Mechanism of saline deposition and surface flashover on outdoor insulators near coastal areas part II: impact of various environment stresses

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Mechanism of Saline Deposition and Surface Flashover on Outdoor Insulators near Coastal Areas Part II: Impact of Various Environment Stresses

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ABSTRACT

This is the second in a two-part paper series dealing with sea salt transportation and deposition mechanisms, and discussing the serious issue of degradation of outdoor insulators resulting from various environmental stresses and severe saline contaminant accumulation near the shoreline. The deterioration rate of outdoor insulators near the shoreline depends on the concentration of saline in the atmosphere, influence of wind speed on the production of saline water droplets, moisture diffusion and saline penetration on the insulator surface. This paper comprises two parts. The first part, deals with the impact of different environmental stresses on insulator surface degradation, including wind speed and direction, cold fog and rainfall. The second part concerns the flashover process related to saline contamination of the surface under constant and variable cold fog wetting rates and equivalent salt deposit density (ESDD). The experiments were performed on high voltage insulators based on the model presented in Part-I. Based on the proposed model, the influence of wind speed and direction on the pollution accumulation rate and impact of wetting rate on discharge current and surface flashover process were investigated. The equations $S=S_0 e^{(Vdep0/\alpha h)}[e^{(-\alpha x/v)-1}]$ and $D=D_0 e^{(Vdep0/\alpha h)}[e^{(-\alpha x/v)-1}]$ are derived from the model for saline concentration and deposition show good reliability and well represent the results obtained. Test results also show that due to the different wetting and contamination deposition rate, surface discharge current characteristics of tested insulator in rain are different with that in cold fog, which lead to different surface flashover voltages. An experimental setup was mounted for artificial saline contamination deposition. The proposed model can be therefore used to investigate insulator flashover near coastal areas and for mitigating saline flashover incidents.

Index Terms — **Cold fog, rainfall, discharge current, wind speed, outdoor surface flashover, climate conditions, shoreline.**

1 INTRODUCTION

NOWADAYS, because of the increasing demand for electricity and the need to upgrade existing power system networks, huge investments will be required for utilities to upgrade for future needs. However, such investments are worthless if utilities cannot also provide reliable and secure operations to consumers. Outdoor high voltage insulator applications are often exposed to various environmental stresses, such as saline, ash and dust pollution. The dry contaminating deposits covering insulators do not degrade the insulator surface or result in decreased insulator surface performance. However, the moisture, water vapour and humidity, when applied to these atmospheric agents, can create a considerable reduction in surface resistivity and lead to insulator surface degradation and decreased dielectric strength, leading to surface flashover.

It is recognized that various natural processes such as temperature exposure, relative humidity or moisture level, counter-diffusion of hydroxide ions, environmental load of salts and other adverse climate conditions affect saline deposition and diffusion. Several researchers [1-6] have extensively studied the effect of various types of contamination deposition on insulator surface flashover. However, they have not considered the influence of wind speed and direction on saline accumulation rate, diffusion and penetration rate and distance from the sea. The rate of contaminant accumulation on outdoor insulators near the ocean depends on wind speed and direction, distance from the shoreline and natural cleaning phenomena. However, specific studies and research on pollution distribution with high-speed wind are limited [7-8]. High-speed winds contribute to increased saline particle migration and insulator pollution near the shoreline. Pollutants mainly comprise marine specific soluble salts (NaCl and NaSO$_4$), dissolved in water droplets. These droplets leading to the development of a continuous water film and distribution of pollution layers on the insulator surfaces cover the surface of the insulators. When the contaminated insulator surfaces become wet, some of these particles are dissolved causing the insulator surfaces become conductive [9-12]. The development of the contamination layer is almost similar for both ceramic and non-ceramic insulators near the shoreline. However, the levels of contamination may differ. The flashover of a polluted insulator is extremely complex; several experimental and theoretical studies have been carried out in an attempt to understand it [13-14]. However, none presents a mechanism for saline transportation and deposition on insulators near the shoreline.

In this paper, the experiments were performed on high voltage insulators based on the model presented in Part-I and shown in Figure 1, that indicates the saline concentration (S) and its variation (S$_0$, S$_1$ and S$_n$) from shoreline (S$_0$) to inland (S$_n$). In this model, oceanic winds, distance from the sea to inland, diffusion and penetration of saline and gravitational settlement (horizontal and vertical settlement flux) of saline on outdoor insulators are taken into account. The investigation is based on the effects of wind speed and direction on pollution accumulation rate and impact of wetting rate on discharge current and surface flashover for different types of insulators. Flashover voltage and discharge current were also measured under various environmental stresses, simulating natural climate conditions. Furthermore, the influence of salt deposit density (SDD) and wetting rate on discharge current and surface flashover were investigated by analyzing the discharge current and flashover voltage.
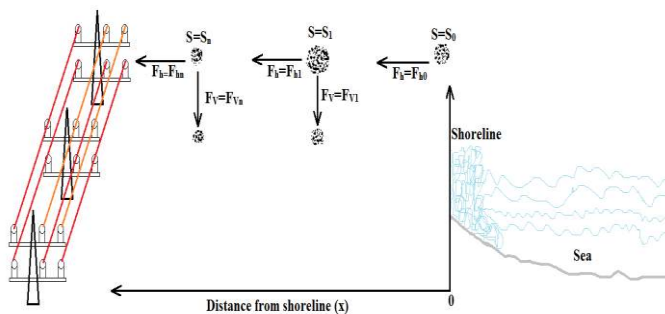
Figure 1. Schematic diagram of sea salt transport and deposition phenomenon.

2 EXPERIMENTAL FACILITIES AND TEST PROCEDURES

2.1 INTERPRETATION OF EXPERIMENTAL DATA

The test is intended to replicate natural climate conditions near the shoreline. In the west of Scotland, high voltage transmission lines run through the shoreline, affected by high humidity and low temperatures. Shorelines also encounter heavy rain and dense cold fog throughout the year. Atmospheric parameters such as ambient air temperature, relative humidity, rainfall, fog and wind speed, together with rate and type of precipitation, were obtained from the Royal Meteorological Society (RMetS). The influence of periods of rainfall over most of the year was more significant than that of cold fog. The average annual rainfall and fog were 4577 mm and 1.6 kg/h/m^3 respectively. The annual mean temperature varied ±0.3 ^{0}C of 9 ^{0}C, while the wind blowing from the sea cooled off at approximately the same temperature. Foggy wind blew during the winter and early spring, with a velocity of approximately from 2 m/s to 12 m/s. A few comments about that kind of climate conditions might help in giving an idea of the saline deposition and diffusion on insulator surfaces in an environmental chamber. To replicate the same natural climate conditions on outdoor insulators an experimental setup was designed and installed inside an environmental chamber and was equipped with a wind generator and shoreline specification salts (NaCl, CaSO$_4$), as well as a kaolin powder injection system as show in Figure 2.

2.2 TEST FACILITY AND EXPERIMENTAL SETUP

Generally, the steam fog method is used to initiate flashover on artificially contaminated insulator surfaces. However, when flashover performance of contaminated insulators is determined by the steam fog method, the temperature of the environmental chamber using steam fog is significantly higher than the environmental temperature near the shoreline. Subsequently, the temperature near the shoreline in winter and early spring is between 0 ^{0}C and 2 ^{0}C, it is unwise to use the steam fog method for the pollution flashover test. To simulate natural environmental conditions, some modifications were made to the test procedures in order to reproduce natural field operation conditions in the environmental chamber, detailed below.

To simulate the natural climate condition in environmental chamber during experiment, temperature of the tested insulator surface was monitored using infrared camera and the water temperature was checked with a mercurial thermometer. When the insulator surface and water temperature were the same, cold fog was generated and the temperature of the chamber was maintained between 0 and 2 ^{0}C. During fog and rainfall generation, the flow of air was constant at 8 m/s to ensure a constant distribution of temperature in the chamber in a way related to natural climate conditions.

The tests were carried out in an environmental chamber as shown in Figure 2. All tests were carried out using a 10 kVA, 100 kV and 50 Hz transformer. The applied 33 kV AC rated voltage can be increased manually or automatically at a rate of 1 kV/s. In both the cold fog and rain tests, the test voltage and wetting mode were applied simultaneously at temperatures between 0 and 2 ^{0}C.
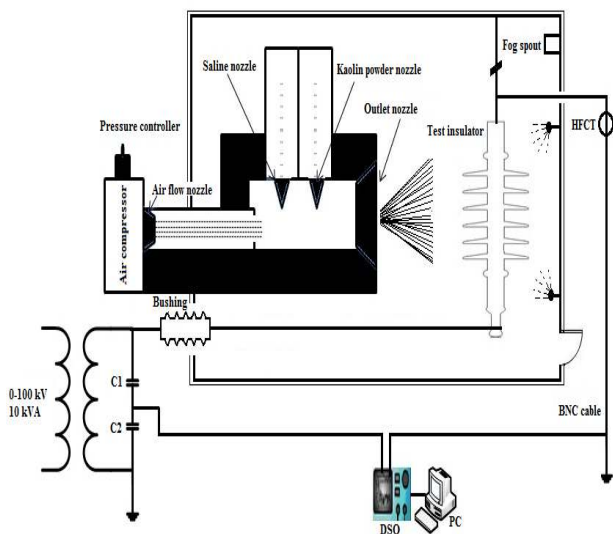
Figure 2. Experimental setup.

2.3 PRODUCTION OF ARTIFICIAL SALINE AND WETTING PROCESS

The latest changes in the IEC 62217:2013 standard do not include the solid layer pollution test method for high voltage non-ceramic insulators. In the absence of such tests, an experimental setup and procedure was developed for application of solid layer pollution to high voltage insulators. The experimental setup for artificial saline and kaolin mixtures and cold fog has been described in a previous paper [15], and a brief description is provided here. Before the tests, the insulators were carefully cleaned so that all traces of dust and grease were removed. The samples were then dried naturally. The artificial contamination method was used to contaminate the insulators, involving the use of mixtures of marine specification salts ($NaCl+CaSO_4$) and kaolin powder to simulate conductive and inert materials, respectively. The amount of salts ($NaCl+CaSO_4$) was varied to obtain the specified equivalent salt deposit density (ESDD) and non-soluble deposit density (NSDD). Cold fog was generated ten minutes before contamination deposition and insulator energisation. After the cold fog test, the same procedure was repeated for the rainfall test: the sample was carefully washed, cleaned, dried and re-polluted, and that the tests were performed under the same experimental setup. Rain nozzles located at the top of the environmental chamber provided a moderate spray of water. The angle of the nozzles was set at 45^0 with the tested insulator. Visually, it was observed that the insulator wetting was reasonably similar to an insulator being wet by moderate rain in service near the shoreline.

During the experiment, the relative humidity was kept saturated (100%) in the environmental chamber, which helped to bond the saline mixtures on the insulator surface, and the temperature was sustained between 0 and 2 ^{0}C.

2.4 RAPID FLASHOVER METHOD

The rapid flashover voltage technique was initially proposed by [16] for application of salt fog on test insulators. This procedure has previously been used extensively only with the salt fog contamination method. In this paper, a solid layer contamination deposition technique was used on insulator samples with variable wetting rate from 2.0 kg/h/cm^3 to 6.0 kg/h/cm^3 to simulate the natural climate conditions near shoreline. For mean surface flashover voltage (FOV), two configurations were considered: first, for a short period of wetting, the lowest surface flashover value may be considered; second, during five random tests, an average of the lowest surface flashover and the highest withstand values was obtained. In this paper, the factors affecting the characteristics of surface flashover were investigated. Contamination severity, wetting rate, conductivity level and minimum flashover voltage were measured.

In order to determine the surface flashover voltage, a rapid flashover method was adopted from [17]. A solid layer contamination test according to IEC 60507 uses an 'up and down' rapid flashover method to determine the performance of tested samples. The preferred sequence is as follows and carried out for each configuration.

1. A clean sample is hanged in environmental chamber;
2. Sample was polluted according to the guidelines recommended by IEC 60507 using the adopted experimental setup;
3. Both the normal cold fog and rain was generated five minutes before the contamination deposition;
4. Sample was energized and voltage maintained for 3 minutes or until surface flashover occurred;
5. If no surface flashover taken place within 15 minutes or by the time to maximum discharge current was reached, the voltage was increased at a rate of 1 kV/s until flashover occurred;
6. When surface flashover taken place the sample was re-energized at a constant voltage 5% below the last surface flashover voltage, but in the case of higher wetting rate (5.0 kg/h/m^3 to 6.0 kg/h/m^3) it was 4% below the last surface flashover voltage.
7. This sequence was repeated for each sample with the series of tests ending once surface flashover voltage values decreased to a minimum or until 10 consecutive surface flashovers. To ensure repetition and consistency of results, for each configuration five tests were performed.

3 RESULTS AND DISCUSSION

3.1 RELATIONSHIP BETWEEN CONTAMINATION DENSITY AND WIND

It is a well-known fact that wind speed and direction affect the rate of accumulation of contaminants on outdoor insulator surfaces. However, during periods of high wind, some parts of the contaminants can be removed from the insulator surface. This removal process does not have a substantial impact on surface flashover voltage. To establish the relationship between contamination density and wind speed along the

insulator leakage distance, two conditions were configured. For the first configuration, the insulator was hung vertically in the environmental chamber and the deposition of saline contamination and direction of the wind blew perpendicular to the insulator. For the second configuration, the insulator was hung horizontally and the saline contamination injection and the wind blew parallel to the insulator. The angle between the insulator axis and wind direction was defined as θ. This means that, when θ=0^0, the insulator was parallel to the wind direction and, at θ=90^0, it was perpendicular to the wind direction. It is clearly shown in Figure 3 that at θ=90^0 the contamination density increased with an increase of wind speed on the upwind side and a decrease on the downwind side, both on the lower and upper surfaces of the insulator weather sheds. When the wind speed was higher than 10 m/s, the contamination density tends to be constant on the lower and upper surfaces of insulator weather sheds. The contamination density along the insulator leakage distance was discontinuous and non-uniform. The contamination densities were also different on the upper and lower surfaces of the weather sheds. In fact, at a wind speed of 12 m/s the contamination densities values were almost constant on the upwind and downwind sides on the insulator's upper surface, at 0.363 mg/cm^2 and 0.295 mg/cm^2, but on the lower surface, these values were 0.075 mg/cm^2 and 0.069 mg/cm^2 respectively.
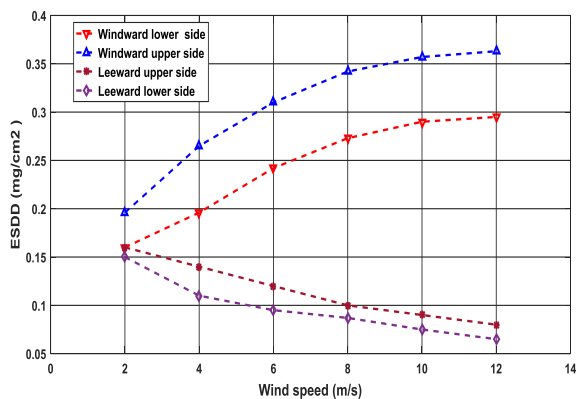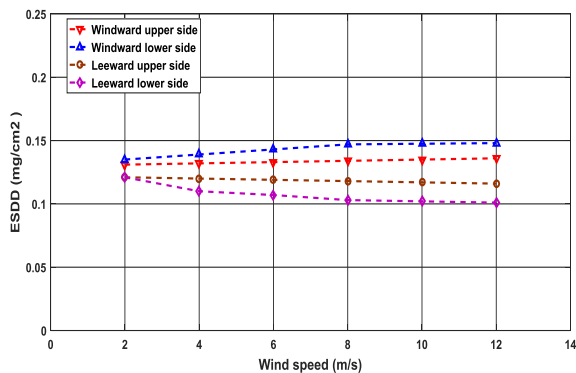
such as at θ=0^0, the contamination density on the upwind and downwind sides were almost the same: 0.143 mg/cm^2 and 0.139 mg/cm^2 on the upper surface and 0.121 mg/cm^2 and 0.11 mg/cm^2 on the lower side of the weather sheds, as shown in Figure 4. On the other hand, the values were much smaller when compared to the insulator axis and wind direction were at θ=90^0.

3.2 DISTORTION OF INSULATOR WEATHER SHEDS IN STRONG WIND

Near the shoreline, strong winds have a significant effect on insulator weather sheds. During the experiments, it was observed that, when the wind speed was more than 12 m/s, the sheds of the tested insulator would twist at almost 45^0 from its designed position. Figure 5 indicates that, at different wind speeds insulator sheds showed different deformation types. Initially the sheds began to distort soon after the edge began to vibrate at low frequency. As the wind speed increased the wrapping of the sheds increased and the edge of the sheds touched the next sheds.
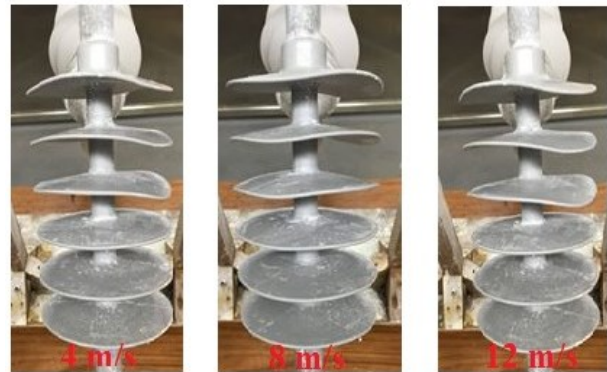
Figure 5. Deformation of sheds in strong wind.

3.3 DISCHARGE CURRENT CHARACTERISTICS PARAMETERS

Discharge current data and characteristics parameters provide details about the insulator surface conditions and degradation processes. Discharge current depends on the equivalent impedance of the contaminated insulator throughout test. During testing, the clean and dry insulator was highly capacitive with very high impedance and had a small value of discharge current with small visible discharges. Three characteristics parameters were investigated in this paper; discharge current pulse amplitude, total harmonic current distortion (THD) and intensity of pulsed discharge number.

Discharge current is related to both pollution severity and the moisture conditions of the contamination layer. In addition, discharge current density and strength also depend on water conductivity. Characteristics parameters extracted from the discharge current can therefore replicate corresponding wetting rates and SDD. Discharge current amplitude, which is exaggerated by wetting rate and SDD, can reflect the discharge arc intensity to some degree. The relationships between discharge current pulse amplitude, total harmonic distortions, wetting rate and SDD are represented by the following

**Figure 3.** Relationship between contamination density and wind speed at θ=90°.

Figure 4. Relationship between contamination density and wind speed at θ=0°.

When the wind direction was parallel to the insulator axis,

equations:

$$I_a = \left(\left| i(t)_{\max} \right| \right) \qquad (1)$$

$$Q = +(i \geq 3i_{avg} \,) \qquad (2)$$

$$THD = \frac{\sqrt{\sum\limits_{n}^{\infty} I_n^2}}{I_1} \qquad (3)$$

where I_a is the highest amplitude of discharge current waveforms, $i(t)$ is the discharge current, i_{avg} is the average value of discharge current, I_n is the nth order harmonic for n=2, 3… 11, I_1 is the fundamental component, Q represents the concentrated pulsed discharge and total harmonic distortion (THD) describes the distortion of discharge current waveforms. The 100 kS/s sampling rate was used to analyse the results.

It is a fact that the natural moist rate of a contaminated insulator varies with climate conditions. In some climate conditions, the moist rate is rapid, but in others, it can be slow. Discharge current increases with the increase in the moisture level. Once, dampness reaches saturation, the discharge current increases to its highest value. In order to investigate the influence of the moisture rate to the discharge current, the test has been done both with cold fog and with rainfall separately.

Before the contamination test, the composite insulator was tested without contamination. No flashover occurred in uncontaminated conditions on the composite insulator at 2 ^{0}C and 100% humidity level, but above 33 kV small visible discharges were followed by surface leakage current waveforms of less than 2.5 mA.

In Figure 6, the discharge current magnitude indicates the level of resistance of contamination degree, which is a function of the level of wetting rate. It can be inferred from Figure 6 that, discharge current magnitude changes with the variation of wetting rate and contamination degree. However, the amplitude is different under cold fog and rainfall wetting rates. In both cases, at lower wetting rates of up to 3.0 kg/h/m³, contaminant composition has no significant influence on discharge current amplitude. The amplitude increases linearly with the increase in wetting rate and SDD. It can be assumed that, with certain values of SDD, resistances of different contamination layers were constant at low wetting rates because of low discharge current and weak heating effect. At moderate wetting rates, the amplitude increases in a non-linear fashion, and there is an obvious distinction between cold fog and rainfall at different values of SDD. At higher wetting rates, amplitude under cold fog increases more rapidly when compared with rainfall at the same wetting rates. This reveals that the capacity of moisture absorption in cold fog is stronger than rainfall above 4.0 kg/h/m³. As a result the strong moisture absorption capacity of cold fog, lower contamination layer resistance occurs, with more moisture absorbed. Thus, with constant electrolytic content, a higher discharge current flows and heats the polluted insulators surface. The comparisons
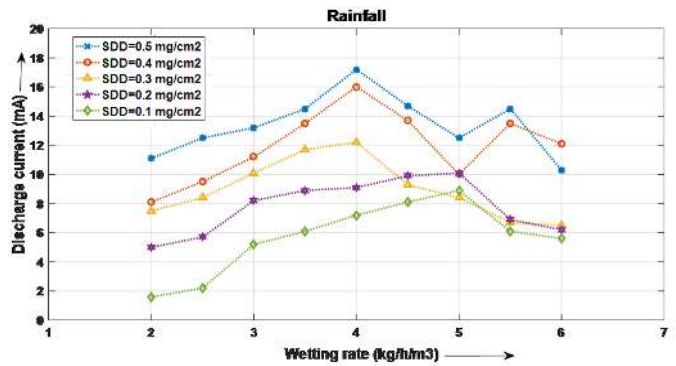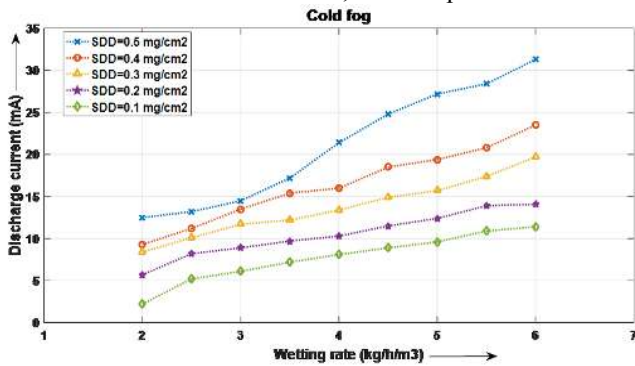

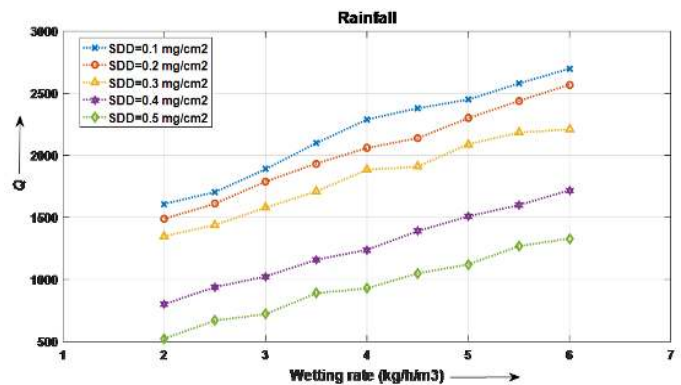**Figure 6.** The relationships between discharge current, wetting rate, and SDD.
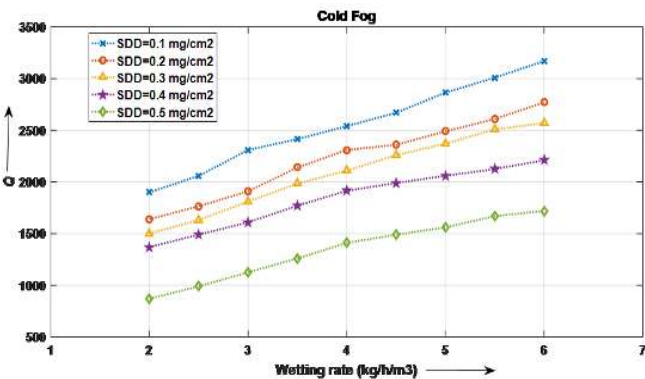

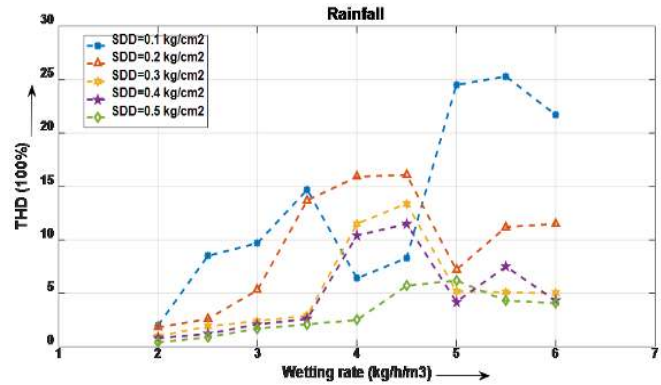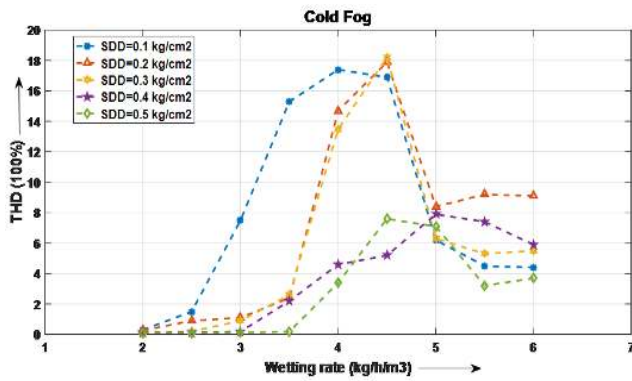**Figure 7.** The relationships between Q, wetting rate, and SDD.

Figure 8. The relationships between THD, wetting rate, and SDD.

between the cold fog and rainfall ensures that the discharge current amplitude during rainfall is much lower than in cold fog. From these results, the following points can be concluded: Discharge current amplitude in heavy rainfall is much lower than in cold fog as heavy rainfall can clean the contamination on the insulator surfaces. The value of SDD on the insulator surfaces can therefore be two or three times lower than in cold fog conditions. This action can take some time and the current starts to increase and rapidly decrease again because of the insulator surface cleaning, which makes the surface hydrophobic so that no continuous water film is formed. However, in slow absorption rate especially in the form of cold fog, the discharge current rise starts soon after the contamination layer starts in saturation. Because of slow wetting rate, the contamination layer becomes more soluble, meaning that soluble contamination results in a higher discharge current. Figure 7 shows the relationships between wetting rate, SDD and pulsed number Q, while Figure 8 indicates the relationships between wetting rate, SDD and THD. Analysis of discharge current is performed to examine its harmonic contents at different stages prior to the occurrence of surface flashover on polluted insulators during rainfall and cold fog generation. Figure 7 shows the harmonics contents on the insulator in cold fog and rain during the various stages of discharge current development. It is revealed that, there is an increase in the 5th harmonic component due to occurrence of small visible discharges prior to complete surface flashover.

3.4 EFFECT OF RAINFALL AND COLD FOG ON FOV

As a result of increasing environmental contamination, water conductivity in the air is becomes an important factor for the flashover performance of polluted insulators. Figure 9 shows the variation in the average value of the surface flashover voltage in rain and cold fog as a function of the surface contamination conductivity. These results show that surface flashover voltage decreases in a nonlinear manner and that is slightly affected at relatively high conductivities. The hypothesis is that, at higher conductivity levels, the speed of arc propagation increases and causes the surface flashover.

Experiments revealed that the condensation processes of the insulator in artificial rainfall and cold fog are different. In rainfall, most parts of the top surface and outward parts of the bottom surface of the weather sheds became wet easily. Whereas, the lower surface and parts near the end fitting of the fiberglass reinforced polyester (FBP) rod were not easy to get wet, so that dry bands developed across this area. In this condition, the saline is dissolved on the upper surface, and surface partial discharge commonly appears on the upper side of the weather sheds. Thus, in artificial rain, the dry bands were much extended and needed very high voltage to be crossed by a local arc. When a local arc developed, elongated and propagated along the shed to the lower surface, discharges became connected, ultimately causing surface flashover. In artificial cold fog, the insulator sheds gradually become damp and the surface wetting is relatively uniform, while the surface resistance distribution along the insulator is also even. Dry bands appear because of heat produced by leakage current. Generally, dry bands are formed in locations on insulator surfaces where the density of leakage current is high. Thus, dry bands easily cause partial discharges and electric field alteration and, consequently, cause lower surface flashover than in rainfall.
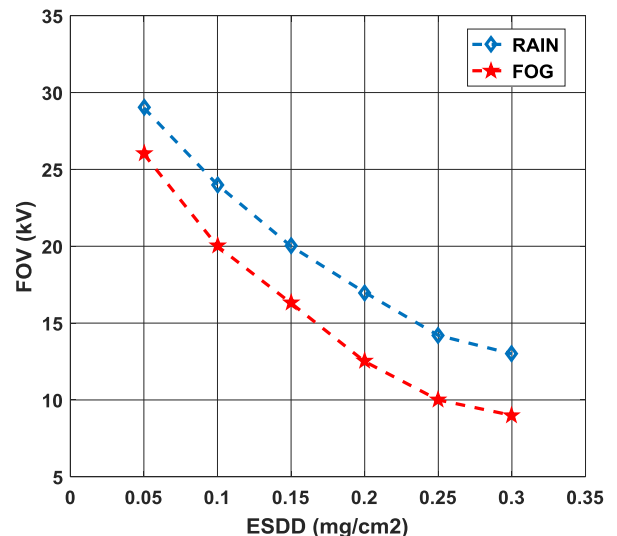

Figure 9. Surface FOV with cold fog and rainfall.

As shown in Figure 9, in cold fog, surface flashover voltage decreases more than in rainfall at constant wetting rate. It also shows that for relatively high wetting rates, surface flashover voltage is slightly affected by the increase in wetting rate and has the same kind of saturated trend even though, there are variations in surface flashover voltage under different wetting rates. When wetting rates are low, the decrease in surface flashover voltage is significant: up to 27.3% for cold fog and 19.5% for rainfall, but only 14.4% for cold fog and 9.1% for rain at a higher wetting rate. To identify the reason for this, the hypothesis is that heavy rain can clean the contamination on insulator surfaces. Meanwhile, for the slow rate of wetting and higher salt absorption rate, especially in the form of cold fog, serious surface degradation can result. Consequently, this leads to further decreases in surface flashover voltage.
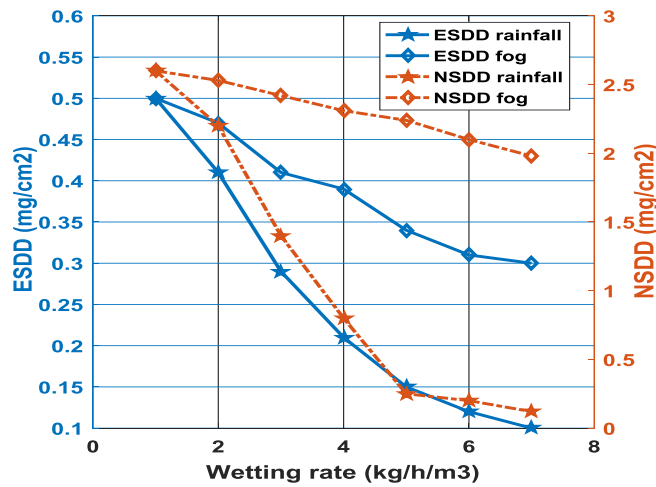

Figure 10. Contamination deposit densities after 20 minutes of wetting.

After each test, the ESDD and NSDD values were measured on the insulator surfaces; it was found that, at lower wetting rates the ESDD values in rainfall were lower than in cold fog by 34.7%, while the NSDD in rainfall was lower than that of cold fog by 21.6 %. This was caused by both wetting rate and duration. In each experiment, the rainfall rate was 30% lower than in cold fog, and the rainfall duration was 25% less than in cold fog. It is evident that the effects of rainfall rate and duration on contamination deposits are more significant than those with cold fog. Therefore, contamination deposit density decreases significantly when rainfall rate is within a certain range, and tends to be stable after that. Thus, it is clear that the washing effect on insulator contamination is greater in rainfall than in cold fog at the same wetting rate, as shown in Figure 10.

3.5 IMPACT OF POLLUTION LEVEL AND WETTING RATE ON FOV

The relationship between SDD and surface conductivity is different for same materials with different wetting rates. For the same materials, the surface conductivity values are much higher for hydrophilic materials such as EPDM, glass and porcelain with different wetting rates than for hydrophobic materials such as silicone rubber [18]. Experiments were carried out in the environmental chamber to investigate the relationship between SDD and wetting rate on surface flashover voltage. The experiments were conducted on the four types of insulators listed below in Table 1, through the method mentioned before.

Table 1. Parameters of Insulators.

Insulator Type	Leakage distance (cm)	Shed spacing (cm)	Shed diameter (cm)
Silicone rubber	30	2.5	10
EPDM	24	2	8
Glass	21	1.6	11
Porcelain	18	1.3	14

The nature of cold fog and rain has different performance under various environmental stresses and geographical positions. The impact of pollution level and wetting rate of artificially cold fog and rain on the surface FOV of the polluted insulator were considered in this study. The results were experimentally obtained for different contamination levels and wetting rates. The average standard deviation of FOV under pollution levels and wetting rates was measured using equations (4) and (5) that derived from Fick's second law and presented below:

$$FOV \propto P_s^{-\alpha} \times C_w \tag{4}$$

$$FOV \propto W_r^{-\beta} \times C_p \tag{5}$$

where, C_w and C_p are constants for wetting and pollution respectively, P_s is the pollution severity, α accounts for the impact of pollution severity on FOV at a constant wetting rate, W_r is the wetting rate and β accounts for the influence of the wetting rate on the FOV at constant SDD.
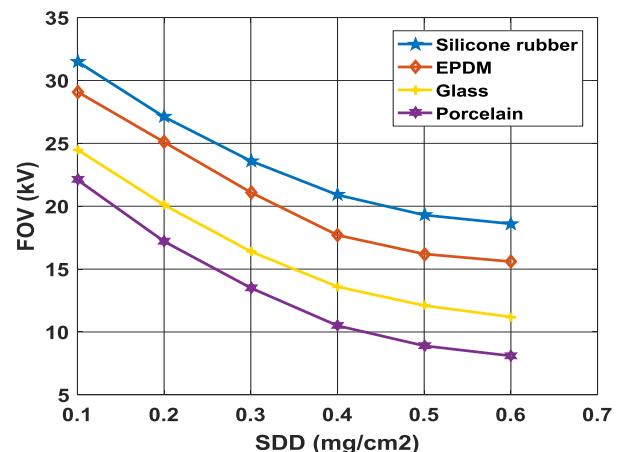

Figure 11. Surface flashover voltage at constant wetting rate.

The FOV on tested insulators was measured under two different conditions. In the first scenario, FOV was measured at a constant wetting rate and variable contamination severities. In the second scenario, the value of contamination was constant but the wetting rate was variable. Figure 11 indicates the measured FOV for each contamination severity at constant wetting rates (2.0 kg/h/m^3). The results confirm a strong reduction in flashover voltage caused by increasing contamination levels. It clearly shows that SDD influences the surface flashover voltage whatever the wetting rate is. It is also observed that the insulator in its most vulnerable condition at the highest value of pollution severity when the contamination layer is fully wet. It can also be inferred from Figure 11 that the FOV steadily decreases from lower to higher pollution levels. However, at higher SDD values, the rate of FOV increase becomes less and less ranging between 0.4 and 0.6 mg/cm^2. This can be explained by the increasing pollution severity and constant wetting rate.

Flashover voltages were measured at different wetting rates and at constant SDD (0.3 mg/cm^2). The stated results, which are the average values of surface FOV versus wetting rate, are shown in Figure 12. In this figure, a little change in the surface FOV at a smaller wetting rate is observed. This can be linked to the hydrophobic properties of polymeric materials. However, the FOV at a higher wetting rate is as much as two to three times lower than at a lower wetting rate.
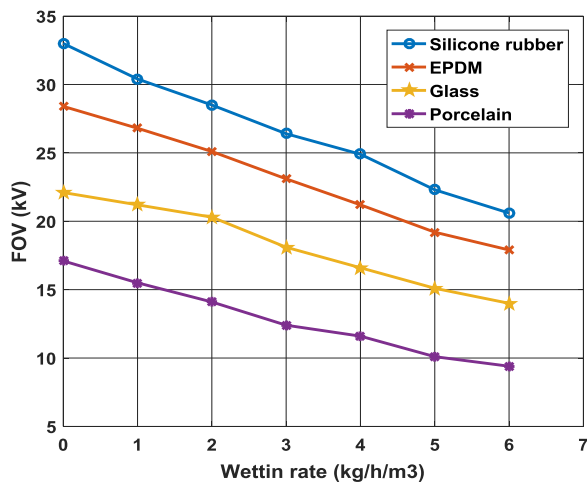

Figure 12. Surface flashover voltage at constant SDD.

Figure 12 shows that, at a higher wetting rate, some of the contamination layer is gradually wiped off on the insulator surfaces. This causes the setting of a discontinuous non-uniform contamination layer on the insulator surface, resulting in the production of non-uniform heating along the insulator surface, significantly increasing surface leakage current. Joule heating causes more water evaporation, leading to the formation of dry bands where the current density is highest. The electric field strength in the electrolytes increases, supported by various dry band regions along the insulator. This significantly increases the surface leakage current and decreases the surface flashover voltage.

CONCLUSIONS

In this two-part paper series, a model is presented to introduce a new phenomenon related to saline transportation and deposition on high voltage outdoor insulators near the shoreline. Through analysis of characteristics and mechanisms of saline transportation and deposition, surface flashover is predicted under various environmental stresses near the shoreline. From the results obtained, the following conclusions can be drawn:

1. Pollution accumulation rate on insulator surfaces increases with increased wind velocity and decreases with the increased distance from the shoreline to inland. However, when the wind speed is higher than 10 m/s, contamination density tends to be constant.
2. Contamination densities on insulator surfaces increase with increased aerosol speed at the windward side on the upper and lower surfaces of weather sheds and decreases at the leeward side.
3. Strong winds (above 12 m/s), can deform and damage the insulator's weather sheds.
4. Comparison between cold fog and rainfall shows that discharge current amplitude in rainfall is much lower than in cold fog. However, under certain conditions, the discharge current in rainfall can exceed those in cold fog. This unexpected phenomenon may take place in rainfall, when the difference in temperature is large and the discharge current increases.
5. Surface flashover voltage in rainfall is two to three times lower than in cold fog. The hypothesis is that heavy rainfall can clean contamination on insulator surfaces, while slow wetting rate and higher absorption, especially in the form of cold fog, can cause lower surface flashover voltages.
6. It was also observed that the SDD influences surface flashover voltage regardless of the wetting rate.

REFERENCES

[1] M. El-A Slama, H. Hadi, and S. Flazi, "Investigation on influence of salts mixture on the determination of flashover discharge constant Part I: A Preliminary Study," IEEE Conf. Electr. Insul. Dielectr. Phenomena, pp. 674-677, 2008.
[2] W. Sima, T. Yuan, Q. Yang, K. Xu, and C. Sun, "Effect of nonuniform pollution on the withstand characteristics of extra high voltage suspension ceramic insulator string," IET General Trans. Distribution, Vol. 4, No. 3, pp. 445-455, 2009.
[3] I. Kimoto, T. Fujimura, and K. Naito, "Performance of insulators for direct current transmission line under polluted condition," IEEE Power Eng. Soc., pp. 944-949, 1972.
[4] K. Naito, K. Morita, Y. Hasegawa, and T. Imakoma, "Improvement of the dc voltage insulation efficiency of suspension insulators under contaminated conditions," IEEE Trans. Dielectr. Electr. Insul., Vol. 17, No. 4, pp. 1025-1032, 1988.

[5] T. Seta, N. Arai, and T. Udo, "Natural pollution test of insulators energized with HVDC," IEEE Trans. on Power App. and Syst., Vol. 93, No.3, pp. 878-883, 1974.

[6] I. Kimoto, T. Fujimura, and K. Naito, "Performance of Insulators for direct current transmission line under polluted condition," IEEE Trans. on Power App. and Syst., Vol. 92, No.3, pp.943-949, 1973.

[7] M. N. Horenstein, and J.R. Melcher, "Particle contamination of high voltage DC insulators below corona threshold," IEEE Trans. Dielectr. Electr. Insul., Vol. 14, No. 6, pp. 297-305, 1979.

[8] W. Lampe, T. Hogluend, C. Nellis, P. Renner, and R. Stearns "Long-term tests of insulators under natural pollution condition at the big eddy test center," IEEE Trans. Power Del., Vol. 4, No.1, pp. 248-258, 1989.

[9] E. Nasser, "Contamination flashover of outdoor insulation," ETZ-ABD, Vol. 93, No. H-6, 1972.

[10] S. Huafeng, D. J. Zhidong, C. G. Zhicheng, and L. Licheng, "Mechanism of contaminant accumulation and flashover of insulator in heavily polluted coastal area," IEEE Trans. Dielectr. Electr. Insul., Vol. 17, No. 5, pp. 1635-1641, 2010.

[11] Z. Fuzeng, J. Zhao, M. L. Wang, and C. G. Zhicheng, "Experimental investigation on outdoor insulation for DC transmission line at high altitudes," IEEE Trans. Power Del., Vol. 25, No. 1, pp. 351-357.

[12] IEEE standard techniques for high voltage testing (Std. 4-1987), New York, U.S.A.

[13] F, A. M. Rizk, and S. I. Kamel, "Modeling of HVDC wall bushing flashover in non-uniform rain," IEEE Trans. Power Del., Vol. 6, No. 4, pp. 1650-1662, 1991.

[14] R. Sundararajan, and R. S. Gorur, "Dynamic arc modeling of pollution flashover of insulators under dc voltage," IEEE Trans. on Electr. Insul., Vol. 28, No. 2, pp. 209-219, 1993.

[15] M. M. Hussain, S. Farokhi, S. G. McMeekin, and M. Farzaneh, "Effect of Cold Fog on Leakage Current Characteristics of Polluted Insulators," IEEE 2nd Int. Conf. on Condition Assessment Techniques in Electrical Systems (CATCON), pp.163-167, 2015.

[16] P. J. Lambeth, "Variable-voltage application for insulator pollution tests," IEEE Trans. Power Del., Vol. 3, No. 4, pp. 2103-2111, 2002.

[17] C. H. A. Ely, R. G. Kingston, and P. J. Lambeth "Artificial and natural pollution tests on outdoor 400 kV substation insulators," Proc. IET, Vol. 118, No. 1, pp.99-109, 1971.

[18] A. de la O, R.S. Gorur, and J. T. Burnham, "Electrical performance of non-ceramic insulators in artificial contamination tests. Role of resting time," IEEE Trans. Dielectr. Electr. Insul., Vol. 3, pp.827-835.

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