Risk assessment of desert pollution on composite high voltage insulators

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ABSTRACT

Transmission lines located in the desert are subjected to desert climate, one of whose features is sandstorms. With long accumulation of sand and with the advent of moisture from rain, ambient humidity and dew, a conductive layer forms and the subsequent leakage current may lead to surface discharge, which may shorten the insulator life or lead to flashover thus interrupting the power supply. Strategically erected power lines in the Egyptian Sinai desert are typically subject to such a risk, where sandstorms are known to be common especially in the spring. In view of the very high cost of insulator cleaning operation, composite (silicon rubber) insulators are nominated to replace ceramic insulators on transmission lines in Sinai. This paper examines the flow of leakage current on sand-polluted composite insulators, which in turn enables a risk assessment of insulator failure. The study uses realistic data compiled and reported in an earlier research project about Sinai, which primarily included grain sizes of polluting sand as well as their salinity content. The paper also uses as a case study an ABB-designed composite insulator. A three-dimensional finite element technique is used to simulate the insulator and seek the potential and electric field distribution as well as the resulting leakage current flow on its polluted surface. A novel method is used to derive the probabilistic features of the insulator’s leakage current, which in turn enables a risk assessment of insulator failure. This study is expected to help in critically assessing – and thus justifying – the use of this type of insulators in Sinai and similar critical areas.

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Introduction

Leakage current on polluted insulators’ surface is a major cause of insulation failure in high voltage power lines. Maintenance of those lines thus necessitates the periodic cleaning the insulators’ surfaces, which is known to be a costly operation. The magnitude of leakage current on a polluted insulator depends on pollution severity and the contamination salinity, which subsequently affects the conductivity of the contamination layer. With thousands of kilometers of transmission and subtransmission lines in Sinai, rather than relying on the costly insulator washing, composite insulators are nominated to be used instead of ceramic insulators. Composite insulators are now widely used worldwide because of their lower weight, higher mechanical strength, higher design flexibility, and their reduced maintenance. They display lower leakage current due to their higher surface resistance [1,2]. Silicone rubber – used to fabricate insulators – can provide long-term and satisfactory service even under polluted and wet conditions. This is due to its long-term hydrophobic surface properties. The hydrophobic
surface inhibits the formation of a continuous water film and the flow of leakage current along the surface. This blocks the initiation of dry band arcing that leads to flashover. In a study by Zhang and Hackam, the strong relation between hydrophobicity and high surface was established when high temperature vulcanized (HTV) silicone rubber rods were subjected – under high voltage – to accelerated wetting in salt-fog and immersion in a saline solution [3]. The surface resistance was measured and found to depend on the duration of the exposure to the salt-fog without electric stress, the duration of the exposure to combined salt-fog and electric stress, and the specimen length.

The pollution layer accumulated on the insulator surface during normal desert atmospheric weather has a thickness that depends on the type of soil in this region and on the polluting sand grain sizes. When sand is deposited on insulator surface and in the presence of a major source of wetting, such as dew in the early morning, leakage current would flow on the surface. Conductive sand areas are then heated, and dry bands are formed leading to possible surface flashover [4].

Relevant previous work in this area included estimating the current density distributions along polluted insulator surface, using surface charges simulation method [5]. Other studies simulated the leakage current while accounting for amount of salt in the contamination layer [6]. Other experimental studies were made on the effect of desert pollution on polymeric insulator [7,8]. In another study, leakage current was estimated using the FEMLAB software with different conductivities of contamination layer [9].

This paper aims to investigate the prime factor responsible for initiating insulator failure under power-frequency voltage, namely leakage current flowing through surface pollution.

Insulator simulation was carried out using an accurate 3-D ANSYS software program, which is based on the Finite Elements method. The program required higher performance computing and gave results with high accuracy. The ratings of transmission lines in Sinai are mainly 500 kV, 220 kV, and 66 kV. A typical two-shed insulator, which may be used on 220 kV power lines is used as a case study. Such leakage current distributions are determined with different sand grain thickness and with different sand conductivities. Realistic data are used, which are based on sand samples collected from Sinai desert near present and future transmission lines' corridors and were reported by an earlier study [10]. In that study, the statistical distributions of sand grains size in the desert soil were acquired from random samples, where their salinity and subsequent conductivity were measured. Based on the calculated influence of sand grain size and salinity on the resulting leakage current, statistical distribution mapping was carried out to produce the overall probability density distribution of leakage current. The cumulative statistical distribution of leakage current was then employed to assess the risk of insulator failure.

**Methodology**

**Insulator computational model**

This paper uses a 220 kV ABB silicone rubber insulator as shown in Fig. 1a; its dimensions are given in Table 1. The UNIGRAPHICS program was used to create the insulator model in 3-D and export it to the ANSYS program, where the material of the insulator was defined to be silicone rubber, as shown in Fig. 1b. In ANSYS program, appropriate finite-element meshes were then used for analysis, where the potentials at the ends of the insulator were ground at one end and the peak phase voltage $220 \times \sqrt{2} = 311.06$ kV at the other side.

**Sample insulator sector**

It is both a tedious task and unnecessary to micro-analyze the leakage current distribution along the entire insulator. Instead, a sample sector of the insulator was selected, where the boundary conditions (local potential and electric field) resulting from those conditions were placed around that sector. The insulator sector has two sheds; one shed is long and the other is short with a total creepage distance of 186.14 mm. The leakage current density materialized on the insulator surface as then sought by means of ANSYS. Unigraphics was used to simulate this sample insulator sector as shown in Fig 1c. The directional components $x$ and $y$ of leakage current density were obtained, from which the tangential (surface) current subsequently resulted.

**Results and discussion**

**Effect of contamination layer thickness**

The selected sample insulator simulation section of Fig. 1c was subjected to the boundary conditions, where the potentials on the two ends of the sample sector – as acquired from the global analysis – were 54.196 kV and 49.828 kV.

Based on the statistical distributions of sand grain sizes in Sinai – reported in an earlier study [10] – sand grains with diameters in the range of 1–2 mm prevailed. Therefore, this
study takes this range of grain sizes and assumes that enough accumulation creates a contamination layer of an equal thickness. Furthermore, chemical analysis carried out on acquired samples determined the equivalent salt content (ESC, in mg of salt/g of sand) of the pollution layer. It was observed that a range of salinity of 0.5–1.5 mg salt/g sand was the most likely to exist in Sinai.

To convert the salt content expressed in ESC (mg of salt/g of sand) – as produced by the chemical analysis – into pollution layer electrical conductivity (S/m), the solution salinity is first obtained from the expression [11]:

\[ S_a = 10^{-3} \times \text{ESC} \times Q \]  

\( S_a \) is the salinity of the solution. \( Q \) is the amount of sand deposited on insulator surface with a certain amount of water.

Layer salinity is then related to electrical conductivity of such solution is determined [12]:

\[ S_a = (5.7 \times \sigma_{20})^{1.03} \]  

\( \sigma_{20} \) is the conductivity at a temperature of 20 °C in (S/m).

Using the theories of lattice geometry, the quantity \( Q \) can be expressed as:

\[ Q = \left[ \frac{\lambda}{1 - \lambda} \right] \times \rho \]  

where \( \lambda \) is the lattice arrangement density, which is the proportion of the actual amount of particles (sand) that occupies a given space; \( \rho \) is the specific gravity of wet sand (1.92 g/ml).

The parameter \( \lambda \) was calculated to fall in the range from 0.523 to 0.740 depending on the level of compactness [11].

The former value is much more realistic since sand will deposit of the insulator surface in a rather loose fashion and it is, therefore, not likely to deposit in an orderly space-optimized manner. The lattice arrangement density \( \lambda \), in this work, is thus chosen as 0.523.

The above values give a realistic \( Q \) value = 2.1 g/ml.

The above relations were applied over the reported range of ESC to obtain the corresponding electrical conductivity. Table 2 shows the different conductivity of sand grain collected from Sinai desert according to its ESC range using the value \( Q = 2.1 \) g/ml.

These values were readily used in polluted insulator simulation in seeking the statistics of tangential electric field along composite insulator, which drives the leakage current. The effects of those conductivities in each contamination layer on the leakage current density on insulator surface were sought.

As an example, Fig. 2a shows the leakage current density distribution over the creepage distance for a 1 mm contaminating layer thickness and with 284.9 \( \mu \)S/cm contaminant conductivity. By surface integrating current densities, the overall surface leakage current was found to be 54.6 mA.

Figs. 2b–2d depict the effects on the surface distribution of leakage current density of different conductivities in a 1, 1.5, and 2 mm contamination layers, respectively. Surface integration was numerically performed to produce the surface leakage currents in the above cases. The results are summarized in Table 3.

Interdependence of leakage current on sand grain size and conductivity

Leakage current intensities are seen to depend on changes in the polluting sand’s salinity (and hence conductivity) and grain size.
Based on the above results, the relation between leakage current and conductivity with different sand grain sizes, or layer thickness, was numerically derived and is shown in Fig. 3a. Similarly, the relation between leakage current and grain size with different sand conductivities was produced and is shown in Fig. 3b.

The joint dependence of leakage current on sand grain size and on surface conductivity is the key to eventually deriving the overall statistics of leakage current, on which the insulator’s failure risk assessment is based. This joint dependence has been numerically derived using all available data and results. Its general features are graphically seen in Fig. 3c.

Leakage current has been shown to depend on both the sand’s contamination layer thickness and on its salinity and hence its electrical conductivity. The above two variables were reported to be random and may thus be expressed in statistical terms. Subsequently, the leakage current can also be viewed as a random variable, whose probability density distribution is inevitably a product of the probability density distributions of the

| Table 2 | Conductivity of deposited wet sand layer estimation. |
|---------|-----------------------------------------------------|
| Equivalent salt content (ESC) (mg salt per g sand) | Salinity ($S_a$) (mg/ml) | Conductivity ($\sigma_{20}$) ($\mu$S/cm) |
| 0.5 | 1.05 | 284.9 |
| 1.0 | 2.10 | 558.4 |
| 1.5 | 3.15 | 827.8 |

| Table 3 | Leakage current in mA for different layer thickness and conductivity. |
|---------|-----------------------------------------------------|
| Layer thickness (mm) | Conductivity |
| | 284.9 $\mu$S/cm | 558.4 $\mu$S/cm | 827.8 $\mu$S/cm |
| 1.0 | 54.60 | 96.00 | 140.87 |
| 1.5 | 56.23 | 98.34 | 145.78 |
| 2.0 | 58.93 | 115.5 | 171.22 |

Risk assessment of leakage current-based insulation failure

Leakage current has been shown to depend on both the sand’s contamination layer thickness and on its salinity and hence its electrical conductivity. The above two variables were reported to be random and may thus be expressed in statistical terms. Subsequently, the leakage current can also be viewed as a random variable, whose probability density distribution is inevitably a product of the probability density distributions of the
pollution layer conductivity and that of the pollution layer thickness, which is – in turn – dictated by the sand grain size.

The two variables, conductivity \( c \) and sand grain size \( g \), are reasonably assumed to be statistically independent. If the probability distributions of the conductivity and sand grain size are, respectively, \( p(c) \) and \( p(g) \), then the probability distribution of leakage current \( p(I) \) would be

\[
P(I) = P(c) \times P(g)
\]

From the sand samples collected from regions in different places in the desert, the frequency of occurrence distribution of the equivalent salt content ESC (mg of salt/gm of sand) could subsequently be built as shown in Fig. 4a. Fig. 4b subsequently shows the probability density distribution of the sand conductivity \( p(c) \). In the following sections, statistical distributions were sought to describe the randomness of different variables (variables) relevant to this paper. In each case, a goodness-of-fit test was performed using MATLAB to select the statistical distribution that best fits the variable. A brief account of the characteristics of each selected distribution is given in each case.

Search was made for the standard probability function that best fits the distribution of sand conductivity and was found to be the Beta distribution. The Beta distribution is a family of continuous probability distributions parameterized by two positive shape parameters, denoted by \( \alpha \) and \( \beta \), where the degree of skewness is highly dependent on these parameters making this distribution versatile and may accommodate various physical effects such as those seen with surface conductivity. It is, therefore, very suitable for the case at hand. It is expressed by:

\[
P(c, \alpha, \beta) = \frac{(\alpha + \beta - 1)!}{(\alpha - 1)!(\beta - 1)!} c^{\alpha - 1}(1 - c)^{\beta - 1}
\]

whose parameters are \( \alpha = 3.0818 \) and \( \beta = 0.547 \); its mean is 298.7 \( \mu \)S/cm, and the standard deviation is 557.4 \( \mu \)S/cm with a square error = 0.003504.

Fig. 4c shows the frequency distribution of sand in Sinai and the associated probability density distribution of the sand grain size \( p(g) \). Search was made for the standard probability function that best fits that distribution and was found to be the log-normal distribution. A log-normal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. A variable might be modeled as log-normal if it can be thought of as the multiplicative product of many independent random variables each of which is positive. The distribution is always skewed toward...
lower values as it is in the case study, where the degree of skewness increases as the relative standard deviation increases. It is expressed by:

\[
P(x; \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad x > 0
\]  

whose mean is 0.401 mm, and the standard deviation is 0.346 mm with a square Error = 0.110271.

**Deriving the leakage current probability distribution**

Since – based on the above results – no analytical formulation for the resultant leakage current probability density distribution \( p(I) \) could be derived, an alternative way was to use the Monte Carlo technique. Monte Carlo simulation is a computerized mathematical technique that permits accounting for risk in quantitative analysis and decision making. It performs risk analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from the probability functions. Depending upon the number of uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete. Monte Carlo simulation produces distributions of possible outcome values. By using probability distributions, variables can have different probabilities of different outcomes occurring. It is emphasized in this paper that probability distributions are a much more realistic way of describing uncertainty in variables of a risk analysis.

This procedure is diagrammatically described in Fig. 5. Random numbers \( R_g \) and \( R_i \) were first numerically generated. Random values of contamination layer conductivity \( c_i \) and layer size \( g_i \) were in turn generated. Random magnitudes of leakage current \( I_i \) using the two random \( c_i \) and \( g_i \) values were then generated using the numerical techniques described in this paper.

Using large enough generated sample of \( I_i \) values, the overall probability density distribution of leakage current was produced and is shown in Fig. 6a. Search was made for the standard probability function that best fits that distribution and was found to be the Weibull distribution. The Weibull distribution has the ability to assume the characteristics of many different types of distributions. This has made it extremely popular among engineers and quality practitioners, who have made it the most commonly used distribution for modeling reliability data. It is flexible enough to model a variety of data sets, and having displayed the best fit to the present case study, it has been adopted. It is expressed by:

\[
P(x; \lambda, k) = \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}, \quad x > 0
\]  

whose parameters are \( \lambda = 49.7 \) and \( k = 0.344 \); its mean is 67.5 mA, and the standard deviation is 21 mA with a square error = 0.018915.

The above leakage current, whose mean value is 67.5 mA, describes the actual expected leakage current for this particular case study, i.e., the specified insulator with those prevailing pollution conditions mentioned in the paper. Other insulators under different conditions would produce other statistics.
However, it is advisable for the electric power utility to assess the danger of a leakage-current-based insulator breakdown in a probabilistic—rather than deterministic—way. In other ways, the degree of uncertainty in predicting a flashover is to be estimated. In this case, reliance is not on the estimated mean leakage current (67.5 mA) but rather on its statistical distribution. The mean current is, therefore, not particularly marked in Figs. 6a and 6b since the distribution of risk is of value.

**Risk failure calculation**

Research has consistently shown that the magnitude of leakage current is a reliable predictor of insulator surface discharge and the ultimate insulator failure. Therefore, the probability distribution of leakage current can be used to assess the risk of insulator failure.

Based on the probability density distribution, the cumulative probability of the leakage current can be produced.

A critical magnitude of leakage current may be set by the electricity utility as that, beyond which insulator failure is imminent. The cumulative probability function then indicates the chances for that set leakage current value to be exceeded, and hence, it also indicates the chances for insulator failure to occur. Fig. 6b displays the final result of the present case study. For the given insulator, placed in the presently defined environment, and under the given power line voltage (220 kV), the figure gives—for any arbitrarily set value of critical leakage current—the risk of having an insulator failure under desert pollution conditions. For example, a set critical leakage current magnitude of 100 mA reflects a 60% chance of insulator failure.

**Conclusions**

1. Under conditions of desert pollution and wetness, the leakage current density along the contaminated layer on composite insulator for a given contaminant layer thickness and salinity (hence, conductivity) was computed and subsequently produced the total leakage current magnitude.
2. The interrelationships between grain size, conductivity, and leakage current were estimated. The statistics of surface leakage current that depend on the probability distribution for those two independent variables (conductivity and grain size) was produced using a Monte Carlo technique. The log-normal distribution was found to best fit the leakage current statistical distribution, with mean value of 6.75 mA and standard deviation 2.1 mA in the present study case.
3. A novel method is given to estimate the risk of flashover under pollution, where the cumulative probability density of the leakage current is used in this work as a direct tool for the risk of insulation failure.

**Conflict of interest**

The authors have declared no conflict of interest.

**Compliance with Ethics Requirements**

This article does not contain any studies with human or animal subjects.

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