown [4]: in that model, the length \((C+S)\) of the discharge comprises a channel \( C \) (gradient 100 V/mm) and
its associated streamer $S$ (gradient 500V/mm). On physical grounds for a.c. arc reignition, the length ratio $C/S$ is estimated to be 5:1. Thus for $(C+S) = 4.44$mm, the corresponding voltage fall across the discharge would be 740V, which is of the same order as the experimental value of eq.(6). The model also predicts that the discharge current can be estimated from $i_D = 0.46(C+S)$ [A,m], or 2.05mA. Although this value is below he observed currents (Figure 10) in the range 15-25mA, the measured values may represent a number of parallel discharge events. Overall, the experimental results support the model of a low-current, small-scale spark development.

4.3 Comparison with arc model
An alternative approach would be to ascribe to the dry-band discharge a partial-arc characteristic [5-8] of the form

$$U_D = NL_D / (i_D)^n$$  \hspace{1cm} (8)

Using the typically employed values of $N = 10^4$ and $n = 0.5$, this gives the discharge gradient for the initial discharge current of 26.6mA as

$$[U_D/L_D]_{arc} = 61V/mm$$  \hspace{1cm} (9)

But this is lower than the maximum gradient of 100 V/mm in the pollution layer, and would not be consistent with the reduction in current observed with the dry-band discharges. On the contrary, it would represent a runaway flashover condition. The nature of equation (8) does allow, however, adjustment of the empirical constants $N$ and $n$ to represent better the test data.

5 CONCLUSIONS

Fog tests:

- The leakage current in a silicone-rubber insulator surface in fog conditions is significantly reduced by surface heating.
- The increase in surface leakage resistance is mainly associated with the formation of dry bands revealed by infra-red recording
- Surface discharges across dry bands can bridge the surface between adjacent bands, to form longer partial arcs.
- The leakage-current in the pollution layer was reduced by the onset of the dry-band discharges.
- The reproducibility of the tests enabled the voltage-current characteristics of dry-band to be established, which were shown to be better described by a streamer-spark model than by an arc model.

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7 REFERENCES


