Infrared Analysis of Dry-band Flashover of Silicone Rubber Insulators

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ABSTRACT

Wetting of a pollution layer by mist or light rain is inhibited, in the case of silicone rubber (SiR) insulators, by the migration of hydrophobic polymeric chains from the insulator to the layer surface. However, recent laboratory fog-chamber tests have shown that a salt/kaolin layer applied to the surface of an 11kV SiR insulator can reduce the specific creepage distance (SCD) at flashover to as low as 16mm/kV. Even for larger values of SCD, potentially damaging partial arcs can arise along the insulator surface. It has been shown that some mitigation of partial-arc activity and an increase of flashover voltage can be achieved by appropriate texturing of the SiR insulator housing. The present paper describes additional infrared (IR) recording which accompanied these previous tests. Although a reduction of the flashover voltage in polluted environments is generally surmised to be the result of the formation of dry bands in a conducting moistened surface layer, no direct observations of dry bands appear to have been previously demonstrated in the laboratory. Such observations are described here, where details of dry-band location and growth are revealed by IR recording. Dry bands are shown by close-up visual photography to be invariably bridged by small streamer/spark discharges which maintain current continuity in the pollution layer. Local surface heating by these discharges are the probable cause of the delayed rewetting of the bands. Partial-arc channels that may result in flashover develop from and across the dry-band streamers. It has become clear that clean-fog testing with infrared recording and leakage current measurements provide new possibilities for the modeling of dry band discharges and improvement of insulator design.

Index Terms — **Outdoor insulation, flashover, high voltage, insulation contamination, silicone rubber insulation, pollution, insulator testing, dry-banding.**

1 INTRODUCTION

DRY-BAND formation on the wet pollution layer is known to cause a significant reduction of the withstand level of external insulation in some coastal, desert and industrial regions. In such environments, designs with an increased leakage path are used to maximize the unified specific creepage distance (USCD in mm/kV). The Technical Specification IEC/TS 60815-3 (2008) [1] describes procedures for the selection and dimensioning of polymeric insulators for polluted environments. No laboratory tests such as those available for ceramic insulators [2] are specified because of the perceived difficulty of applying artificial pollution coatings without at the same time compromising the surface hydrophobicity. It is also recognized that the determination of withstand voltages by the up-and-down method may be unreliable because of the risk of destroying hydrophobicity by flashovers [3]. The Specification thus suggests instead that tests can be agreed between utility and manufacturer.

This somewhat undefined situation was addressed in a previous paper [4], where it was shown that it is possible to perform tests to discriminate without ambiguity between the pollution performance of silicone-rubber 11 kV insulators of different housing materials. These test data also quantify the inverse relationship of pollution severity and flashover voltage (FOV). The use of constant rate-of-rise ramp voltages in these tests eliminates the need for up-and-down iteration and excessive flashovers. Leakage current measurements [5] were found to corroborate the inverse relationship between FOV and pre-flashover leakage current.

The present paper describes infrared (IR) recording which accompanied most of the tests. These records reveal the formation and development of heated bands in the pollution layer which are found always to precede the arc initiation.

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The combination of clean-fog testing with infrared recording, visual photography and leakage current measurements can extend the laboratory data that are needed to improve future insulator performance. Models of the mechanism of failure of polluted insulators [6-11] are generally based upon quantifying the properties of the partial-arc that precede flashover. The initiation mechanism of a partial-arc channel in polluted environments has long been envisaged to be caused by the presence of a dry band [12-16]. The mechanism is shown in the present tests to be a transition from a streamer across the dry-band.

2 TEST RESOURCES

2.1 PROCEDURES

A full description [4] has already been given of:

- The in-house fabrication of test insulators from two different silicone-rubber formulations;
- The method of deposition of layers of salt deposit density in the SDD range 0.21 to 1.15 mg/cm^2.
- A 3 m x 2 m x 2 m chamber in which a clean fog is produced by pressurized water nozzles;
- A 150 kVA source of suitable rating to supply a linear ramp test voltage. A rate of rise of 4 kV/minute, provided repeatable test results. It also avoided both the significant loss of surface pollution, and the long recovery-time after flashover, which were experienced with standard up-and-down testing.
- The acquisition and post-processing of voltage and leakage current data with a synchronised video recording.

2.2 INSULATOR GEOMETRY

The profile dimensions (mm) of sets of four-shed 11kV insulators manufactured for the tests are: creepage length L (375), trunk diameter (28), shed diameter (90) and axial length (175), corresponding to a form factor F_f of 2.76. The layer conductance k for uniform pollution is obtained from the measured leakage conductance G and the insulator form factor:

$$k = F_f \cdot G \tag{1}$$

2.3 INFRARED AND VISUAL RECORDING

The facilities of Section 2.1 were augmented by a FLIR A325 camera of spectral range from 7.5 to 13 µm with an image resolution of 320 x 240 pixels. The maximum imaging frequency is 60 frames/s. This enabled the temperature changes of the insulator surface to be recorded synchronously with the leakage current and the applied voltage throughout the tests. The precision of the IR temperature measurement in the fog environment was calibrated to be ± 0.5 °C by using a test insulator preheated at 40 °C. Laboratory conditions external to the chamber were close to normal sea-level values of 18-22 °C, 98-102 kPa and 10-12 g/m^3 throughout all tests. The temperature of the saturated fog within the chamber was slightly cooled by the spray injection and was in the range 16-18 °C.

As well as the video records described in [4], a Nikon D700 digital camera with 200mm focal length was used with long exposure time to detect low-luminosity streamer discharges.

3 TEST RESULTS

Four to six insulators were tested at each of the four SDD pollution levels and each test consisted of a series of up to ten ramp voltages. The results below are typical examples from different ramps during a series at an SDD of 0.64 mg/cm^2.

3.1 DRY-BAND ONSET AND DEVELOPMENT

3.1.1 BEFORE DRY-BAND FORMATION

The maximum measured leakage conductance G is usually achieved after 20-30 minutes of wetting in the clean-fog chamber, and has a value of the order of 1 µS for an SDD of 0.64 mg/cm^2. The corresponding maximum pollution-layer conductance is obtained from equation (1) to be about 2.8 µS.

3.1.2 ONSET OF DRY BANDS

Figure 1a illustrates the initial steps of a full-voltage ramp test, which was applied to a fully wetted insulator. The voltage control system has not at this stage achieved the steady-state rate of 10 x 400 V steps/minute. Figure 1b is the resulting leakage current. For the first two voltage steps, the leakage conductance is maintained constant at about 1.25 µS, and the trunk sections were shown by the IR camera to be uniformly heated, which confirmed that the pollution layer conductance k was also uniform. This is changed by a further voltage step to 1.6 kV, which soon leads to a reduced conductance of about 0.3 µS. At 2 kV the leakage conductance falls within 2 s to 0.25 µS or less. This discontinuity and loss of conductance is strongly indicative of the formation of local drying of part of the moist pollutant surface, with the inevitable formation of a complete dry band. Subsequent characteristics of the leakage current are later shown in Figure 5d.

3.1.3 DRY-BAND DEVELOPMENT

Figure 2 shows the development of dry-bands on the top and middle insulator trunk sections during a ramp voltage test. A heated ring (dry band) is formed on the middle trunk at low voltage (2 kV). This brightens with increasing voltage (see images in Fig. 2 at 4.5kV, 7 kV and 9.4 kV) until, in this case at 14.6 kV, a second dry band forms just below the first on the same trunk, with the third band forming on the upper trunk. At 27.1 kV, five bands are present, although in this instance, none forms on the third lowest trunk section before flashover occurs at 27.5 kV.

3.3.2 DRY-BAND TEMPERATURE

The temperature rise associated with dry-band formation is modest. The insulator in Figure 3 is in a fog environment at 17 °C, yet most of the trunk surfaces are at 22 °C and the dry bands reach 26-27 °C.

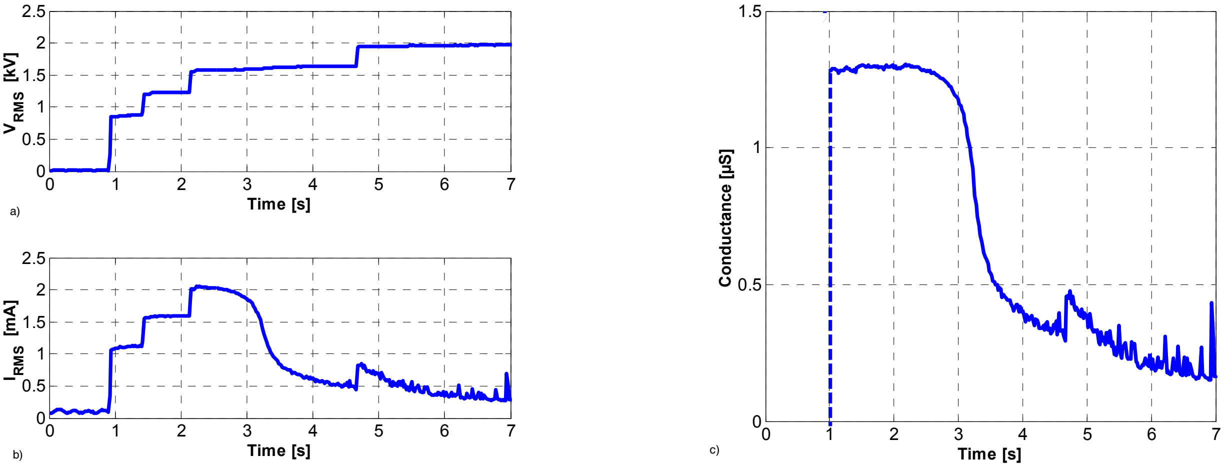

Figure 1. Dry band inception on insulator at the start of a ramp voltage test. SDD 0.64 mg/cm^2
Stepped applied voltage (a), Leakage current (b), Leakage conductance (c).

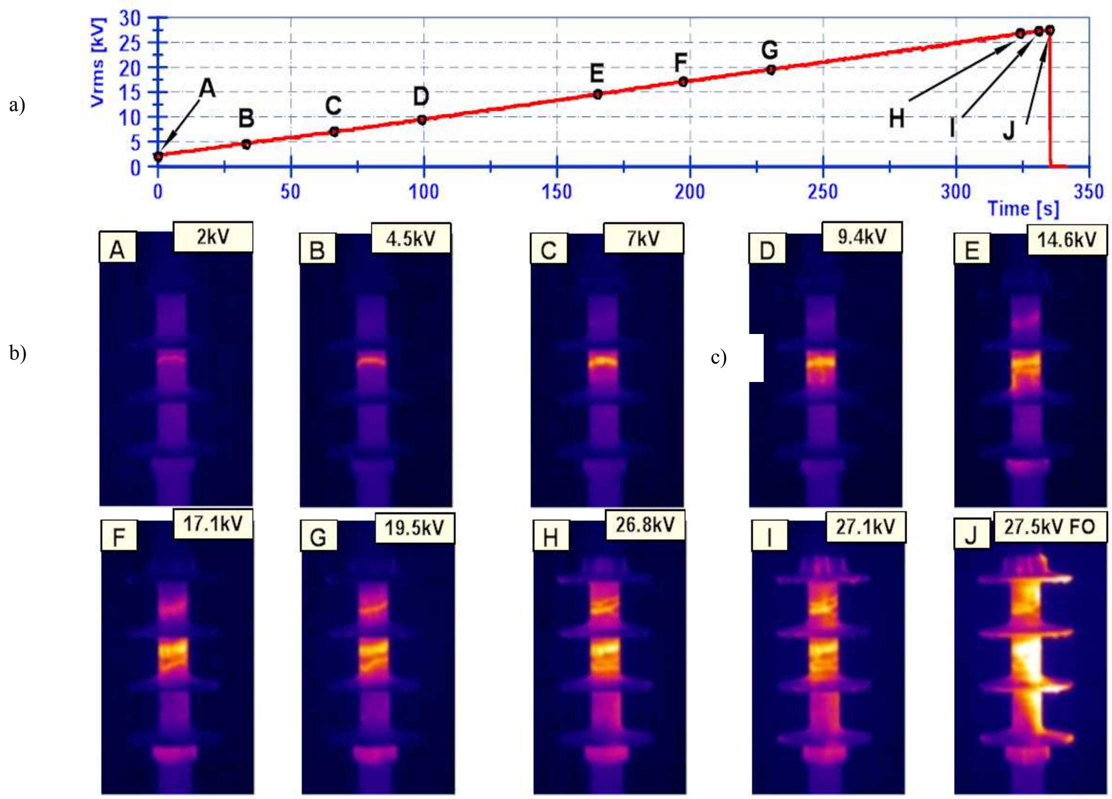

Figure 2. Formation and development of dry-bands at stages A – J during a ramp voltage test. SDD 0.64 mg/cm^2.

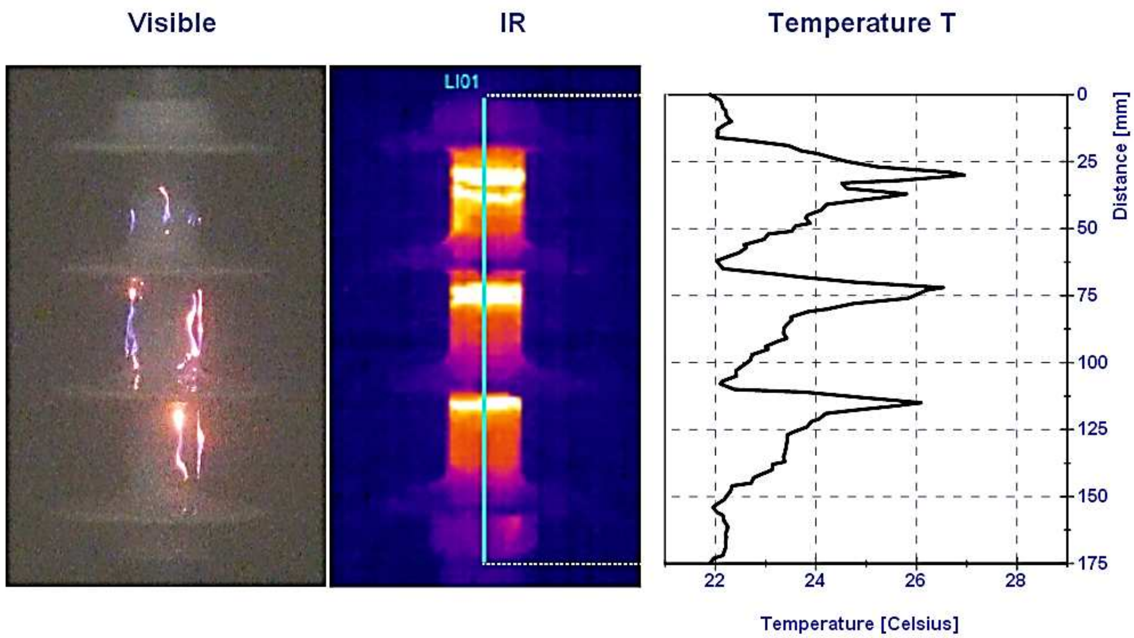

Figure 3. Visible image, infrared record and temperature profile at 22 kV on ramp

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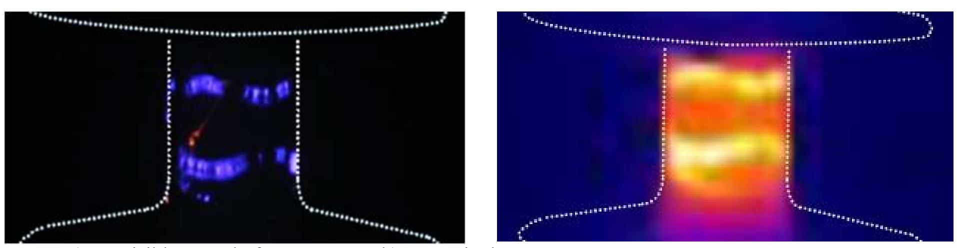
Flashover at 25 kV. SDD 0.64 mg/cm^2.



a) Visible record of streamer b) Equivalent IR record

Figure 4. Visible and IR close-ups of streamer discharges and dry-band heating at 17 kV on ramp. SDD 0.64 mg/cm^2.

3.3 DRY-BAND STREAMER DISCHARGES

Close-up visual photography (Figure 4) reveals faint discharges that bridge the bands, whose violet colour is consistent with the appearance of atmospheric streamer breakdown. The shapes of the heated surfaces of the dry bands that are visible in Figure 4b are congruent with the shapes of the bands of streamer discharges in Figure 4a. The voltage fall across the band associated with a low-current glow or streamer discharge is significant, and may ensure that the local power dissipation within the band sustains a rate of evaporation that matches the wetting rate. This persistence of dry-band heating indicates that these streamer discharges provide current continuity across each band despite the low conductance caused by moisture loss. A transition to a spark channel would account for the partial-arc development visible in Figure 3.

3.4 DRY-BAND NUMBER AND LOCATION

Figure 5 represents results from a test similar to that of Figure 2. The horizontal bars indicate the times of onset of each band, its location and the increasing number of dry bands during an applied ramp leading to a FOV of 23 kV. The first bands in this example are located on the upper (high voltage) trunk section of the insulator, with seven bands appearing at the middle and then lower (ground) sections before a flashover in this instance at 290 s.

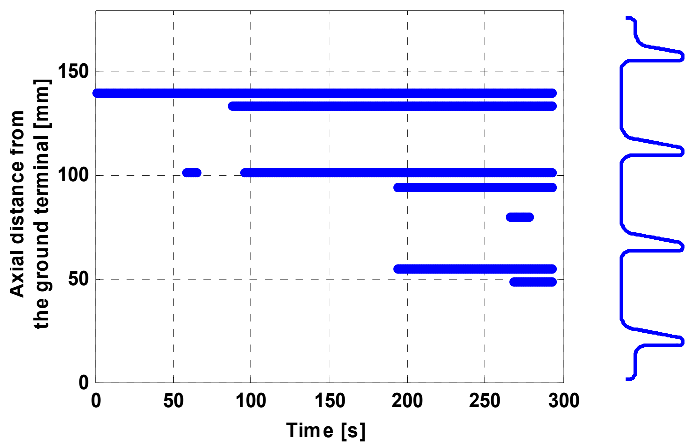
Throughout this period, the average band temperature rise remains fairly constant (Figure 5) at about 10 °C above the fog temperature. At higher voltages, increases in band temperature of up to 15 °C above ambient temperature could occur. The transient increases to higher temperatures are associated with short-lived partial arc discharges which bridge the dry bands (Section 3.5).

3.5 PARTIAL ARC DEVELOPMENT

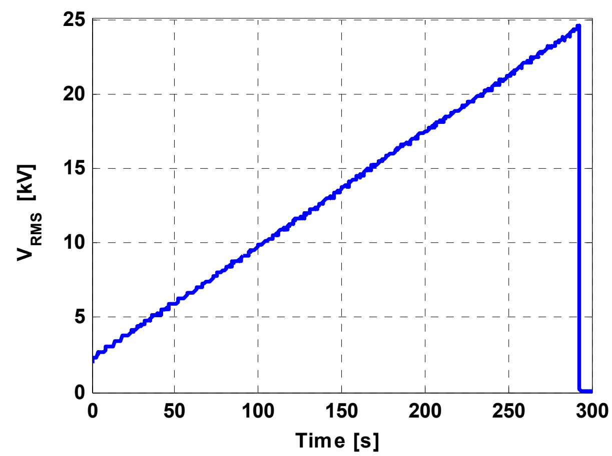
The pre-flashover RMS ramp voltage and current accompanying the dry-band development of Figure 5a are seen in Figures 5c and 5d to attain a typical partial-arc value of 60 mA, compared with less than 1 mA in dry-band streamers. Figure 6 shows the correlation of visual and infrared records with post-processed electrical data of a ramp test at successive instants during the 290 s before flashover (n.b. a scale of time-before-flashover is used here to facilitate comparison with other tests). Such tests confirm that the streamer discharges of a dry band are always a necessary precursor for the formation of partial arcs that may eventually lead to insulator flashover. Partial arcs are brighter than the streamers, and their often yellow colour suggests the presence of sodium ions from the pollution layer. During post-processing the number of partial arcs per second (N_p) is computed from the number of current transients greater than 0.5 mA during successive windows of 1 s [5]. It is noticeable that N_p reduces with increasing voltage. This reduction of partial-arc activity near flashover may be the result of the increasingly numerous and wide dry bands revealed by the IR records, so that even the substantial partial arc of event numbered VI in Figure 6b does not lead to flashover, which later occurs at 29 kV. The energy dissipation shown in Figure 6a is the mean energy loss per partial arc. This is given by the ratio P_{av}/N_p, where the mean power loss P_{av} during each time window is calculated from leakage current and voltage measurements. Power dissipation can exceed 1 kW in partial-arc events, and energy loss in the largest arcs is usually 10 J or more. Although the streamer discharges of a dry band appear to be a necessary precursor for the formation of a partial arc, any streamers which are not so transformed may act as a stabilising influence, since significant local voltage falls are necessary to maintain the dry-band streamers.

3.6 INSULATOR RECOVERY

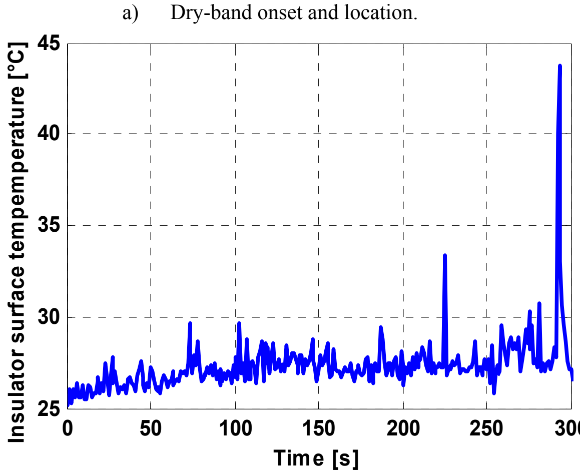
The thermal recovery of the silicone-rubber housing can be expected to be slow because of low thermal conductivity. IR records after completion of a ramp test, but with continued fog, showed the temperature difference to remain above 1 °C after 200 s. This produces a continuing reduction in the insulator strength if up-and-down constant-voltage tests are attempted, although the overcurrent protection prevented damage of insulator surfaces during the series of flashover tests. For this reason, all tests included interval of 5 minutes between successive ramps.



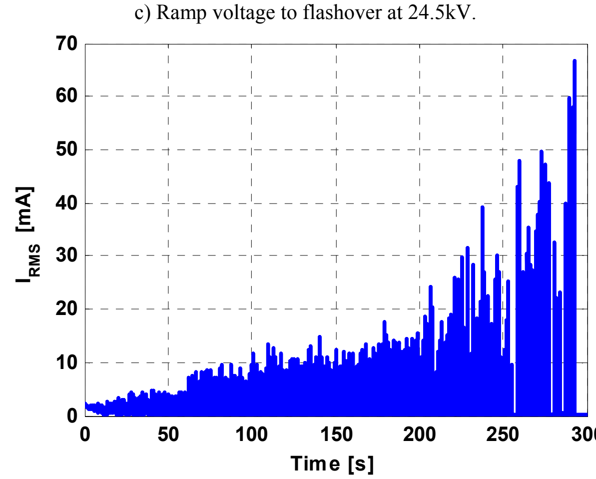
a) Dry-band onset and location.



c) Ramp voltage to flashover at 24.5kV.



b) Insulator surface temperature.



d) RMS leakage current

Figure 5. Pre-flashover dry-band development and leakage current growth. SDD 0.64 mg/cm^2.

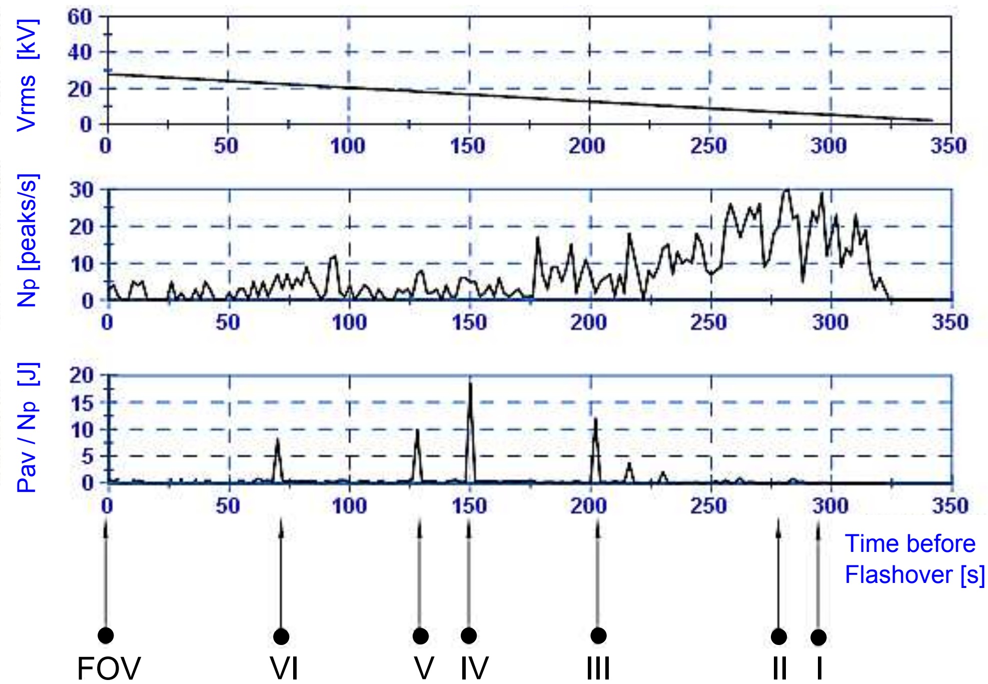


Figure 6a Voltage ramp.
Partial-arc activity (current peaks> 0.5A) per second).
Energy dissipation in events I – VI.

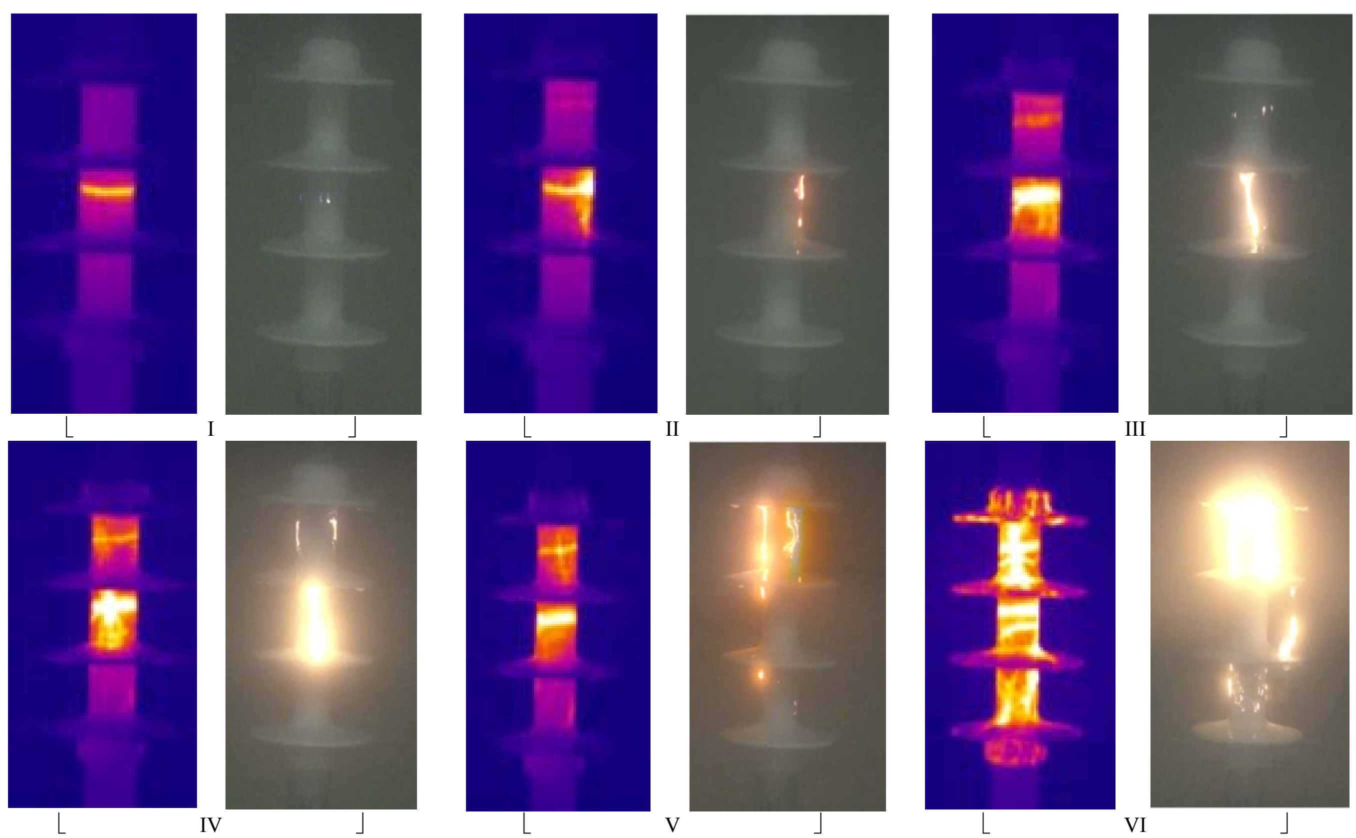


Figure 6b. Correlation of digital camera and infrared records with events **I – VI** of electrical data.

4 CONCLUSION

Infra-red imaging reveals the detailed development of dry bands which are normally invisible to observation. A leakage current of only a few milliamperes is sufficient to create the first dry band. For the range of salinity levels in the tests, the surface temperature of the pollution layer in the dry-bands is merely a few degrees Celsius above ambient. This appears to be sufficient to prevent rewetting. Current continuity and heat losses in the dry bands are associated with small-scale streamer discharges.

Comparison of visible and infrared emissions indicates that dry-band discharges are necessary to initiate extended, higher-current partial arcs. These frequently link or span dry-band regions. However, where a number of dry bands develop, partial-arc activity may be reduced prior to flashover.

The thermal and electrical data from these tests are currently being used by the authors to improve existing and alternative models of the flashover of polluted insulators. It is possible to discriminate and quantify the convective and evaporation heat losses associated with the leakage current power dissipation, and to estimate the consequent distortion of the voltage gradient along the polluted insulator.

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