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**GUIDE FOR THE ESTABLISHMENT
OF NATURALLY POLLUTED
INSULATOR TESTING STATIONS**

**Working Group
B2.03**

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1. INTRODUCTION

Having a direct bearing on both system reliability and cost, high voltage, outdoor insulators are critical components of electrical transmission and distribution networks. The selection of the correct insulator type is thus most important to ensure a secure supply but, unfortunately, the testing of insulators in order to identify those designs and materials which will provide satisfactory long term performance for a particular application is no easy task. The combination of the many variable environmental parameters which influence an insulator's behaviour over its lifetime are difficult to artificially simulate and, moreover, to accelerate. The validity of laboratory tests is thus often questioned as the procedures adopted may not take into account significant factors which would be encountered in service or they may over-emphasise others. The situation is further complicated by the variety of modern polymeric materials in use today which behave very differently to various over-stresses.

In view of the above, the evaluation of insulator performance in naturally polluted outdoor test stations is becoming more important and popular. Although involving a longer test duration, and still requiring care in the correct interpretation of the test data, the results tend to be accepted with more confidence.

This document serves as a general guide for the establishment of natural test stations which will facilitate the overall comparison of various insulator designs, the exploration of particular aspects of insulator performance and/or the selection of the most appropriate insulation for a particular application. It relates specifically to insulators intended for use under AC conditions but aspects are applicable to DC stations as well.

This guide is largely based on practical experience with test stations in South Africa, in particular the Koeberg testing facility which was established in 1974.

2. SCOPE OF THE TESTS

Before the design of the proposed test station can be initiated and its location selected, it is necessary to define the exact scope and nature of the tests to be undertaken. The goals of the testing programme will dictate the configuration of the facility, the number of specimens to be accommodated at any one time, the applied voltage, the type of instrumentation to be included and so on. Typical test aims may be one or more of the following:

- To compare the performance of insulators of different design.
- To compare the performance of insulators from different manufacturers.
- To dimension insulators for a particular environment or application.
- To examine the behaviour of insulators of different dielectric materials.
- To compare the performance of insulators in different orientations, e.g. vertical and horizontal.
- To explore the affects of specific parameters such as profile geometries or insulator diameters.
- To identify possible weaknesses or failure mechanisms of an insulator design.
- To estimate the life expectancy of various insulators.
- To serve as a qualification test for potential suppliers.
- To establish the effectiveness and life of insulator treatments such as washing, greasing, silicone rubber coating, shed extenders, etc.
- To assess the performance of other outdoor equipment insulation such as transformer bushings, surge arresters, cable terminations, etc.

Often one series of tests raises further questions and the scope of the investigations needs to be expanded and, perhaps, additional specimens accommodated to include different types and/or orientations or for statistical reasons. It is thus advisable to allow some leeway and flexibility in the dimensioning of the facility. If flashover problems on just one line are avoided, the establishment cost of the station will be more than justified.

3. SITE SELECTION

The location of the facility must be carefully considered. For example, if the environments of interest are those characterized by long dry spells and pre-deposited pollution, the test site should not be subjected to severe conductive fogs which may mask the key design parameters being sought and/or yield an incorrect order of merit for the types under test.

The severity of the pollution and the prevailing climate must be examined and should be representative of conditions found on the system. As is the case for laboratory tests, an over-acceleration of the ambient stresses can produce misleading results. Contamination severity assessments by means of ESDD (Equivalent Salt Deposit Density) and NSDD (Non-soluble Deposit Density) measurements and/or directional dust deposit gauges should be undertaken to ensure that an appropriate site is selected. Details of pollution severity measurement procedures and the interpretation of the results are provided in Appendix A.

The availability of land, the cost of supplying the station with power and other resources and the accessibility of the location will also influence the positioning of the facility.

4. STATION CONFIGURATION

Insulator test stations have a wide range of size and sophistication and may be categorized as one of four basic types. These are listed below.

4.1 Research Station:

A fixed, permanent installation equipped with comprehensive instrumentation for detailed leakage current and meteorological data analysis. It would possibly permit the support and monitoring of more than fifty test specimens and have the capability of energizing these at various voltage levels. Examples are shown in Figure 1. [1]



Figure 1. Permanent insulator research stations at Koeberg and Sasolburg, South Africa.

4.2 Simplified, On-line Station:

A temporary or semi-permanent test arrangement, teed-off from an existing line or substation, usually supporting less than 25 specimens of a single voltage rating. Leakage current amplitude and meteorological data recording is normally provided [2]. Examples are shown in Figure 2.



Figure 2. On-line insulator test stations.

4.3 In-Service Test Structure:

The installation and monitoring of insulators on an existing, in-service overhead line structure represents an economical means of undertaking natural testing of insulators. To maximise the number of test positions, a strain tower is usually preferred. This also allows the comparison of insulator performance in both horizontal and vertical orientation. Leakage current amplitude and meteorological data recording is often provided. A directional dust deposit gauge and/or ESDD insulator string should also be installed for the monitoring of the pollution severity [3]. Examples of in-service test arrangements are shown in Figure 3.

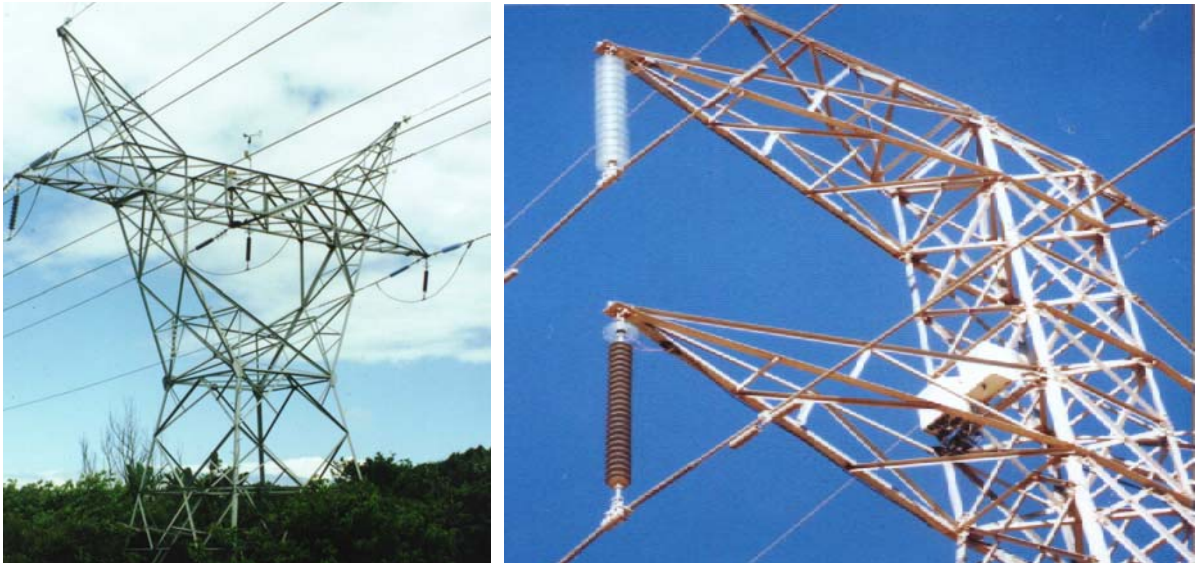


Figure 3. In-service insulator test structures.

4.4 Mobile Insulator Test Station:

Mobile test units are useful for evaluating the performance of insulators at particular sites. Usually energising the specimens at medium voltage, they are designed for temporary installation to provide guidance on the selection of appropriate insulators for a specific project or to explore the effectiveness of various maintenance procedures. Data logging is limited but leakage currents and meteorological parameters may be monitored. Examples are shown in Figure 4.

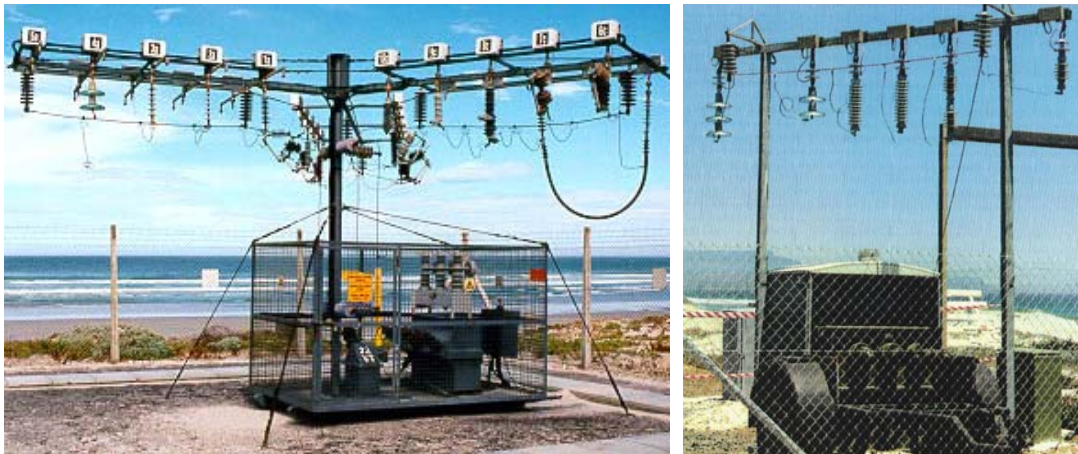


Figure 4. Mobile insulator test stations.

The type of station to be employed will depend on the aims of the studies as defined in Section 3 and the budget and staff available for its establishment and operation.

5. POWER SUPPLY

Procedures adopted at some test stations involve the variation of the voltage applied to the insulator specimens. It is, though, preferred that a fixed voltage – equal to the system highest voltage for which the insulators are intended divided by $\sqrt{3}$ – is maintained throughout the test period.

It must be appreciated that the leakage current amplitudes may exceed an amp and the supply must be able to deliver such currents without significant voltage regulation. The wetting and drying of insulator surfaces is a dynamic process and there will thus be some diversity in the maximum currents drawn by the specimens. However, the general level of activity will increase on all units when adverse weather conditions occur. IEC Standard 60507 [4], which covers the artificial pollution testing of single insulator strings, calls for a short circuit rating, I_{sc} , of the test plant of 6 to 14 amps for insulators of 16 to 24mm/kV specific creepage distance respectively. Perhaps more meaningful for the testing of multiple strings, it is also stated that I_{sc} should be at least 11 times greater than the highest total leakage current expected.

Further conditions specified by IEC for the test source are that the resistance/reactance ratio is at least 0,1 and that the capacitive current/short circuit current ratio lies in the range of 0,001 to 0,1. On-line stations and in-service test towers will usually have a more than adequate fault level and voltage regulation is not a concern.

Of course, the lines feeding the stations should themselves be well insulated and reliable. It would be unacceptable if the test facility lost its supply with the occurrence of adverse ambient conditions – energy and data thus being unavailable at the time of most interest.

With regard to protection, this will depend on the nature, configuration and location of the test station. It should, though, be ensured that the flashover of a single test specimen does not disrupt the supply to the whole station and that events in the station do not disrupt supply on the network. A typical arrangement for a station teed-off an existing line is illustrated in Figure 5 [5].

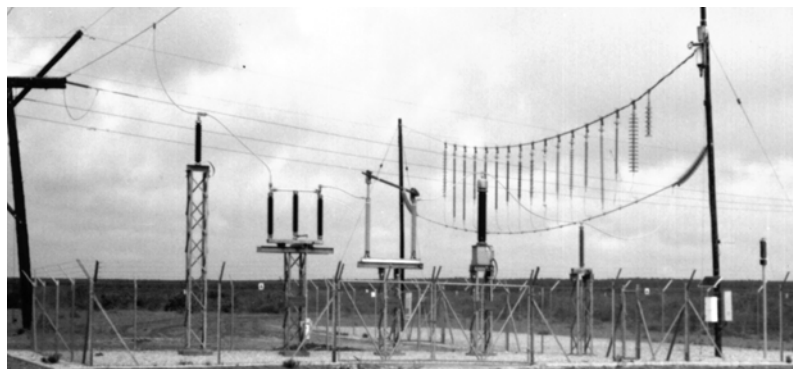
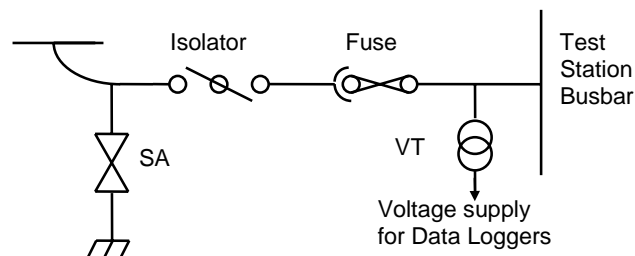


Figure 5. Station supply arrangement.

6. TEST SPECIMEN ARRANGEMENT

In order to capture the leakage current, a stand-off insulator is normally installed between the specimen under test and earth. The arrangement for suspension type insulators is illustrated in Figure 6 [6].

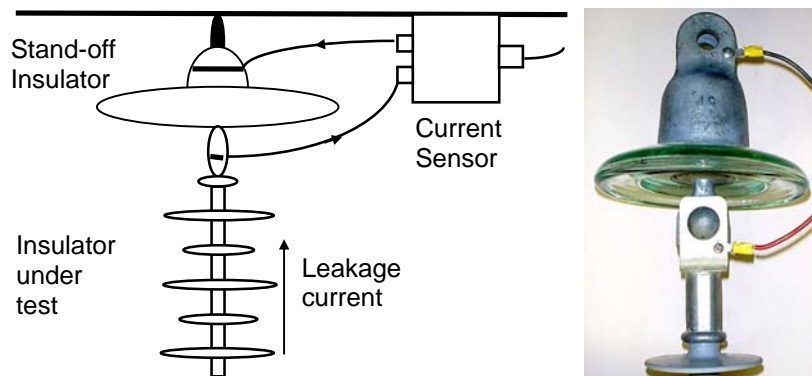


Figure 6. Test insulator mounting.

In order to disconnect a specimen that flashes over, or is about to flashover, so that the supply to the other samples is not interrupted, explosive fuses may be employed. These typically operate at current amplitudes of 750mA to 1A, automatically disconnecting the insulator from the station busbar. A threshold of 1A is also used in the accelerated ageing tests of product standards such as IEC 61109 [7]. Figure 7 shows various insulators under test with their stand-off insulators, leakage current sensors and explosive fuses in the live end jumper. Note that the jumper ends are coiled to limit the mechanical stress on the fuse under conditions of insulator or busbar swing.

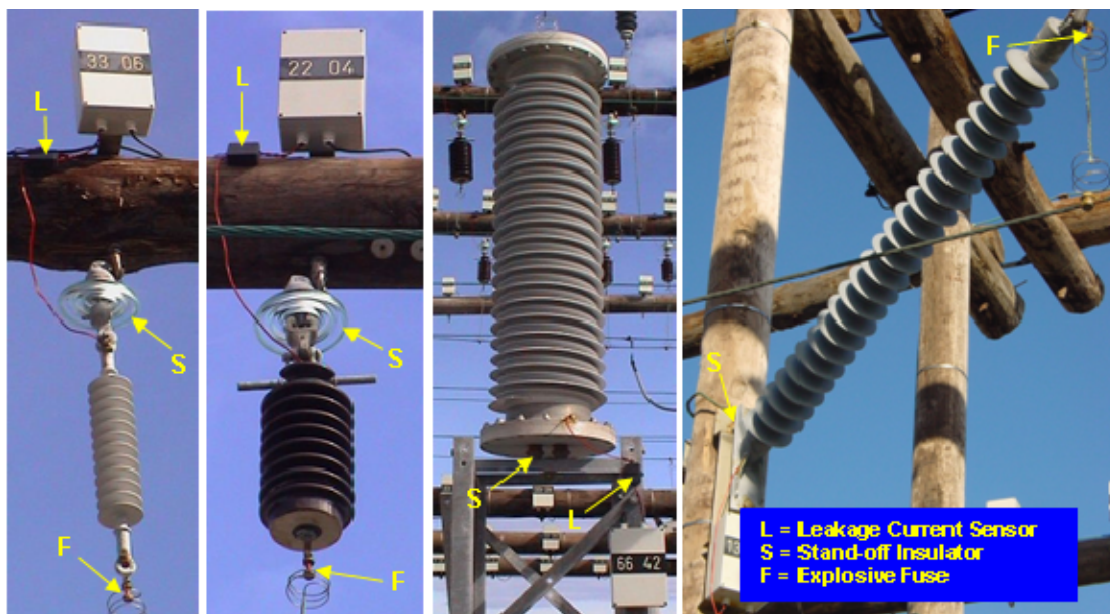


Figure 7. Test sample connections.

In some stations, the insulator is connected directly to the busbar and several earth leads incorporating explosive fuses are attached at various points along the length of the insulator so that, on flashover, the section of the string under test is automatically lengthened and remains energised.

7. MEASUREMENTS AND INSTRUMENTATION [1] [6]

The instrumentation installed in the test facilities will depend on the type of station and the nature of the tests being conducted but leakage current activity, climatic effects and pollution severity are usually monitored. The measurement equipment needs to be robust and immune to damage from severe electrical and physical environments.

7.1 Leakage Current Measurements

The amplitude and frequency of occurrence of leakage currents flowing over the insulator surfaces are recognised as important indicators of insulator performance. Current parameters monitored and logged may be one or more of the following:

- Maximum positive and negative peaks over a set time interval (highest peak current, I_{highest}).
- Number of current pulses exceeding selected amplitude thresholds.
- Average leakage current over a set time interval.
- Leakage current waveforms.
- Positive and negative charge (Coulomb) flowing over the insulator for a set time interval.
- Integral of the leakage current squared (Coulomb ampere) over a set interval.
- Real power loss (watts) over the insulator for a set interval (when the supply voltage waveform is available).

Details of leakage current measurement and the interpretation and analysis of the results are provided in Appendix B2.

7.2 Meteorological Measurements

The interaction between the prevailing weather conditions and the contamination on the insulator surface dictates the performance and probability of flashover. The monitoring of the meteorological parameters is thus important to the understanding of the behaviour and vulnerabilities of the insulators under test. As illustrated in Figure 8, the following measurements are usually made:

- Wind Speed and Direction.
- Average Relative Humidity.
- Temperature.
- Accumulated Rainfall.
- UV B Solar Radiation.

In addition to the weather conditions, the pollution severity should also be monitored. This is normally achieved by regular ESDD/NSDD measurements and/or directional dust deposit gauges. These are described in Appendices A.1 and A.2 respectively.

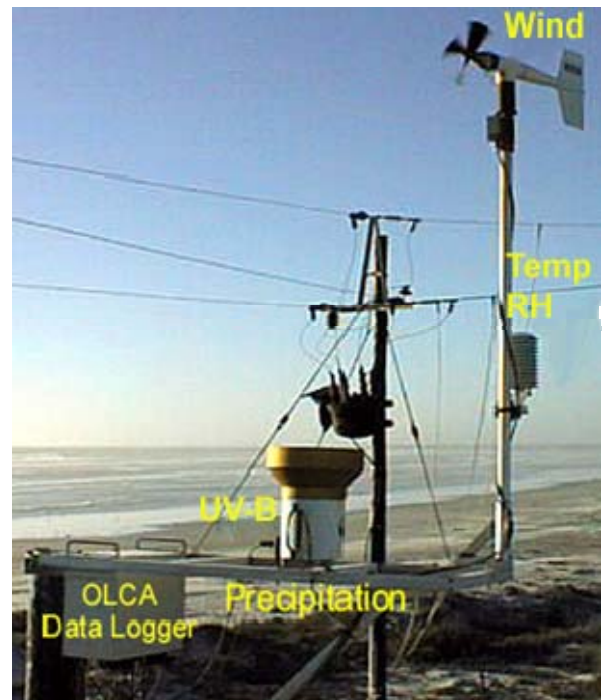


Figure 8. Typical meteorological monitoring system.

7.3 Instrumentation and Data Protection

The station equipment and instrumentation must be on an equi-potential platform. All external connections, e.g. supply and telephone lines, must be isolated and protected against incoming surges. The instrumentation should be energised via an uninterruptible power supply. If optical fibre is not used, the sensor cables should be tightly twisted, double screened and properly earthed. The use of coaxial cables and voltage signals are not recommended. The leakage current sensors must be protected from over-voltages caused by the flashover of the test insulators. This can be achieved by the use of a 1 kV gas discharge tube in parallel with a voltage clamping circuit.

Remote test stations should be inspected and all data backed-up on at least monthly intervals. The recorded data should be downloaded daily via a telephone, cellular or satellite modem.

8 INSULATOR INSPECTIONS

In addition to the amplitudes of the leakage currents monitored and the number of flashovers experienced, the performance of the test samples should be judged by a regular inspection of the insulators in both the energised and un-energised state. The inspections should include a close visual examination of the surfaces, an assessment of the hydrophobicity of the dielectric material and the viewing of electrical activity preferably with the aid of an image intensification device.

8.1 Visual Examination.

A periodic study of the insulators should be undertaken to detect signs of degradation. Depending on the insulator design and material, various types of damage may occur. Typical signs of deterioration to be noted are: [8] [9]

Discolouration – a change in the base colour of the housing material of a composite insulator – Figure 9(a).

Chalking – the appearance of some filler particles of the housing material, forming a rough, powdery surface – Figure 9(b). This is caused by loss of polymer owing to electrical activity and/or solar radiation.

Crazing – surface micro-fractures of depths approximately 0.01 to 0.1 mm – Figure 9(c).

Alligating – surface micro-fractures deeper than 0.1 mm – Figure 9(d).

Dry band marking – the signs left on the insulator material surface after dry-band activity has taken place – Figure 9(e).

Embrittlement – Loss of elasticity of the polymer and possible breakage – Figure 9(f).

Splitting – the splitting of composite insulator sheds or housings – Figure 9(g).

Tracking – the irreversible degradation of the dielectric material by the formation of conductive (often carbonaceous) paths starting and developing on the surface – Figure 9(h). These paths are conductive even under dry conditions.

Erosion – the irreversible and non-conducting degradation of the surface of an insulator that occurs by loss of material – Figure 9(i). This can be uniform, localised or tree-shaped.

Puncture – the electrical puncture of sheds or housings – Figure 9(j).

Peeling – for coated units, the loss of adhesion between the coating and the insulator surface – Figure 9(k).

Oxidation – for silicone greased insulators, the degradation of the layer to a silica – Figure 9(l).

Metalware corrosion – the degradation of galvanised coatings and the rusting of end fittings – Figure 9(m).

Pin Erosion – the spark erosion and corrosion of the pins of disc insulators – Figure 9(n).

For reference, examples of some of the forms of deterioration are shown in Figure 9.



(a) Discolouration



(b) Chalking



(c) Crazing



(d) Alligatoring



(e) Dry band marking



(f) Embrittlement



(g) Shed splitting



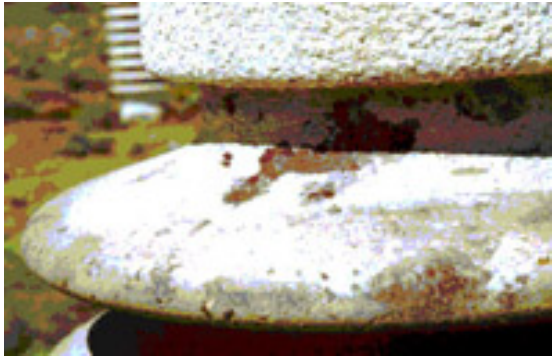
(h) Tracking



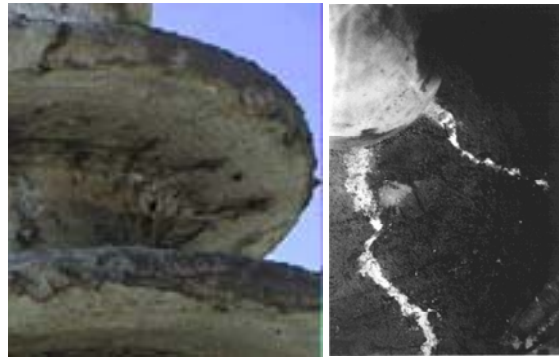
(i) Erosion



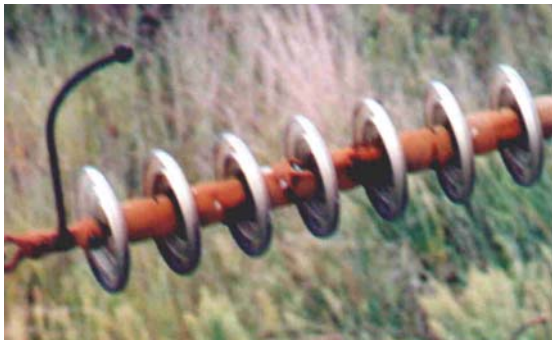
(j) Shed puncture



(k) Peeling and chalking of coating



(l) Tracking and oxidising of grease



(m) Metalware corrosion



(n) Pin corrosion

Figure 9. Examples of insulator degradation.

8.2 Surface Hydrophobicity

The water repellency of insulator surfaces – particularly for those of the silicone rubber type – has a marked influence on the performance. Such repellency may, however, be destroyed by severe electrical activity and then recover when conditions improve. The degree of hydrophobicity is thus a good indicator of the state of a silicone rubber insulator or coating and may provide an indication of its expected life. It must, though, be appreciated that contamination on a silicone substrate may be hydrophilic on its outer surface but still maintain a significant degree of water repellency within the pollution layer. Evidence of this is often seen by the lower leakage current amplitudes flowing on silicone insulators as compared to others even though the surfaces on all the units appear hydrophilic.

The degree of hydrophobicity can be defined by taking close-up photographs of water droplets on the surface and measuring the contact angle. An easier, approximate method is to use the IEC “wettability” classification [10]. Photographs of Classes 1 to 6 are shown in Figure 10. Class WC7 relates to the case of a continuous water film present on the entire area (not shown). It should be noted that the water repellency may vary over the insulator surface. For example, the sheds may be hydrophobic on their undersides but wettable on top.

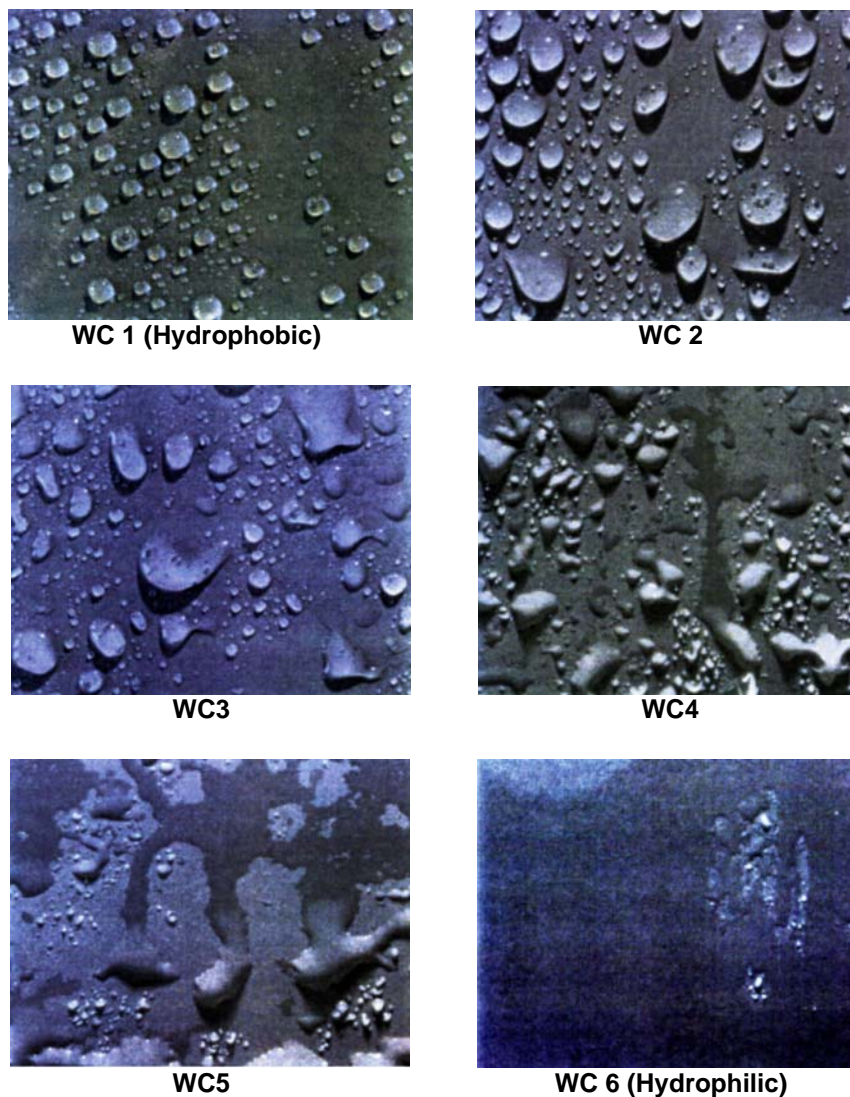


Figure 10. Wettability Classes.

8.3 Electrical Observations

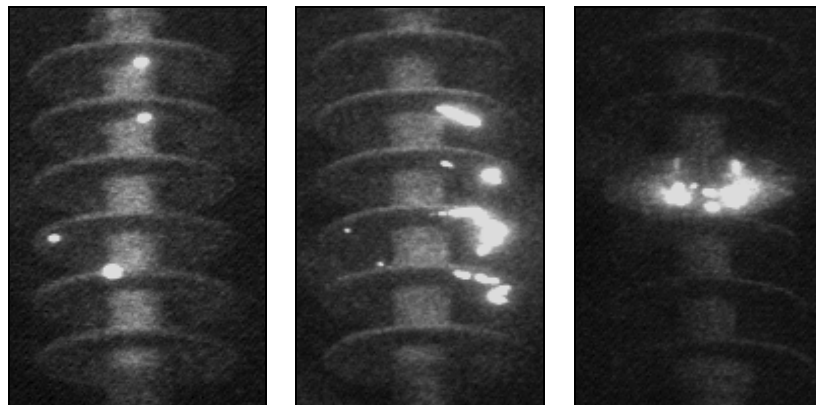
An image intensifier, operating in the UV spectrum, is a sensitive and useful tool to gauge the relative electrical activity on the samples under test. As illustrated in Figure 11, dry band arcing and corona are easily seen and the images can be recorded electronically or on video tape. The results may be correlated with the ambient weather conditions, the surface hydrophobicity and the leakage current amplitudes. The types of activity that can be recorded are: [11]

Water drop corona - water droplets can cause a localised increase in the electric field strength, which may precipitate corona generation.

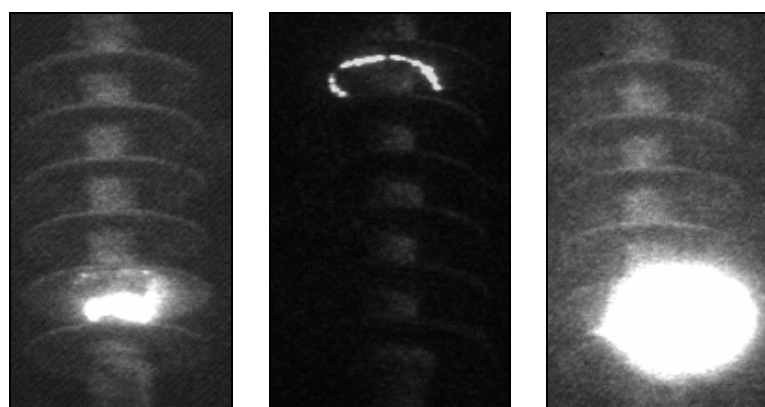
Spot corona - corona around an electrolytic filament or discharges between water droplets or electrolytic filaments.

Dry-band corona - corona within the dry band zones.

Dry band arcing - streamer, spark and arc discharges bridging the dry-band zones.



(a) Corona Activity



(b) Dry Band Arcing Activity

Figure 11. Examples of electrical activity.

9. COMPARISON OF RESULTS

Clearly, the reason for establishing a test station is to permit the comparison of the performance of various insulator types and arrangements under identical environmental conditions. The station layout should thus be carefully considered to minimise the influence of the test sample position within the facility. Where it is thought that the location of the units on the test rack may affect the results, identical control insulators should be installed at different points and their leakage currents compared.

The comparison of results from different test stations is complicated by the potentially significant differences in the climatic conditions and pollution types and sources to which the test specimens are exposed. In order to assist in the meaningful interpretation of data from various sites, some standardisation of the measurement techniques would be helpful. In this regard, the following recommendations are offered:

- The assessment and definition of the pollution severity needs to be uniform. For example, identical glass discs and porcelain long rods should be used for ESDD and NSDD measurements. The dimensions of the directional dust deposit gauges should be those provided in Appendix A and they should be mounted at the same height (preferably 3 metres to the bottom of the collection slots). The test procedures used should be those described in Appendix A.
- In addition to any other current measurements made, the absolute value of the maximum peak amplitude of the leakage current on each sample should be logged for each 10 minute interval. This can be referred to as the I_{highest} value and can serve as a basic comparison of insulator performance.
- A reference string of, say, standard cap-and-pin disc insulators of 25mm/kV Um specific creepage distance (and/or 31mm/kV for heavily polluted sites) with I_{highest} leakage current monitoring should be installed at each station.
- Meteorological data should include the average relative humidity, average wind speed and accumulated rainfall for each 10 minute interval. Wind measurements should be taken at a height of 10 metres.
- Visual inspection reports, including detailed images, describing the state of the insulators should be prepared every three months.

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APPENDIX A

SITE SEVERITY ASSESSMENT

Site severity assessment, based on the measurement of pollution levels and a study of the weather conditions, is required to define the environment in which the test insulators operate. To establish the pollution level, the surface deposit on a sample insulator is measured and/or directional dust deposit gauges are used. Both of these methods are discussed in Sections A.1 and A.2 respectively. To obtain a reliable pollution severity classification, as described in Section A.3, the measurement period should be at least two years. At test stations, however, the measurements should continue to be taken even after this period to identify any uncharacteristic or extreme events which may affect the results of the tests being conducted at the time.

A.1 SURFACE POLLUTION DEPOSIT TECHNIQUE [1]

The surface pollution deposit technique determines the natural pollution deposit on an insulator after a specific period, during which some natural washing may have occurred. Both the active and inert pollution are measured.

At the site to be assessed, a string of seven cap-and-pin disc insulators is installed at a height of at least 3 metres and clear of obstructions. The first and last disc in the string are not tested, they are merely included to ensure aerodynamic similarity in the string. The active and inert (non-soluble) pollution values are determined monthly on disc number two, three-monthly on disc three, six-monthly on disc four, annually on disc five and two-yearly on disc six. The maximum values obtained during the test period are used to determine the site severity class.

If the above procedure cannot be used, then a surface pollution deposit measurement on existing insulators in the network can be made. However, this is more risky as the measurement represents one snapshot in time, and could indicate a lower pollution severity for the site than is really the case.

A.1.1 Active Pollution - Equivalent Salt Deposit Density (ESDD)

The ESDD value is defined as the equivalent amount of NaCl deposit, in mg/cm^2 , on the surface area of an insulator which will have an electrical conductivity equal to that of the actual deposit dissolved in the same amount of water. The ESDD technique involves washing of the contaminants from the insulator surface with distilled water and measuring the conductivity of the solution obtained.

The measurement procedure for a cap-and-pin disc insulator is as follows:

On site...

1. Without touching the glass or porcelain surface, cover the metal cap and pin with plastic cling wrap.
2. Measure a volume of 500 to 1000 ml (or more if required) of demineralised water ($< 5 \mu\text{S}/\text{cm}$) and pour into a clean bowl.
3. Place the test insulator on its cap in the water and wash the convex surface with gentle strokes of a brush, sponge or swab. On completion, turn the insulator over and wash the concave surface.
4. Remove the insulator, gently shaking off any remaining water into the bowl. Pour the wash water into a labelled container, taking care that all the deposits are transferred from the bowl and utensils.

Note:

- (i) Wear clean surgical gloves to avoid the possibility of contamination of the sample
- (ii) The bowl, container, measuring cylinder, etc. must be washed thoroughly to remove any electrolytes prior to the measurement
- (iii) The top and bottom surfaces of the disc insulator can also be treated separately.

At the measurement location...

1. Swirl or stir the wash water solution until all the soluble salts are dissolved.
2. Measure and record the volume conductivity and temperature of the solution.
3. The ESDD value is obtained from the measurements of the volume conductivity, solution temperature, and volume of the wash water solution. The conductivity probe measures the volume conductivity, σ_t , at the solution temperature t_s . If the instrument used does not automatically compensate for temperature then the measurement must be corrected to a standard temperature of 20 °C by using the equation:

$$\sigma_{20} = \sigma_t \cdot [1 - k_t (t_s - 20)] \quad (\text{A.1})$$

where,

- σ_t : measured volume conductivity, in $\mu\text{S}/\text{cm}$
 t_s : solution temperature, in $^{\circ}\text{C}$
 σ_{20} : volume conductivity corrected to 20 °C
 k_t : temperature constant.

The temperature constant is calculated using the equation:

$$k_t = -3.200 \cdot 10^{-8} \cdot t_s^3 + 1.032 \cdot 10^{-5} \cdot t_s^2 - 8.272 \cdot 10^{-4} \cdot t_s + 3.544 \cdot 10^{-2} \quad (\text{A.2})$$

The salinity, S_a (kg/m^3), of the solution at 20°C is given as:

$$S_a = (5.7 \cdot 10^{-4} \cdot \sigma_{20})^{1.03} \quad (\text{A.3})$$

The equivalent salt deposit density (ESDD) in mg/cm^2 is given as:

$$\text{ESDD} = \frac{S_a \cdot V_d}{A_{\text{ins}}} \quad (\text{A.4})$$

where,

- V_d : volume of distilled water used, in cm^3
 A_{ins} : area of washed surface, in cm^2 .

A.1.2 Inert Pollution – Non Soluble Deposit Density (NSDD)

The NSDD defines the amount of non-soluble, inert pollution deposit per square centimetre of the insulator surface. After measuring the conductivity as described above, the liquid is filtered through a pre-dried, clean and weighed filter paper of grade GF/A 1,6 µm or similar. The contaminated filter paper is then dried and re-weighed.

The NSDD value is calculated using:

$$\text{NSDD} = \frac{M_2 - M_1}{A_{\text{ins}}} \quad (\text{A.5})$$

where,

- NSDD : non-soluble deposit density, in mg/cm²
- M₁ : weight of dry clean filter paper, in mg
- M₂ : weight of dry contaminated filter paper, in mg.

A.1.3 Chemical Analysis of Pollutants

A quantitative chemical analysis of both the soluble and non-soluble materials captured by the dust gauge may be undertaken to identify the types and sources of contamination to which the test specimens are subjected.

A.2 DIRECTIONAL DUST DEPOSIT GAUGE [1]

The dust gauge, as shown in Figure A1, is comprised of four vertical tubes each with a slot milled in the side - these being so arranged as to face north, south, east and west. A removable container which collects the deposits blown into the slots is attached to the bottom of each tube.

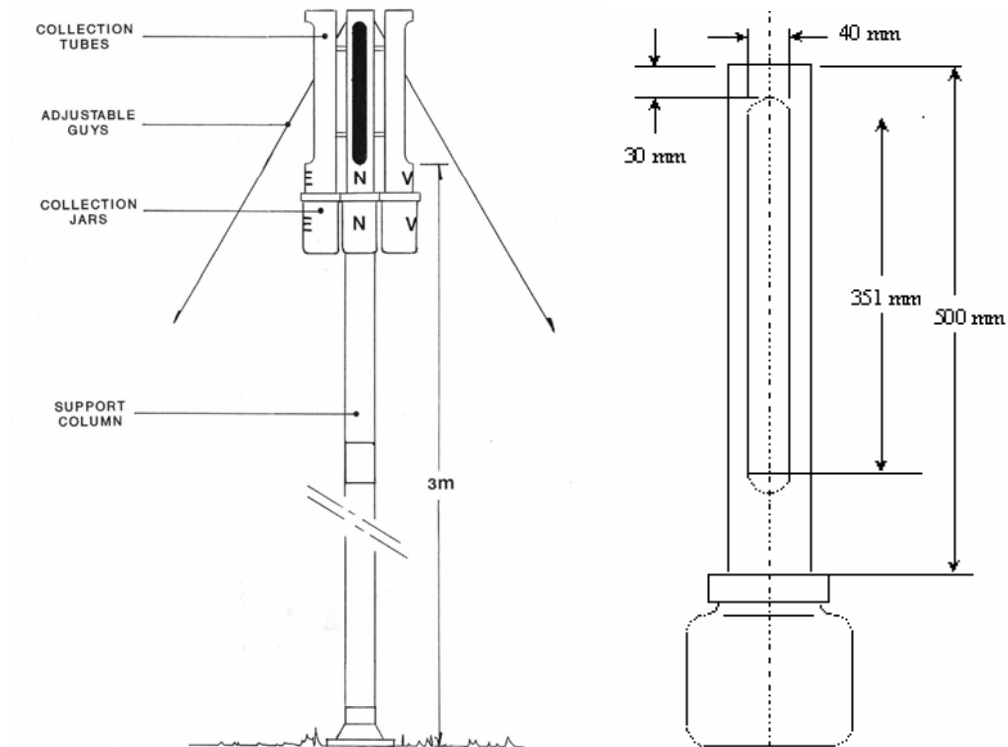


Figure A1. Directional dust deposit gauge.

To facilitate comparison of the results, the slot size as shown in Figure A1 should be used.

The monthly measurement procedure is as follows:

On site....

1. Remove the four collection containers from the tube ends and close with the lids provided.
2. Record the date of removal on the container label.
3. Attach four clean containers to the tubes, having completed the label on each container to indicate the site, the direction and the date of installation.

At the measurement location...

1. Add 500ml of demineralised water to each collection container. The conductivity of the water must be less than 5 $\mu\text{S/cm}$. Should the vessel contain rain water, add demineralised water to make up the volume to 500 ml. If, owing to heavy rainfalls, there is more than 500 ml in the container, no additional water is required.
2. Swirl or stir the contents until all the soluble salts are dissolved.
3. Measure the conductivity of the solution - preferably with a conductivity meter which automatically corrects the reading to 20°C. If the meter is not compensated to 20 °C, then measure the temperature of the solution as well.
4. If the volume of the solution is not 500ml, for example in the case of excessive rain having accumulated in the jar, measure the actual volume.
5. Calculate the corrected conductivity for each direction – this being the conductivity at 20°C, expressed in $\mu\text{S/cm}$, and normalised to a volume of 500ml and a 30-day month. The normalised DDG value is calculated using the equation:

$$\text{DDG} = \sigma_{20} \cdot \frac{V_d}{500} \cdot \frac{30}{D} \quad (\text{A.6})$$

where,

- DDG : corrected directional deposit gauge conductivity, in $\mu\text{S/cm}$
 σ_{20} : measured conductivity of the solution in $\mu\text{S/cm}$
 V_d : volume of water in the collection container in ml
D : number of days the container was installed.

If the conductivity reading is not compensated for temperature by the measuring instrument, the value can be corrected to 20°C using Equations A.1 and A.2.

6. Calculate the Pollution Index (P) for the month by taking the average of the four corrected directional conductivities, expressed in $\mu\text{S/cm}$, i.e.

$$P = \frac{(\text{DDG}_{\text{North}} + \text{DDG}_{\text{South}} + \text{DDG}_{\text{East}} + \text{DDG}_{\text{West}})}{4} \quad (\text{A.7})$$

Note:

- i. Some contamination can collect on the inside of the tubes and will be washed into the collection containers when it rains. The pollution indices for the wet months may therefore show slightly higher values than those when there was no precipitation. If the readings are averaged over a period then this makes no difference. However, if accurate monthly figures are required, then the internal walls of the tube can be rinsed off using a squeeze bottle of demineralised water before the collecting containers are removed for analysis.
- ii. If an assessment of the non-soluble deposit is required, following the conductivity measurements, the solutions should be filtered using a funnel and pre-dried and weighed filter paper of grade GF/A 1,6 μm or similar. The paper should then be dried and weighed again. The weight difference represents the Non-Soluble Deposit (NSD).
- iii. For more detailed information on the nature and/or source of the pollution, the gauge contents may be sent to a laboratory for comprehensive chemical analysis.

A.3 SITE SEVERITY CLASSIFICATION [1]

The site severity class can be determined from the surface deposit and dust gauge measurements as described below.

A.3.1 Surface Deposit Index

The surface deposit index is directly given by the ESDD value, calculated as described in Section A.1.1.

The relationship between the respective pollution severity classes and the surface deposit index, preferably measured over a period of at least one year, is tabulated in Table A.1[1].

Table A.1: Surface deposit index in relation to severity class.

Surface deposit index, ESDD (mg/cm²) (monthly maximum)	Site severity class	
< 0.06	I	Light
0.06 – 0.12	II	Medium
> 0.12 – 0.24	III	Heavy
> 0.24	IV	Very Heavy

To take into account the influence of the non-soluble contaminants, as a rule of thumb, the site severity class should be increased by one level if the measured NSDD value is above 2 mg/cm², or, if not measured, if a high NSDD is expected such as encountered in the vicinity of a cement factory.

A.3.2 Dust Deposit Gauge Pollution Index

The site severity class can be obtained from the monthly average or the maximum of the pollution indices measured by the dust gauge.

The relationship between the site severity class and the pollution index, preferably measured over a period of at least one year, is provided in the Table A.2 [1].

Table A.2: Dust deposit gauge pollution index in relation to site severity class.

Dust deposit gauge pollution index, P ($\mu\text{S}/\text{cm}$)		Site severity class	
(monthly average)	(monthly maximum)		
0 to 75	0 to 175	I	Light
76 to 200	176 to 500	II	Medium
201 to 350	501 to 850	III	Heavy
> 350	> 850	IV	Very Heavy

If weather data for the site in question is available then the dust deposit gauge pollution index can be adjusted to take into account climatic influences. This is done by multiplying the pollution index (P), as determined in Section 2 above, by the climatic factor (C_f) and using the value of $P \times C_f$ in place of P in Table A.2.

The climatic factor [1] is given by:

$$C_f = \sqrt{\frac{\frac{F_d}{20} + \frac{D_m}{3}}{2}} \quad (\text{A.8})$$

where,

F_d : number of fog days (visibility less than 1000m for some part of the day) per year
 D_m : number of dry months (< 20 mm of precipitation) per year.

To take into account the influence of the non-soluble contaminants, as a rule of thumb, the site severity class should be increased by one level if the average mass of the non-soluble deposit collected exceeds 500mg, or, if not measured, when a high NSDD is expected, such as is encountered in the vicinity of a cement factory.

A.3.3 Reference

[1] Vosloo W. L., Macey R. E., de Turreil C., The practical guide to outdoor high voltage insulators. Crown Publications, July 2004, ISBN No. 0-620-31074-X.

APPENDIX B

LEAKAGE CURRENT MEASUREMENT

B.1 LEAKAGE CURRENT THEORY [1]

Leakage current is generally recognised as a meaningful indicator of insulator performance. Its amplitude and shape is determined by the surface impedance, which, in turn, is the result of the interaction between the insulator surface and the environment in which it operates. However, what aspects of the current should be monitored and how they should be compared needs careful consideration. A typical leakage current recording is shown in Figure B1.

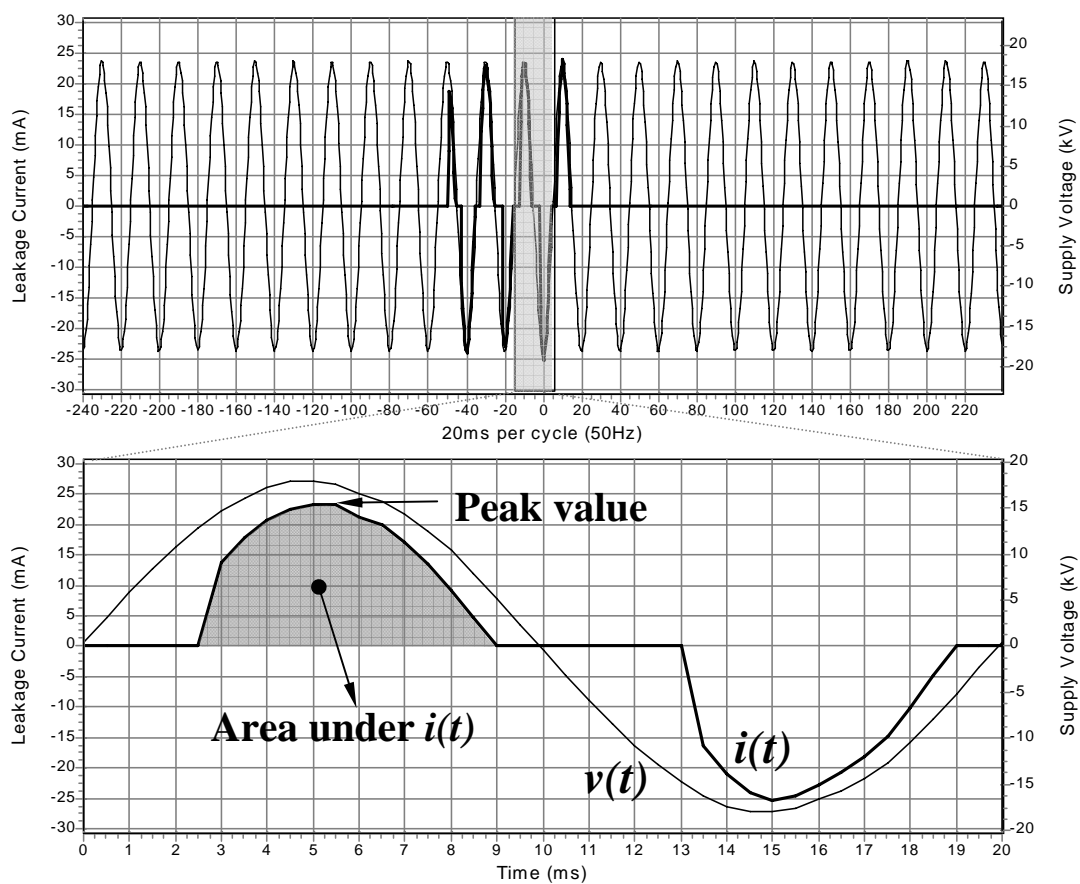


Figure B1. Typical leakage current $i(t)$ and supply voltage $v(t)$ waveforms showing an expanded view of the shaded 20 ms cycle.

The peak amplitude of the leakage current gives an indication of the flashover probability. For example, the empirical formula of Verma [2] defines the peak leakage current one cycle before flashover, (I_{max}), in amps, as:

$$I_{max} = \left(\frac{S_{CD}}{15.32} \right)^2 \quad (B.1)$$

with S_{CD} being the specific creepage distance in mm/kV, given by

$$S_{CD} = \frac{L}{U_{max}} \quad (B.2)$$

where,

- L : total insulator creepage distance, in mm.
- U_{max} : maximum rms system voltage phase to phase, in kV.

Thus, the peak leakage current values recorded on the test insulators can indicate their likelihood of flashover.

The rate of occurrence of peak leakage current pulses above selected amplitude thresholds can also be monitored and will serve to provide a measure of performance and probability of flashover. It should be noted that although leakage currents may be small (in the order of several mA), and thus indicating a low flashover risk, they can cause ageing and damage to non-ceramic insulator materials.

It should also be appreciated that leakage current waveforms having exactly the same peak values could vary from pure sinusoidal to pulse-shaped, from capacitive to resistive, and the non-linear nature of the spark/arc over the dry-band could result in a large variation of wave shapes. Thus, the peak value of the current should not be used on its own to compare relative performance.

The leakage current waveform can be analysed for harmonic content by carrying out a Fast Fourier Transform (FFT) to obtain a frequency fingerprint. The FFT plot of the leakage current waveform train of Figure B1 is shown in Figure B2. A strong 50 Hz fundamental and 150 Hz third harmonic was found. However, the FFT method was developed to describe repetitive waveforms of the same shape and not waveforms of a non-repetitive nature, such as leakage current pulses. It cannot be assumed that the shape of a single 20 ms waveform, or a captured leakage current pulse train, is repetitive in time. Thus, the use of FFT is not recommended to characterise the leakage current waveform or for comparative studies.

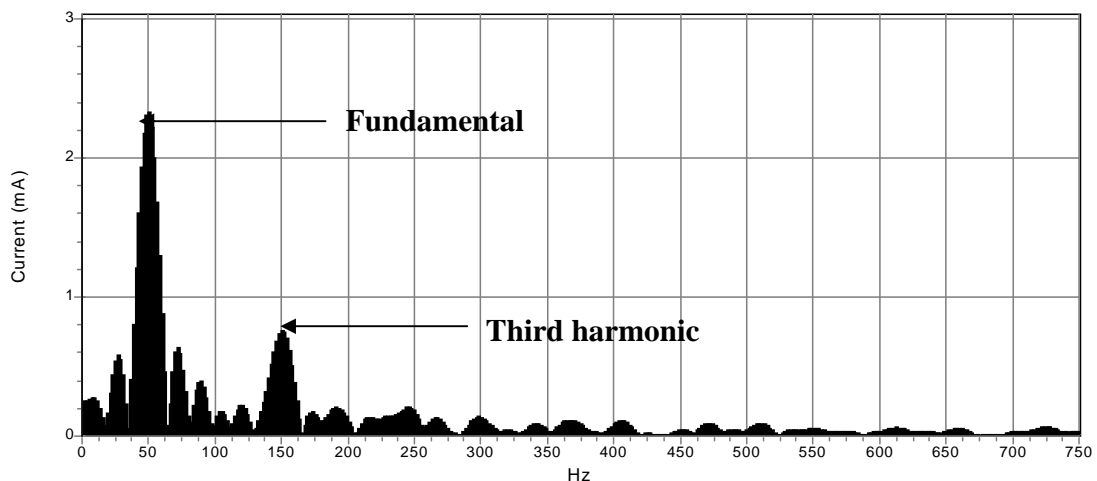


Figure B2: Fast Fourier Transform (FFT) plot of the leakage current waveform shown in Figure B1.

The instantaneous v-i characteristic, plotted with time (one 20 ms cycle) in Figure B3, could possibly be used to characterise the insulator leakage current waveform in relation to the supply voltage.

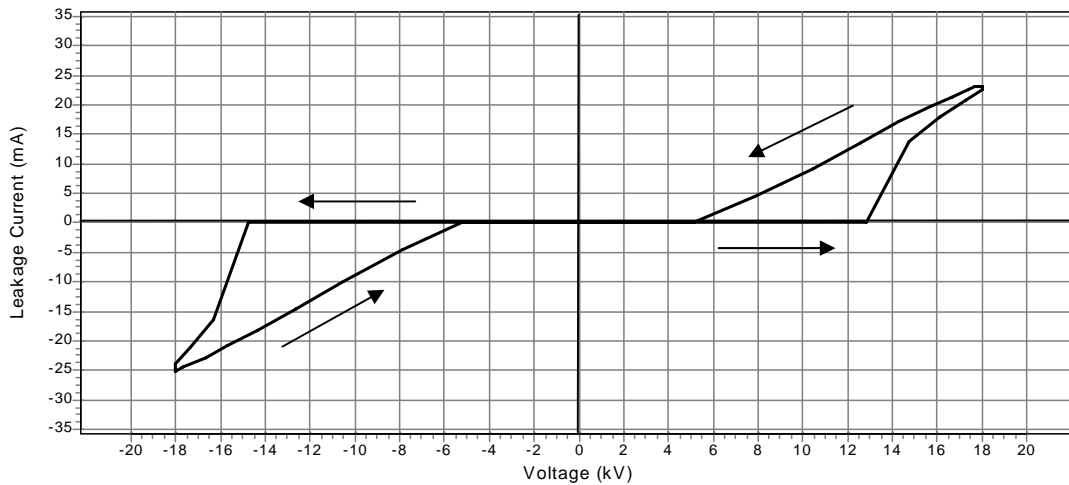


Figure B3. Instantaneous v-i characteristic of the insulator leakage current and supply voltage waveform shown in Figure B1.

When the insulator impedance is purely resistive, the instantaneous v-i characteristic plot will be a near straight line. Figure B3 shows a non-linear impedance plot the shape of which will vary widely between voltage cycles, mainly due to the non-linear nature of the sparks/arcs over the dry-bands. Thus to use these plots to graphically represent how insulator impedance varies over time is considered impractical.

The insulator impedance can be plotted with time as the ratio of the supply voltage over the insulator leakage current. However, when the leakage current approaches zero the insulator impedance tends to infinity, making it difficult to represent graphically. To overcome this, the inverse ratio (the insulator leakage current over the supply voltage) is used. This represents the insulator conductance $G_{ins}(t)$ in μS . The insulator conductance is then related to the insulator conductivity, which takes the profile (F , form factor) of the insulator into consideration, and is represented as:

$$\sigma_{ins}(t) = F \cdot G_{ins}(t) \quad (\text{B.3})$$

where,

$\sigma_{ins}(t)$: conductivity of the insulator at time t , in μS

$$\text{and, } F = \int_0^L \frac{dl}{\pi \cdot D(l)} \text{ is defined as the form factor of the insulator} \quad (\text{B.4})$$

where,

$D(l)$: diameter of insulator at position l along the insulator creepage path, in mm

The insulator conductivity with time from the leakage current and supply voltage waveforms is plotted in Figure B4 below. The maximum insulator conductivity σ_{ins} for the 20 ms cycle is used to represent the nature and severity of the electrolytic pollution present on the insulator surface.

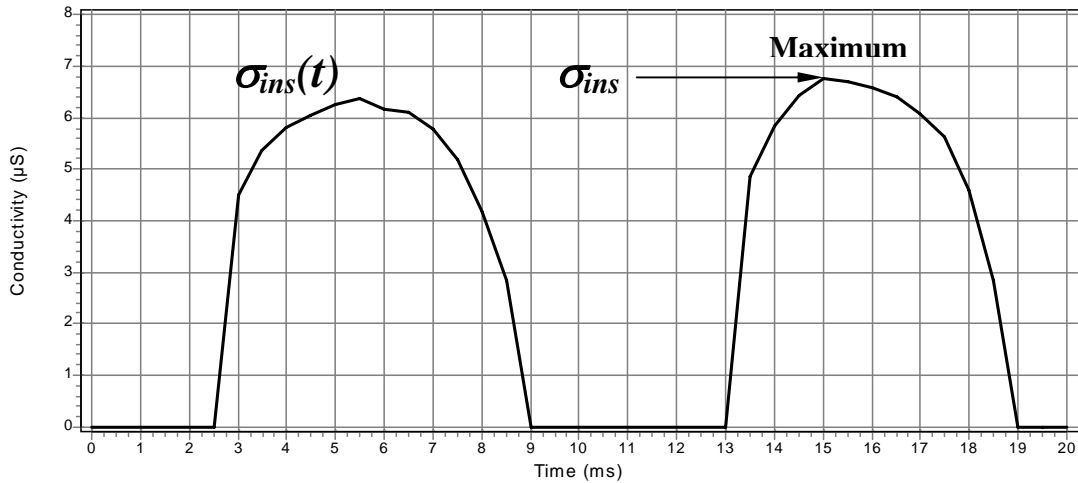


Figure B4. Insulator conductivity $\sigma_{ins}(t)$ and the maximum value σ_{ins} for the 20ms cycle shown in Figure B1.

The minimum insulator resistance for the 20ms cycle can be calculated from the maximum conductivity assuming $R_{pol} \approx R_{ins}$, using

$$R_{pol} = \frac{F}{\sigma_s} \quad (B.5)$$

where,

- R_{pol} : surface layer resistance of the insulator electrolytic pollution layer without an arc, in $M\Omega$
- R_{ins} : resistance of the insulator, in $M\Omega$
- σ_s : surface conductivity of insulator electrolytic pollution layer, in μS

The expected insulator flashover voltage can then be calculated from the minimum insulator resistance using the formula proposed by Rizk [3] and modified by Holtzhausen [4] as:

$$V_c = k_1 \cdot 10^{-3} \cdot \left(\frac{R_c \cdot 10^6}{L} \right)^{k_2} \cdot L \quad (B.6)$$

where,

- V_c : critical insulator flashover voltage, in kV
- R_c : critical insulator resistance, in $M\Omega$ which is the critical value R_{ins}
- k_1 = 7.6
- k_2 = 0.35.

This critical flashover voltage can be used to compare the performance of the test insulators, in terms of the likelihood of flashover.

The area under the leakage current curve (see Figure B1) takes the shape and amplitude of the waveform into consideration. This area is calculated as the integral of the leakage current waveform in relation to time, and indicates the amount of electrical charge Q (coulomb) flowing over the insulator. The accumulative amount of charge flowing over the test insulators can be used to compare the test insulators with one another.

However, leakage current waveforms having exactly the same accumulative electrical charge values could vary in position in relation to the supply voltage waveform and hence have different energy and power dissipation values. The energy calculation not only takes the shape and amplitude of the leakage current waveform into consideration but also its position in relation to the supply voltage waveform. The sinusoidal 50Hz supply voltage waveform as shown in Figure B1 is common to all the insulators tested and is thus used as reference (even though it may alter slightly, in magnitude only, due to dips or surges on the supply network). Figure B5 below shows the real time power and accumulated energy plots for the insulator leakage current shown in Figure B1.

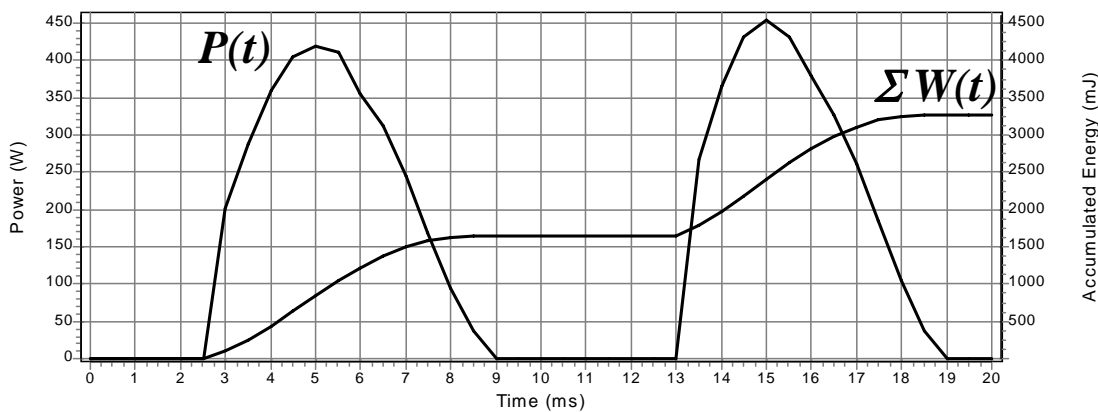


Figure B5. Real-time true power $P(t) = v(t) \cdot i(t)$ and accumulated energy $\Sigma W(t)$ (where $W(t) = P(t) \cdot \Delta t$) plots for the insulator leakage current shown in Figure B1.

True power is an instantaneous value. When averaged over time, singular high value events could possibly disappear into the average value. The accumulated energy should be used to indicate the amount of power dissipated with time over the insulator.

From the above, monitoring the peak value, rate of peak occurrence for different current levels (bin counts), conductivity, accumulative charge, and energy of the leakage current flowing over an insulator, will give the best possible indication of the performance of the insulator as a whole and how it is coping with the environment and can thus be used to compare the performances of the test insulators.

B.2 LEAKAGE CURRENT MEASUREMENT [1]

The leakage current parameters (peak, daily bin counts, daily waveforms, conductivity, accumulative charge and energy) must be measured (or calculated) at a chosen interval – typically 10 minutes - for the duration of the test period. The sampling frequency should be at least 2 kHz, with an accuracy of 0.5%, ignoring all leakage current values below 0.5 mA. As an example, details of one leakage current monitoring system are given below:

- **Peak leakage currents:** The leakage current monitoring instrument compares each leakage current sample measured with registers holding the previous positive and negative peak values. When a higher peak value is detected then the old stored register value is replaced with the new peak reading. At the end of each interval both positive and negative register values are stored to memory. The peak leakage current registers are then zeroed and the process is repeated for the following interval.

- **Daily peak leakage current pulse bin counters:** Per selected period, the stored positive and negative peak leakage current measurements are filtered into daily positive and negative leakage current pulse counter bins of pre-selected values, falling, say, within 1 to 5 mA; 5 to 20 mA; 20 to 100 mA; 100 to 250 mA; and 250 to 500 mA. Note: In this technique, the numbers of bin counts are based on only one peak value stored per 10-minute interval, and are thus may be much less than the actual number of pulses that have occurred for that value or any lower value (which is totally ignored).
- **Daily peak leakage current and supply voltage waveforms and associated conductivity and accumulated energy:** The daily maximum peak leakage current and associated supply voltage waveforms captured and plotted, consisting of 640 samples each (40 samples per 20 ms, 50 Hz cycle). The first half (8 cycles) shows pre-maximum information and the other half (8 cycles) post-maximum information. The conductivity is calculated and plotted for a selected 20 ms cycle using Equation (B.3).

The accumulated energy for the same 20 ms cycle is calculated and plotted per sampling interval as the product of the leakage current and supply voltage values multiplied by the sampling time interval Δt .

- **Daily peak waveform conductivity:** The daily maximum conductivity is calculated using:

$$\sigma_{ins} = F \cdot G_{ins} \quad (B.7)$$

where

σ_{ins} : conductivity of insulator, in μS .

- **Accumulative charge:** The leakage current measurement instrument accumulates the values of the positive and negative samples in two separate registers until the end of the interval. The accumulated register readings are then multiplied with the sampling interval Δt . The resulting values are the positive and negative charges per interval. The applied equation for the positive charge calculation is given as:

$$Q_{ins}(pos) = \sum_{n=0}^N pos(i(n)) \cdot \Delta t \quad (B.8)$$

where,

$Q_{ins}(pos)$: positive electrical charge in Coulomb
 $pos(i(n))$: n^{th} positive value of the leakage current i at time t in ampere
 T = 600 s
 f = 2000 Hz
 N = $f \cdot T$ = 1 200 000
 Δt = $\frac{1}{f}$ = 0.5 ms

The same formula (Equation B.8) holds for the negative electrical charge (pos replaced with neg). As shown in Figure B6, the accumulative (resulting) interval charge is then plotted in relation to time.

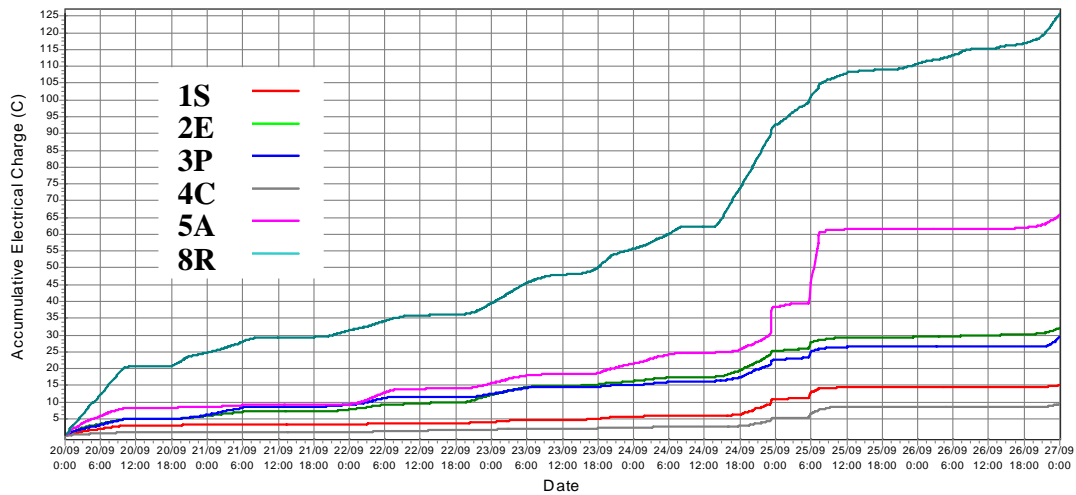


Figure B6. Typical accumulative charge plot for different insulator types over a one week period

- **Energy:** The leakage current measurement instrument accumulates the product of each sampled leakage current value and its corresponding voltage over the 10-minute interval and stores the value to memory. The 10-minute accumulated energy is then calculated by multiplying this value with the sampling interval Δt . The applied equation for the energy calculation is given as:

$$W_{ins} = \sum_{n=0}^N i(n)v(n) \cdot \Delta t \quad (B.9)$$

where,

W_{ins} : energy loss over the insulator in joules
 $i(n)$: n^{th} value of the leakage current i at time t in ampere
 $v(n)$: n^{th} value of the supply voltage v at time t in volts.

The 10-minute interval accumulated electrical energy is then plotted in relation to time and shows the rate of change in the energy.

Note: The 10-minute average power can be determined from the energy plots by dividing the 10 minute accumulated energy value by the time T .

B.3 REFERENCES

- [1] WL Vosloo, "A comparison of the performance of high voltage insulator materials in a severely polluted coastal environment", PhD dissertation, University of Stellenbosch, March 2002.
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