LEAKAGE CURRENT SIMULATION OF A PRE-CONTAMINATED INSULATOR COVERED WITH SNOW

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Abstract: This article deals with the modeling of leakage current on pre-contaminated insulators covered with snow based on an equivalent electrical circuit developed under Alternative Transients Program (ATP) software. Finally, mathematical equations were proposed showing that the rate of leakage current depends on the ratio of polluted snow layer length to insulator length.

1. INTRODUCTION

One of the most serious problems associated with snow and ice accumulation on insulators is flashover occurrence. Although considerable research has been carried out on flashover of ice-covered insulators [1,2], less attention was devoted to flashover of insulators covered with snow. Wet snow accretion on outdoor insulators can result in a considerable reduction of their electrical performance. Study and analysis of results obtained from experimental tests show that wet snow presents a purely resistive medium with non-linear voltage and current characteristics. It was found that when the voltage along a snow layer increases linearly, the current flowing through it increases exponentially. Therefore, as the voltage across snow increases, its resistance decreases rapidly [3].

In this paper a method for predicting the leakage current and thermal losses on polluted insulators under snowing conditions is presented. From that, mathematical equations were derived showing that the rate of leakage current can be controlled by changing the ratio of the polluted snow layer length to insulator length.

2. RESULTS AND DISCUSSION

Under snowing conditions, leakage current amplitude is dependent on several parameters such as contamination level, applied voltage and snow parameters. An increase in the contamination level on the insulator surface causes leakage current to rise, leading to a rise in temperature, resulting in the formation of dry bands. The variation of leakage current under these conditions is provided in Figure 1. Snow density and water conductivity are effective parameters for leakage current. The simulation result shown in Figure 2 indicates that leakage current increases with the snow density level. Under snow conditions, the rate of leakage current is dependent on increasing contaminated snow on the insulator surface. Allowing limitation on the length of the polluted layer can drastically reduce leakage current (Eq. 1).

$$\frac{x}{L} < \left[1 + \frac{Ak\rho_P}{\eta}\left(A_P\rho - A\rho_p k\right)\right] \quad (1)$$

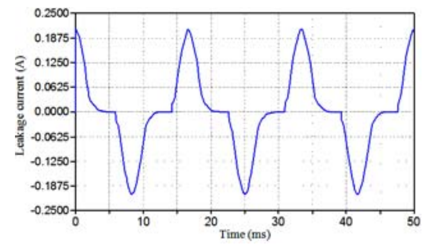

Figure 1: The leakage current on a heavily polluted insulator with dry band under snow condition.

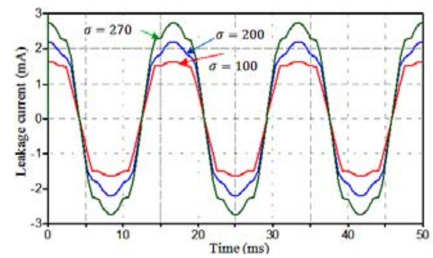

Figure 2: The variations of leakage current for three different snow density.

3. CONCLUSION

The simulated results show that leakage current increases dramatically in presence of snow on the insulator surface. It was shown that an increase in the density of snow and/or the conductivity of water melted from snow results in an increase in the current flowing through the snow.

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***Abstract*— This study deals with the modeling of leakage current on pre-contaminated insulators covered with snow. This model is based on an equivalent electrical circuit developed under Alternative Transients Program (ATP) software. The results show a drastic increase in leakage current under snow conditions. It is shown that the leakage current through snow can be expressed as an exponential function of the voltage across snow, depending on the density and conductivity of the water melted from the snow layer.**
Finally, mathematical equations were proposed showing that the rate of leakage current depends on the ratio of polluted snow layer length to insulator length.

Keywords-Insulator; Pollution; leakage current; Snow

I. INTRODUCTION

Insulators are devices which are used on electricity supply networks to support, separate or contain conductors at high voltage. All insulators have dual functions, mechanical and electrical, which commonly present conflicting demands to the designer. During operation, outdoor insulators may be subjected to certain degree of pollution in regions near industrial, agricultural or coastal areas which can gradually reduce their performance. It is widely known that snow accretion on overhead power lines affects their reliability in various ways. One of the most serious problems associated with snow and ice accumulation is insulator flashover. Although considerable research has been carried out on flashover of ice-covered insulators [1-3], less attention was paid to flashover of insulators covered with snow. It should be noted that those two types of flashover are difficult to distinguish after their occurrence, since the snow or ice covering usually drops off from the insulators shortly afterwards and the auto-reclosing devices can rapidly clear up most of the faults too. None of the above methods have considered the behaviour of polluted insulators under snow condition. Snow covered-insulator flashover resulting in occasional power outages have been reported in many countries such as Canada, United States and Japan [4-6]. These reports confirm that the presence of atmospheric snow together with superimposed contamination sometimes leads to flashover and occasional outages. Study and analysis of results obtained from experimental tests which have been carried out in CIGELE show that wet snow presents a purely resistive medium with non-linear voltage and current characteristics whereas the voltage along the snow layer increases linearly, the current flowing through it increases exponentially [7]. In this paper a method for predicting the leakage current and thermal losses on polluted insulators under snowing conditions is presented. This method is based on an equivalent electrical model simulated under the EMTP/ATP software. The simulation results demonstrate that leakage currents substantially increased under different pollution conditions. Then mathematical equations will be derived that the rate of leakage current can be restricted by changing the ratio of the length of the polluted snow layer to insulator length.

II. SNOW MODELING AND FACTORS INFLUENCING THE ELECTRICAL CONDUCTIVITY OF SNOW

In this study the behaviour of insulator under wet snow is analyzed. In the case of wet snow, it becomes a three-component system composed of air, ice, and water. Thus, it should be treated as a three-phase mixture, where ice and water particles are considered to be inclusions embedded in air. The electrical properties of snow should be altered according to its ice content and density. The parameters characterizing the nature of snow are its resistive volume, dielectric constant, salt content, water content, volume density, particle diameter, crystal structure, and impurities [8,9]. All of these parameters are significant on snow electrical behaviour but some, such as water conductivity, NaCl content, and ice density, have a special merit for the characterization of the electrical properties of snow. Study and analysis of results obtained from experimental tests carried out at the CIGELE laboratories at UQAC show that wet snow presents a purely resistive medium with non-linear voltage and current characteristics [7]. Figure 1 illustrates that when the voltage along the snow layer increases linearly, the current flowing through it increases exponentially. Therefore, as the voltage across snow increases, its resistance decreases rapidly.

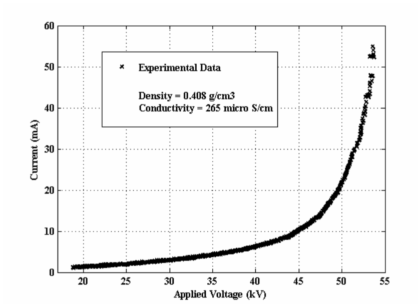


Figure 1. Voltage-current characteristic values of snow covered insulator[7].

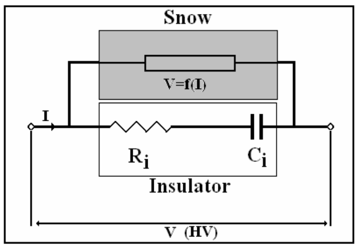


Figure 2. Equivalent electrical circuit of test objects.

Concerning the above explanation, the snow layer can be modeled as a non-linear pure resistance in parallel with the insulator model as shown in Figure 2.

III. Analysis of Leakage Current on Insulator Surface under Snow Condition

Under snowing condition, the leakage current intensity is dependent on several parameters such as the quantity of contamination, applied voltage and snow parameters. In the following analysis, the effect of snow characteristics on leakage current in various polluted conditions was simulated using the ATP software. In this simulation, a chain of four IEEE insulator units with a line voltage of 69 kV, was considered. Following that, the leakage current of the pre-contaminated insulator under snow conditions was simulated by the appropriate model.

A. Snow-covered Clean Insulator

Figure 3 shows the equivalent circuit of a clean insulator under snow conditions. This model consists of a linear resistor R and capacitor C in parallel with a non-linear resistor representing the snow part. As insulator resistance is decreased in the presence of snow the leakage current waveform raises drastically (Figure 4). As shown in Figure 4, snow has a strong effect on leakage current. The flow of leakage current on the insulator's surface causes thermal losses and a rise in temperature. Using ATP, the thermal losses on one time period frequency (f = 60 Hz) can be estimated at 0.55 joule.

B. Snow-covered Pre-polluted Insulator

Figure 5 shows a polluted insulator equivalent circuit with a non-linear resistor Rp, representing surface pollution, added in parallel to the previous one. The contaminated condition can be categorized as lightly and heavily contaminated.

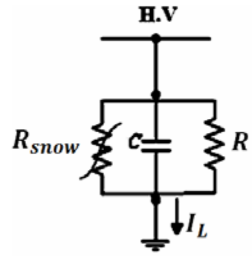


Figure 3. Model of clean insulator equivalent circuit under snow conditions.

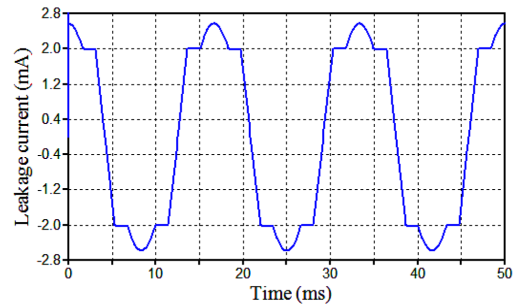


Figure 4. Leakage current waveforms on a clean insulator under snow conditions.

In order to model the contaminated surface, typical voltage/current characteristics for lightly and heavily polluted insulators (Figure 6), reproduced from [10,11], have been used. Figure 7 and Figure 8 show the leakage current waveform of a lightly and heavily polluted insulator under the same snow conditions respectively. According to results derived by ATP, the thermal losses for lightly and heavily polluted insulator are 16.13 and 122.44 joules respectively. Hence the leakage current and thermal losses of a heavily polluted insulator are very important as compared to a lightly polluted one.

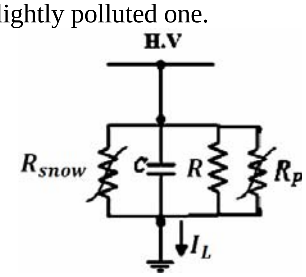


Figure 5. Model of polluted insulator equivalent circuit under snow conditions.

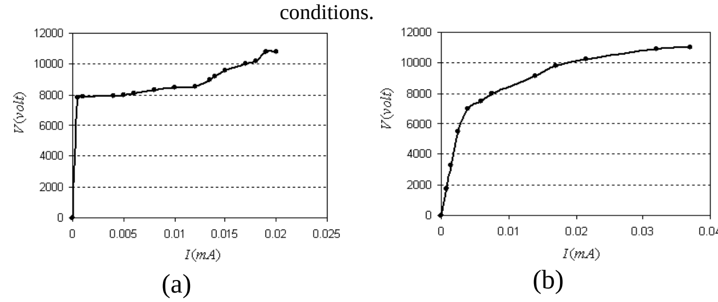


Figure 6. Non-linear V-I characteristics of polluted insulator (a): Characteristics of a lightly polluted insulator (b) : Characteristics of a heavily polluted insulator.

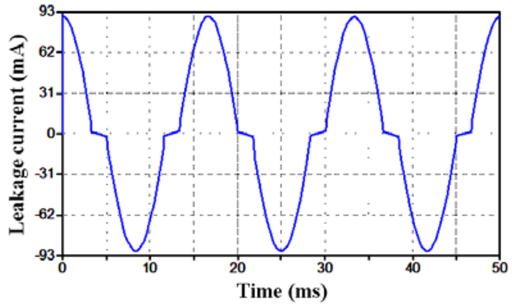


Figure 7. The leakage current waveforms on a lightly polluted insulator under snow conditions

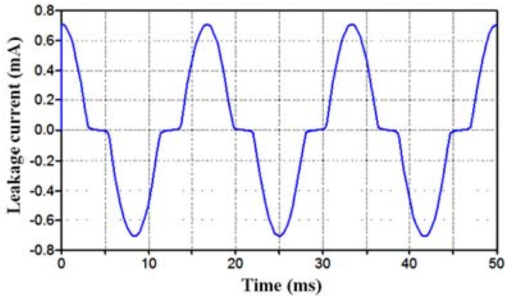


Figure 8. The leakage current waveforms on a heavily polluted insulator under snow conditions.

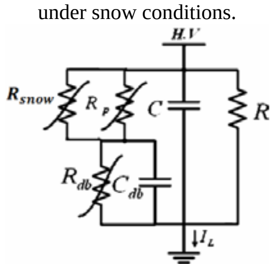


Figure 9. Model of polluted insulator with dry-band equivalent circuit under snow conditions.

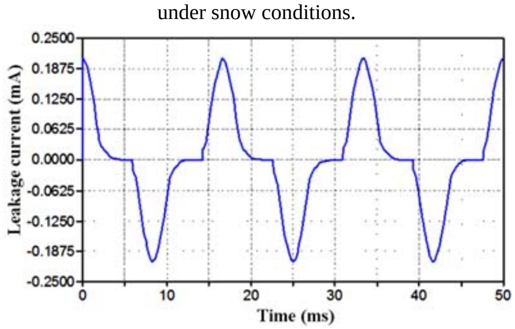


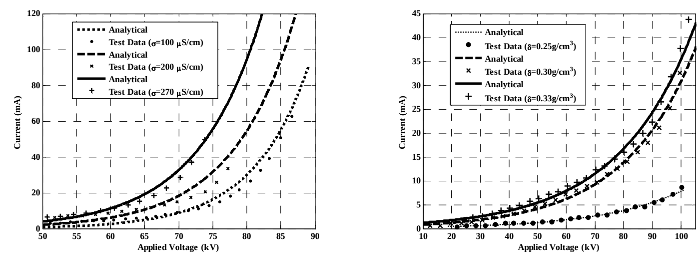
Figure 10. The leakage current on a heavily polluted insulator with dry band under snow conditions.

C. *Snow-covered Polluted Insulator with Dry-band*

The presence and increase of contamination level on the insulator surface leads to a growth in leakage current causing a rise of temperature and resulting in the formation of dry bands. The dry band formation, leads to partial discharges and arcs occurrence along the surface. Figure 9 shows an equivalent circuit of polluted insulator with a dry band under snow conditions. In the equivalent circuit, a dry band is represented as a non-linear resistor Rdb and capacitor Cdb in parallel. The variation of leakage current is provided in Figure 10.

IV. Effect of Water Conductivity and Density Variation on Leakage Current

In this section, the effects of snow density and water conductivity on leakage current are investigated. To determine the effect of these parameters on leakage current, the data presented in Figure 11 can be used. This figure shows the voltage across snow as a function of the leakage current through it, given a snow density equal to 0.367 g/cm3 and a conductivity of water melted from snow equal to 86 µS/cm, for various conductivities of water melted from snow. Considering the clean insulator model in the presence of snow, the leakage current under the mentioned conditions is shown in Figures 12 and 13. The simulation results indicate that the leakage current increases with an increase in water conductivity and snow density level.



(a) (b)

Figure 11. Comparison of voltage-current characteristics of snow-covered insulator. a) Effect of conductivity of water melted from snow (σ=100 µS/cm), b) Effect of snow density (δ=0.25 g/cm^3)[7].

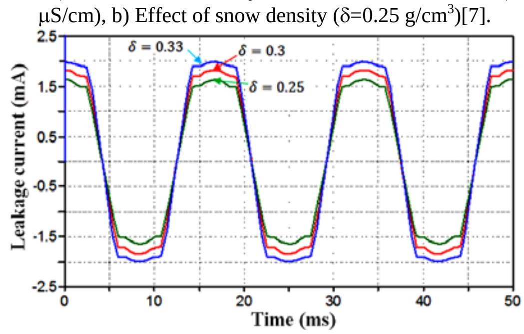


Figure 12. The variations of leakage current for three different water conductivity.

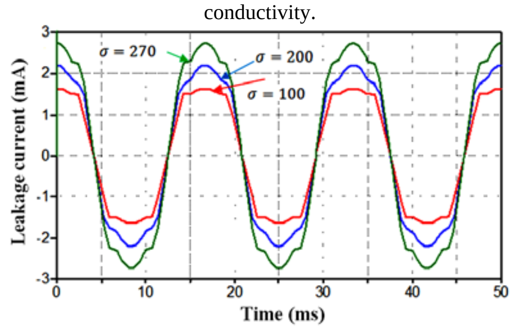


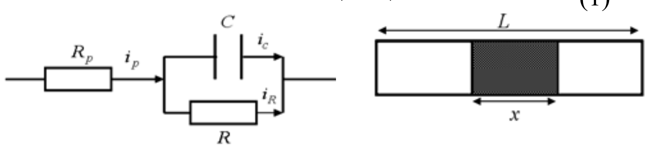
Figure 13. The variations of leakage current for three different snow density.

V. The Leakage Augmentation Current Criteria

Under snow conditions, the rate of leakage current increases with the contamination level on the insulator surface. The contaminated snow layer will be referred to as "polluted layer" hereafter. In what follows, the simplified model for a polluted snow-covered insulator, illustrated in

Figure 14, is used to investigate the influence of the ratio of polluted layer length to insulator length on the leakage current. The polluted insulator is modeled as a polluted layer of length x with resistance Rp in series with a resistance R and a capacitor C in parallel, the two latter variables representing the insulator resistance and capacitance, respectively. The leakage current of the insulator is given by the following relation:

$$|\mathrm{I}| = \left|\frac{\mathrm{V}}{\mathrm{Z_{eq}}}\right| \tag{1}$$



(a) (b)

Figure 14. (a) The electrical circuit; (b) The flat model.

Where Zeq, *V* and *I* are the total impedance, applied voltage and leakage current, respectively. The total impedance is calculated as follows:

$$\mathrm{Z_{eq}} = \mathrm{R_P} + \frac{\mathrm{R}}{1 + \mathrm{jRC\omega}} \tag{2}$$

For an electrical circuit, R and C are expressed as:

$$\mathrm{R} = \rho \frac{\mathrm{L - x}}{\mathrm{A}} \tag{3}$$

$$\mathrm{C} = \varepsilon \frac{\mathrm{A}}{(\mathrm{L - x})} \tag{4}$$

Where ρ , *L* and *A* are the resistivity, the permittivity, the leakage length and the cross section of the polluted layer, respectively. Assuming that the polluted layer is a cylindrical channel, (where *Ap*, x and ρp are respectively cross section, length and resistivity), the polluted layer resistance yields:

$$\mathrm{R_P} = \rho_\mathrm{P} \frac{\mathrm{x}}{\mathrm{A_P}} \tag{5}$$

Substituting (3)-(5) into (2) yields:

$$\mathrm{Z_{eq}} = \frac{\rho_\mathrm{P} \mathrm{x}}{\mathrm{A_P}} + \frac{\rho(\mathrm{L - x})}{\mathrm{A}(1 + \mathrm{j}\omega\rho\varepsilon)} \tag{6}$$

In order to increase the leakage current, the main criterion is:

$$\frac{\mathrm{dI}}{\mathrm{dx}} > 0 \tag{7}$$

$$\frac{dI}{dx} = \frac{d\left(V/Z_{eq}\right)}{dx} = -\left(\frac{V}{Z^2_{eq}}\right)\frac{dZ_{eq}}{dx} \tag{8}$$

Hence, the condition for arc propagation is:

$$\frac{dZ_{eq}}{dx} < 0 \tag{9}$$

The squared modulus of impedance is:

$$\left|Z_{eq}\right|^2 = \frac{1}{\left(1+\omega^2\rho^2\varepsilon^2\right)^2 A_P^2 A^2}\{[\rho_p x A(1+\omega^2\rho^2\varepsilon^2) + \rho A_p(L-x)\ ]^2 + \omega^2 A_p^2 \varepsilon^2 \rho^4 (L-x)^2\} \tag{10}$$

In order to simplify (10), the following relationships are considered:

$$k = 1 + \omega^2\rho^2\varepsilon^2 \tag{11}$$

$$\eta = (\rho_P A - \rho A_P)^2 + \omega^2\varepsilon^2 A_P^2 \rho^4 \tag{12}$$

So, by substituting (11) and (12) into (10), we obtain:

$$\left|Z_{eq}\right|^2 = \frac{1}{k^2 A^2 A_P^2}\{\eta x^2 - 2xL\left[\eta + Ak\rho_P\left(A_P\rho - A\rho_p k\right)\right] + kL^2 A_P^2 \rho_P\} \tag{13}$$

Applying the criterion of current propagation in (9) and with related simplifications, the condition allowing drastic changes in leakage current rate, even up to causing flashover, is thus:

$$\frac{x}{L} < \left[1 + \frac{Ak\rho_P}{\eta}\left(A_P\rho - A\rho_p k\right)\right] \tag{13}$$

Therefore, if the ratio of the polluted layer length to the insulator length reaches to the assumed limitation, the leakage current will increase dramatically.

VI. CONCLUSION

In this study, the effect of contaminated wet snow on leakage current in various polluted conditions is analyzed using related equivalent circuits. The simulated results show that leakage current increases drastically in presence of snow on the insulator surface. It was shown that an increase in the density of snow and/or conductivity of water melted from snow results in an increase in the leakage current flowing through the snow. Also in this article, the ratio of polluted snow layer length to insulator length as an index for determining the point where leakage current has its maximum rate is determined using the proposed leakage current rate criteria and the consequential mathematical equations.

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