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D-76

Probes for spot measurement of surface conductivity on polluted insulators

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Abstract: The surface conductivity of insulators in the field is usually very non-uniformly distributed. In this case the integral surface conductivity is not an appropriate parameter of pollution severity. A better evaluation can be achieved on the basis of local conductivity measurements by means of special probes, e.g. the rod probe or tissue strip probe. In this paper the form factors of different probes are given, and the influence of wet-contamination area, the meniscus and the pollution layer thickness on the measured value of surface conductivity are shown. It was found that the surface conductivity on polluted silicone rubber measured by a tissue strip probe is proportional to the Equivalent Contamination Deposit Density ECDD.

Key Words: surface conductivity; equivalent salt deposit density; pollution

INTRODUCTION

The problems arising from pollution of insulators have been recognised by utilities for nearly a century. With the aim of predicting flashover and improving insulator design, considerable research work has been done towards understanding insulator surface contamination processes and flashover mechanisms under pollution conditions [1-3]. In service, an insulator will carry a resident contamination layer, accumulated since its installation or the last cleaning operation. This layer, which may fluctuate as a result of depositing and purring events, is more or less stable. Whatever their nature, the pollutants, when dry, are rather inactive. However, when exposed to random occurrences like condensation, frost and onshore gales, water and/or ionisable materials are added. This, depending on the design of the insulator, will increase its surface conductivity possibly leading to flashover and consequent power outages.

The surface conductivity is, together with ESDD and leakage current monitoring, a very important parameter of contamination severity. ESDD measurement is a reliable method for assessing contamination severity particularly for porcelain and glass. It involves washing the contaminants off from the insulator surface, and measuring the conductivity imparted by the contaminants [2]. Polymer materials, on the contrary, resist wetting because of hydrophobicity and their molecular chains known to be non-stationary [2]. For example, a thin film of silicone fluid literally engulfs contaminants thus preventing dissolution of the ionic species in the water and thereby providing a low surface conductivity. Thus, for insulators made of polymeric materials, conductivity measurement rather than ESDD, should provide a better indication of the electrical performance under polluted conditions. For ceramic and glass insulators, especially designed probes appear to be accurate for surface conductivity assessment, because field pollution accumulation is generally non-uniform.

INSULATOR SURFACE CONDUCTIVITY AND FLASHOVER PREDICTION

It is possible to evaluate the flashover voltage U_f of an insulator as a function of surface conductivity κ_s. The experimentally well confirmed equation is [4]

$$U_f = K_f \cdot \kappa_S^{-n_\kappa} \qquad (1)$$

where K_f and n_κ are constants influenced by the insulator profile and other factors. The surface conductivity is related to the conductivity κ and layer thickness h of the pollution layer by:

$$\kappa_s = \frac{1}{R_S} = \kappa \cdot h \qquad (2)$$

If the surface conductivity is uniformly distributed on the insulator as in the case of artificial layers then its value can be calculated from current measurement. Usually the current is measured at a voltage lower than the operating voltage (e.g. 700 V per 1 m of leakage distance) which causes no partial discharge or substantial temperature increase [5]. The so called integral surface conductivity of an polluted insulator is then calculated from

$$\kappa_{si} = f \cdot \frac{I}{U} \qquad (3)$$

where f, U and I represent respectively the form factor of the insulator, the applied voltage and leakage current. The form factor is calculated as :

$$f = \int_0^L \frac{db}{2\pi r} \qquad (4)$$

where L represents the leakage length of the insulator, db the incremental leakage length in cm and r the radius at distance db.

Proceedings of the XIVth International Symposium on High Voltage Engineering,
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D-76

The distribution of surface conductivity on insulators in the field is usually very non-uniform. In this case the integral surface conductivity is not a proper parameter of contamination severity. For the same integral surface conductivity the flashover voltage of the non-uniformly polluted insulator, can be either lower or higher than in the case of uniform pollution [4].

PROBES FOR SPOT MEASUREMENTS OF SURFACE CONDUCTIVITY

Special probes for measurement of surface conductivity can be used for the assessment of artificial layer uniformity in the laboratory [5]. These probes can be applied for determining of contamination severity of non-uniformly polluted insulators in the field. Pilling proposed a method for calculation of an effective surface conductivity which can be used for estimation of flashover voltage [4]. Probes have also been described to measure the ESDD on a small area of insulator in order to determine the distribution of contamination deposition [6, 7].
Probes employ differently shaped electrodes. The measured surface conductivity is proportional to the form factor of the probe f_P divided by the surface resistance R_S measured between the electrodes (equation 5). Table 1 lists the form factors of different probes.

$$\kappa_S = \frac{f_P}{R_S} \qquad (5)$$

Table. 1 The probes for spot measurement of surface conductivity and their form factors

Probe type	Wetting method	Form factor f_p (theoretical)
Strip probe (fig. 1)	Wet strip paper	a / b
Coaxial probe (fig. 3)	Sprayed with distilled water	$\dfrac{\ln \dfrac{R}{r}}{2\pi}$
Rod probe (fig. 4)	Sprayed with distilled water	$\dfrac{1}{\pi} \ln \dfrac{a-r}{r}$
IEC probe (fig. 6)	Sprayed with distilled water	$\dfrac{1}{\pi} \ln \dfrac{a-r_C}{r_C}$

Strip probe

The strip probe described by Pilling is shown in the Figure 1. This probe can be recognised as a modification of knife probe used earlier by Pohl (fig. 2). The wetting of the measured area is achieved with a special adsorptive paper strip being held between two plate electrodes (fig. 1). When the probe with a wet paper strip is applied to the dry pollution layer the moisture diffuses into the surface contaminants. The

distance between the plate electrodes and the width of electrodes are each 1 cm. Neglecting both the conductivity of the clean paper strip as well as the boundary field established due to broadening of the moisture region, the surface conductivity is inversely proportional to the resistance between the probe electrodes.
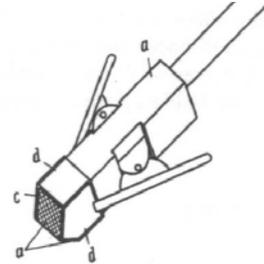

Fig. 1. The strip probe [4]
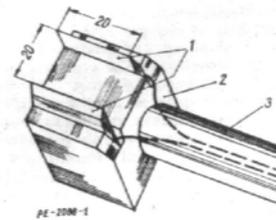a – adsorptive paper strip, b - electrodes

Fig. 2. The knife probe [8], 1 - electrodes

Coaxial probe

The coaxial probe (fig. 3) has a construction in which the current flows only between the electrodes so that the results is not influenced by surrounding pollutants.
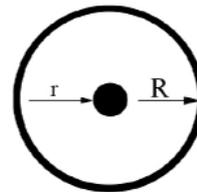

Fig. 3. Electrodes of coaxial probe [9]

Rod probe

The rod probe, built by Erler [10], consists of two cylindrical electrodes with radius r and separation a (fig. 4a). The local current density j and the local field intensity E are related by eq. (6) and the potential at this point shows eq. (7).

$$\bar{j} = \kappa_s \cdot \bar{E} \qquad (6)$$

$$\varphi(P) = \frac{I}{2\pi \cdot \kappa_S} \ln \frac{r_1}{r_2} \qquad (7)$$

Equation (8) shows the form factor of the rod probe precisely calculated by the mirror reflection method.

Proceedings of the XIVth International Symposium on High Voltage Engineering,
Tsinghua University, Beijing, China, August 25-29, 2005

D-76

$$f_P = \frac{1}{\pi} \cdot \ln \frac{\sqrt{a^2 - (2 \cdot r)^2} + a - 2 \cdot r}{\sqrt{a^2 - (2 \cdot r)^2} - a + 2 \cdot r} \approx \frac{1}{\pi} \cdot \ln \frac{a - r}{r} \quad (8)$$
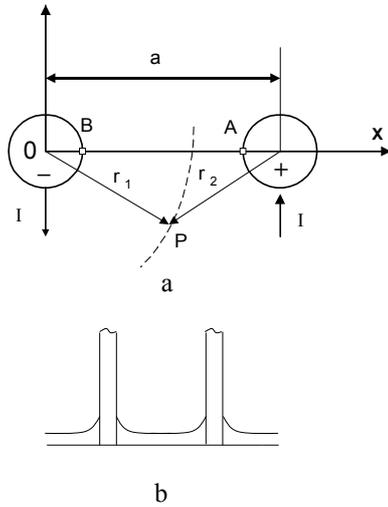
as shown in Table 1.

Fig. 4. The rod probe, a - the drawing for the estimation of form factor f_p, b – meniscus formation

The area of wetted pollution which surface conductivity is measured have to be greater than in the case of the strip probe or coaxial probe. The form factor of the probe in eq. 5 was calculated under assumption that the area of the wet contaminant is large enough. The decreasing of the area of wet contaminants results in increasing of the measured surface resistance (decreasing of measured surface conductivity). The fig. 5 shows that with the area of 100 cm^2 the measuring error is smaller than 3% for the probe with electrodes diameter of 1.5 mm and electrodes distance of 11 mm.
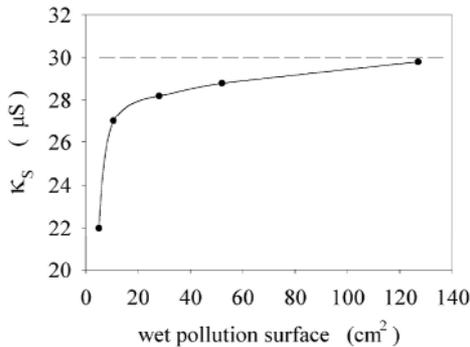

Fig. 5. Influence of pollution area on the value of surface conductivity measured by means of rod probe [8], electrode diameter 1.5 mm, electrodes distance 11 mm. The real value is 30 µS.

The value of form factor of the rod probe estimated during a calibration procedure, $f_P = 1,0$ differs significantly from the theoretical value of 0,83. These different results are caused by the meniscus which is formed at the electrodes. The meniscus changes the effective radius of electrodes and the layer thickness.

This procedure error depends on the viscosity of pollution layer.

IEC Probe [1, 9]

The IEC probe has two rod electrodes with spherically tips (fig. 6). Thanks such a shape the probe can be inclined to the insulator surface with different angles. The rod probe should be perpendicular to the contaminated surface because the form factor f_P given by equation (5) is valid for this position only. The theoretical form factor of this probe depends on the contact radius of pollution layer with the electrode. Neglecting the meniscus formation, this contact radius depends on the layer thickness only. The table 2 shows the form factors of the probe with the very similar dimensions to that recommended by IEC for different contact radiuses.
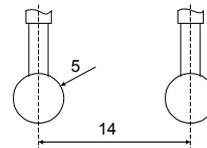

Fig. 6. IEC probe with spherical tips

Table 2. The form factor of the probe with spherical tips for different contact radiuses between electrode and contamination layer

Contact radius r_c (mm)	Form factor f_p	Remarks
1	0,79	Sphere diameter 4,5 mm
1,5	0,65	
1,87	0,59	
2,2	0,51	Distance between sphere centres 13 mm

The meniscus influence for the IEC probe is greater than that of the rod probe. The calibration test results for different layer thickness are shown on the fig. 7. The contamination layer consisting of water and NaCl was sprayed on the flat horizontal plate. The form factor of rod probe is constant for the thickness greater than 0.2 mm. In this region the meniscus influence causes no big difference between the theoretical and experimental values of form factors (1.0 and 0,83 respectively). The experimental value of form factor of IEC probe is about 0.65 for the layer thickness greater than 0.3 mm. The theoretical value of form factor for the layer thickness of 1 mm (contact radius of 1.87 mm) is 0.59. The influence of meniscus is very big in the case of very thin layer. Neglecting the meniscus influence, the form factor for the rod probe does not depend on the layer thickness. In reality the meniscus around the electrode decreases the layer thickness around the electrode and increases the resistance between the electrodes.

Proceedings of the XIVth International Symposium on High Voltage Engineering,
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D-76

Therefore the form factor of the probe calculated from the equation (5) increases.

The viscosity of wet contaminants becomes important for thin layer. The form factor of the IEC evaluated with the contaminants consisted of 30 g Aerosil (highly dispersed silicon dioxide) per litre water is very similar to the form factor calculated for the layer thickness greater than 0.2 mm. For the layer thinner than 0.2 mm the form factor for the layer consisted of Aerosil is smaller.
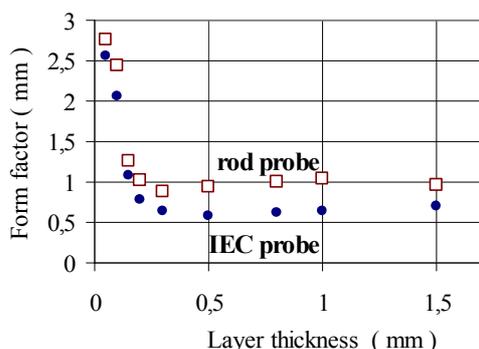
Fig. 7. The experimentally estimated form factor of the IEC Probe and the rod probe as a function of layer thickness

Relation between the surface conductivity K_S measured by strip probe and Effective Contaminant Deposit Density ECDD

The flat plates made from glass and plates with silicon coating were polluted by Kaolin suspension in such manner that the Equivalent Salt Deposit Density ESDD and Dust Deposit Density DDD amounted 0,1 mg/cm^2 and 1 mg/cm^2 appropriately. The conductivity of the NaCl solution (K) was 3500 µS/cm and the used thickness of the layer (h) was 0,05 cm. Therefore, the surface conductivity of the liquid contamination amounted

$$K_S \text{ max} = K \cdot h = 175 \text{ µS.} \qquad (8)$$

The surface conductivity Ks was measured by strip probe. The ESDD on glass plate or ECDD on silicone rubber plates was measured as a function of time according to the procedure described in [6]. Time zero is assumed as time when the plate became dry. The Besztercey's probe was filled with 2 ml of distilled water (fig. 8). The solution conductivity was measured by means of HORIBA B-173 compact conductivity meter 10 minutes after filling the probe. After that the ESDD or ECDD was calculated using formula given in [6].

The mean value of surface conductivity measured by strip probe on polluted glass surface calculated from 10 points amounted about 100 µS. The surface conductivity measured on silicon coating one day or few days later was lower but also proportional to the ECDD values (fig. 9). The simple correlation is found between both surface conductivity and ESDD or ECDD.

$$K_S \approx 1000 \cdot \text{ESDD} \qquad (9)$$
$$K_S \approx 1000 \cdot \text{ECDD} \qquad (10)$$

K_S - surface conductivity measured by the strip probe in µS

ESDD or ECDD   - in mg/cm^2

Fig. 8. The Besztercey's probe fastened to the silicone rubber plate by two clips
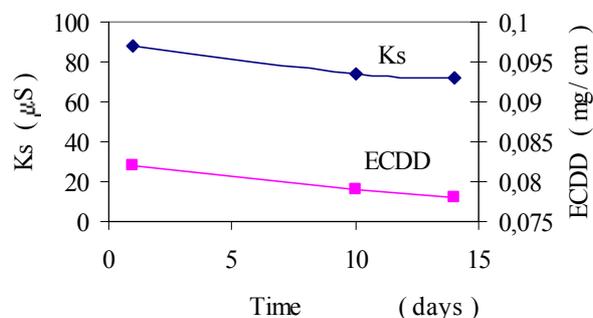
Fig. 9. Surface conductivity measured on SIR plates by strip probe and ECDD measured by Besztercey's probe as a function of time after contamination

The strip probe enables the quick evaluation of ESDD on porcelain insulators or ECDD on silicone rubber insulators. The important advantage of the strip probe is the possibility to measure the surface conductivity in many points including that on the rod and under sheds. The Besztercey's probe can only be used for measurements on horizontal or nearly horizontal surfaces.

CONCLUSIONS

The measurement of surface conductivity of polluted insulators can provide valuable information on several aspects of insulator performance. Probes appear to be a very useful tools for measuring of spot contamination severity of outdoor insulators.

The theoretical values of form factors for different probes were calculated as a function of their dimensions.

The real form factors of the IEC probe and the rod probe depend on the layer thickness and the surface area of wet contamination. The area of wet pollutants should

Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, August 25-29, 2005

D-76

be greater than 100 cm^2 for the rod probe and about 150 cm^2 and for IEC probe.

The surface conductivity measured by means of strip probe is proportional to the Equivalent Salt Deposit Density ESDD and to Effective Contaminant Deposit Density ECDD

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