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The Effect of Conductivity on Surface Leakage Currents on Iced-Covered Insulators

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Abstract
Insulators on power transmission systems today are vital to ensuring high-voltage lines' reliable and effective operation. However, insulators will inevitably encounter problems such as contamination and icing due to natural environmental conditions and environmental factors. Pollution layers and ice buildup that have developed on insulator surfaces harm insulation performance, increase surface leakage currents, and result in power line failures or interruptions. This article focuses on understanding the phenomena of contamination and icing in insulators, evaluating their effects, and investigating methods that can be taken to prevent or reduce these problems. For this purpose, solutions with different conductivity values (1000–4000 µS/cm) were sprayed on the insulators in the laboratory environment, and ice covering the insulator surface was provided. An alternating voltage (5–20 kV) with the frequency of the mains was applied to the insulators to study leakage currents. Data were obtained with the help of the LabVIEW program, and the relationship between leakage currents of porcelain, glass, and silicone insulators and conductivity was compared. The amplitude of leakage current increases with the increase in conductivity in all three types of insulators. The increase in leakage current with conductivity is most observed in the glass insulator, while the least affected element is the silicon insulator.

1. Introduction

Bridging of the insulator surface brought on by the supercooled water droplets landing on the insulator surface results in the transmission line icing problem, which is brought on by the worsening of the electric field distribution of the insulator sheds. A key danger factor for the dependability of insulators in areas with cold climates has been recognized as atmospheric ice formation combined with pollution. A number of interrelated variables cause the flashovers that happen on ice and snow-covered insulators. Flashovers caused by icing in the insulators are influenced by a variety of climatic and meteorological parameters, including changes in air temperature, the type of ice, and the structure of the ice. Icing of insulators, which can happen at normal operating voltage under the worst circumstances, depends on a number of factors, including the presence of surface contamination during the freezing and melting processes and the status of ions at the time of the transition from solid to liquid layers [1].

The conductivity of the ice accumulated on the insulator surface seriously affects the insulation property of the insulator, along with the applied voltage. The effects of ice with different conductivities and ion contents in frozen water have been studied by a number of researchers. For various researchers, the consequences of ice with varying conductivity and ion content in freezing water have

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been studied. The conductivity of ice increased seven times between -15 and 0 degrees Celsius. The relatively restricted temperature range between -2 °C and 0 °C is where the majority of this alteration has taken place. Decembers of the change have been observed. However, ice sample conductivities at 0 °C remained, on average, 187 times lower than solution conductivities at 20 °C. The resistance per unit length of the ice sheet, which is utilized in pollutant flow modeling, cannot be determined using the electrical conductivity of ice alone. Using the length and width of the ice sheet has been effective in providing better modeling results [2]-[6].

Flashover performance in a soiled and icy insulator is related to the level of contamination as well as the level of icing. ISP was used as a characteristic metric to assess the impact of ice accumulations and pollutants on the flashover voltage of an ice-covered insulator. ISP is calculated as the product of ice sheet conductivity and ice sheet weight per centimeter of dry arc distance. As the ISP characteristic parameter increased, the flashover voltage of an insulator covered in ice decreased. The flashover voltage in the ice-covered insulator has increased linearly with the increase in insulator length due to the resistance property of ice formation on the insulator, such as the fouling flashover performance of an insulator [7].

The effect of salt accumulation density (SDD) and the average diameter of insulators on flashover performance shows that the flashover voltage decreases with an increase in SDD. When the icing state is the same, a larger insulator diameter correlates to a larger icing area, which has led to a smaller resistance on the insulator's surface. For this reason, the flashover voltage also decreased with an increase in the average diameter of a fixed SDD. However, the leakage current before the flashover is larger, and this situation is identified with Ohm's law [8]-[9].

On iced porcelain, glass, and composite insulators, it has been shown that the flashover voltage of all three types of insulators decreases with an increase in ice thickness, pollution, and pressure. In comparison to the porcelain and glass insulators, the composite insulator showed a more obvious effect of ice thickness and ambient pressure on the icing flashover voltage. It was determined that, under the same conditions, the value describing the impact of pollution on the flashover voltage is smaller for composite insulators than it is for porcelain and glass insulators covered with ice [10].

The equivalent salt deposit density (ESDD) and the flashover voltage are independent of each other in both rime ice and dry-iced insulators. However, there is a negative power function relationship between the flashover voltage and ESDD on insulators covered with glazed ice with contamination. In addition, when the power function is compared with the exponential function, the relationship between flashover voltage and ice weight is more favorable. The flashover behavior of insulators in different circumstances diverges significantly. When the level of pollution is the same across all natural habitats, the pollution flashover has the biggest arc diameter, followed by the flashover of an insulator covered in glazed and dried ice [11]–[12].

Insulators that have been iced with and without energy have different results from liquid conductivity on icing. When used for spray, melted water has a higher conductivity than frozen water. The salt concentration on the insulator surface rises when icing is produced under electrified conditions because of the heat impact. As a result, during the flashover test, the meltwater conductivity sprayed was higher than it was under de-energized conditions [13].

Pollution and icing are related conditions that affect flashover voltage, together with seasonal conditions. Therefore, the flashover voltage has been studied both in dirty and icy insulators and only in dirty insulators. At the same degree of pollution, the flashover voltage of the insulator in the non-ice-contaminated state is larger than that of the icy insulators. When there is icing or pollution, the composite insulator's leakage current progressively rises as the applied voltage rises. A continuous film of water is formed due to the melting of the ice layer on the insulator surface. This circumstance offers the essential conditions for the creation of a leakage current. As a result, as the voltage is applied, the leakage current that passes through the ice-covered insulator's surface steadily increases [14].

In this study, he focuses on understanding the phenomena of contamination and icing in insulators, evaluating their effects, and investigating methods that can be taken to prevent or reduce these problems. Conductivity values of 1000, 2000, 3000, and 4000 μS/cm were obtained by adding salt to water. The liquid sprayed on the porcelain, glass, and silicone insulators is iced in the cabinet. Voltage was applied to the insulators at 15-minute intervals until the ice melted under 5, 10, 15, and 20 kV values. The relationship between surface leakage currents and conductivity was investigated for all three insulators.

2. Material and Method

The issue of environmental contamination becomes increasingly important as society and the economy evolve. One of the main reasons for insulation mishaps on transmission lines is the issue of insulator flashover brought on by pollution. Global warming has led to an increase in the frequency of extremely cold weather, including ice and snow. Therefore, one of the biggest hazards to the safe operation of the electrical grid is pollution and the icing flashover of insulators brought on by the change in operating conditions.

In this study, solutions were prepared by adding salt to water. The solution sprayed on the surface of insulator types made of different substances was subjected to an icing process in the icing cabinet. Voltages were applied to the iced insulators in the experimental setup schematized in Figure 1.

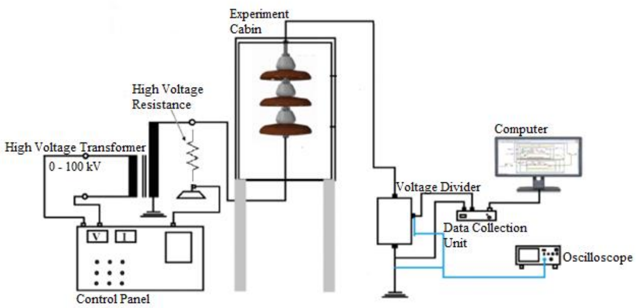


Figure 1. Experimental scheme.

The connection diagram provided in the LabVIEW application, as shown in Figure 2, was utilized to get the data on leakage currents on the insulator surface.

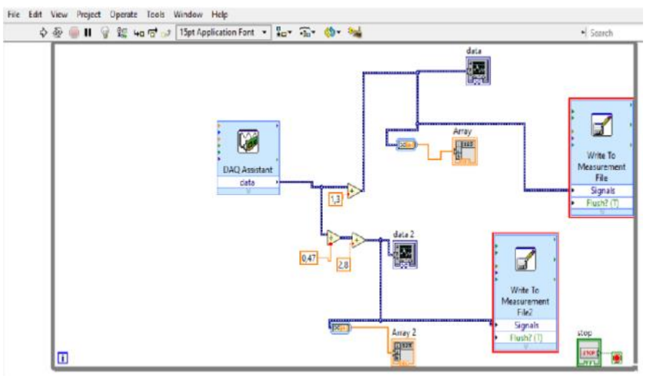
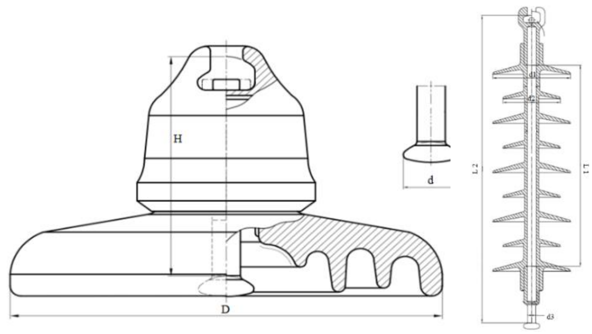


Figure 2. LabVIEW connection diagram.

Sections of porcelain, glass and silicon insulator used in the experiment are given in Figure 3.



(a) **(b)**

Figure 3. (a) Porcelain and glass insulator section (b) Silicone insulator section.

The characteristic values of one element of the glass and porcelain insulator are shown in Table 1.

Table 1. Characteristic values of porcelain and glass insulator.

Insulator Variety (mm)	Diameter (D)	Height (H)	Pin diameter (d)	Leakage current path length
U100 BL (K3) Porcelaın	255	146	16	280
U100 Glass	255	146	16	280

The sizes of the silicon insulator used in the experiments are shown in Table 2.

Table 2. Characteristic values of the silicone insulator.

Insulator Variety (mm)	L1	L2	d1	d2	d3	Leakage current path length
Silicone (K2)	248.8	440	120	90	17	900

2.1. Estimation of Flashover Voltage

The most basic model for calculating the flashover voltage of icy insulators makes the assumption that the effective resistance of the ice sheet is described by multiplying the weight of ice (w) by the conductivity of melted ice (σ20) [15]. The icing voltage product

(ISP) is represented by (w·σ20). The critical flashover voltage E_{50} is given as in equation (1):

$$E_{50\,ac} = 396(\text{ISP})^{-0.19} \quad (1)$$

Flashovers are described by equation (1), which describes the accumulation of ice at normal line voltage and during a phase of AC melting. The critical flashover voltage is defined as equation (2) for experiments utilized in numerous DC flashovers on an ice sheet generated without line voltage [16]:

$$E_{50\,dc-} = 1174(\text{ISP})^{-0.26} \quad (2)$$

Basic modeling of the ice flashover process using the Obenaus model of a serial arc with a distributed resistive layer has been successful [5]. According to equation (3), the flashover model adds the voltage drop along the arc and the voltage drop brought on by the current flow through the remaining ice sheet.

$$V_m = A.x.I_m^{-n} + I_m R(x) \quad (3)$$

Where V_m (V) is the peak value of the applied voltage, x (cm) is the total arc length. A and n are the derived arc constant and R(x) is the residual resistance of the ice sheet. The expression R(x) is defined as in equation (4).

$$R(x) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L-X)}{D+2t} + \ln\left(\frac{D+2t}{4r}\right)\right] \quad (4)$$

Where L is the length of the half cylinder of ice along the dry arc distance (cm), D is the diameter of the insulator (cm), γe is the equivalent surface conductivity of the ice sheet (μS), t is the thickness of the ice sheet, and r is the radius of the effective arc root.

The effective arc root radius in equation (4) is taken as constant with the square root of the current and varies depending on the type of voltage. The values r=0.7√I are valid for DC and r=0.6√Ipk AC arc currents.

2.2. Effect of Contamination on Ice-Covered Insulators

The pre-contamination levels on high voltage DC insulators can be at least 20% higher in insulators with positive polarity compared to negative polarity. This raises the issue of how to account for insulator surface pre-contamination when calculating the DC^+ and DC^- flashover voltages during ice conditions [15].

Equation (5) gives the amount of salt that enters the ice sheet, accumulates in the insulator, and is retained there.

$$\text{m} = \text{F}.\text{ESDD}.\text{A}_{\text{top}} \quad (5)$$

Where; F is the insulator properties split into ice layers factor, ESDD, perfect salt deposit density, Atop is the total area of the insulating surfaces and m is the near salt weight.

The amount of ice in contact with the insulator depends on the degree to which the insulator is fully bridged, which is determined by the deposition thickness t, insulator diameter D, and dry arc or leakage distance L. The water volume is calculated as in equation (6).

$$\text{V}_{\text{water}} = 0.9.\frac{\pi}{4}((\text{D}+2\text{t})^2 - \text{D}^2).\text{L} \quad (6)$$

It is estimated that the DC+ flashover voltage for contaminated insulators remains well above the DC- flashover voltage for clean insulators [15].

3. Results and Discussion

In the study carried out, conductivity values of 1000, 2000, 3000, and 4000 μS/cm were obtained in four separate solutions by means of a conductivity meter. The solution prepared for porcelain, glass, and silicone insulators was sprayed in the icing cabinet, and ice formation was ensured on the insulator surface. Voltages of 5, 10, 15, and 20 kV were applied to the iced insulators at 15-minute intervals until the ice on the insulator surface melted. When applying voltage, with the help of the data acquisition unit, the voltage value on the resistor connected to the output of the voltage divider was measured, and leakage currents were obtained with periods of 100 ms using the LabVIEW program. It has been examined how leakage currents and leakage currents depending on the conductivity state depend on the type of insulator.

Figure 4 shows the leakage currents obtained with a voltage of 5 kV applied to the porcelain, glass, and silicone insulators iced for a conductivity of 1000 μS/cm immediately after removal from the icing cabinet.

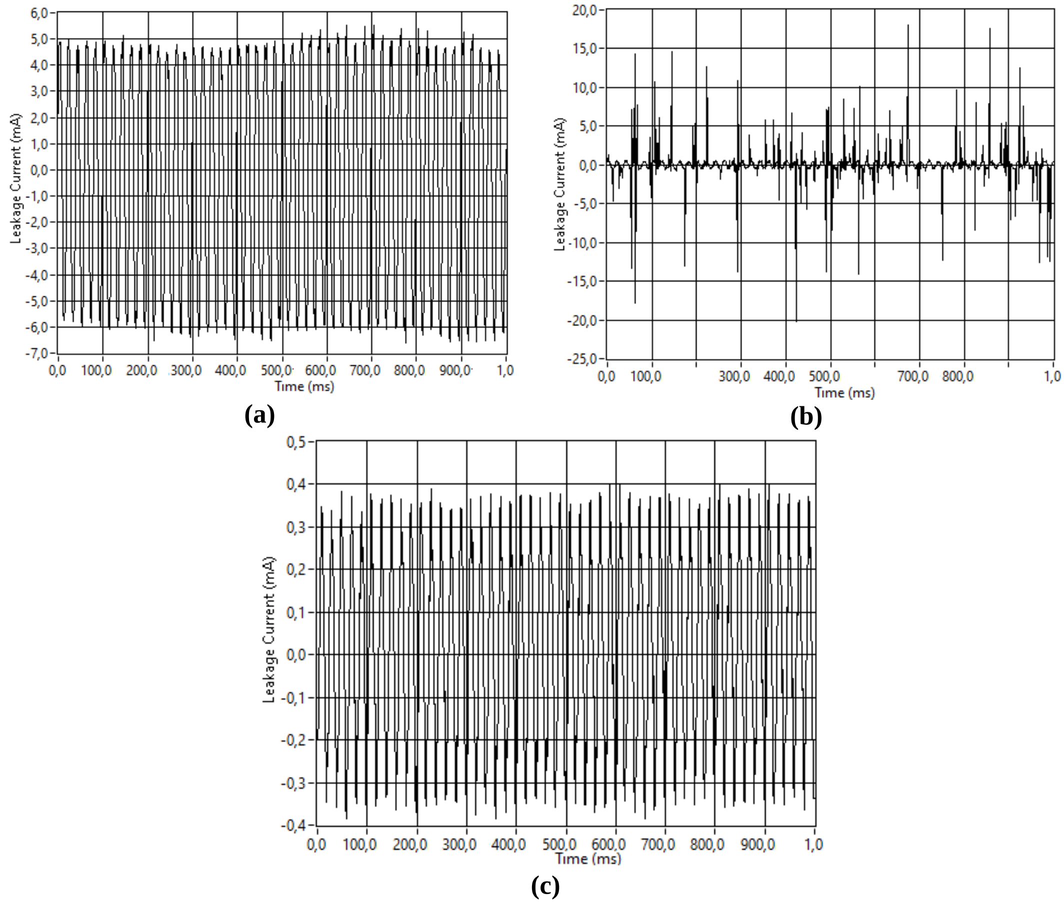
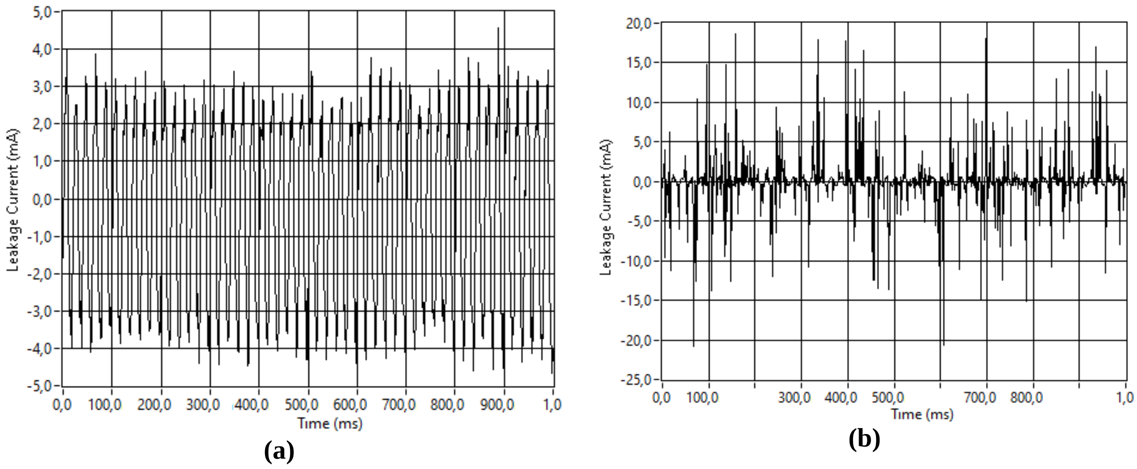
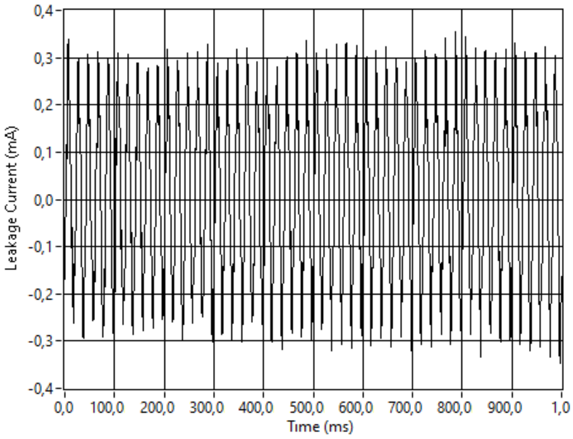


Figure 4. Leakage currents obtained under 5 kV voltage for iced (a) porcelain, (b) glass, (c) silicone insulator with a conductivity of 1000 μS/cm.

Figure 5 shows the leakage currents with a voltage of 5 kV applied to the iced porcelain, glass, and silicon insulators for a conductivity of 1000 μS/cm near melting.





(c)

Figure 5. For a ıced (a) porcelain, (b) glass, (c) silicone insulator with a conductivity of 1000 µS/cm, the leakage currents obtained under a voltage of 5 kV just before the ice liquefies.

Figure 6 shows the leakage currents obtained with a voltage of 20 kV applied to the porcelain, glass and silicone insulator iced for a conductivity of 4000 µS/cm immediately after removal from the icing cabinet

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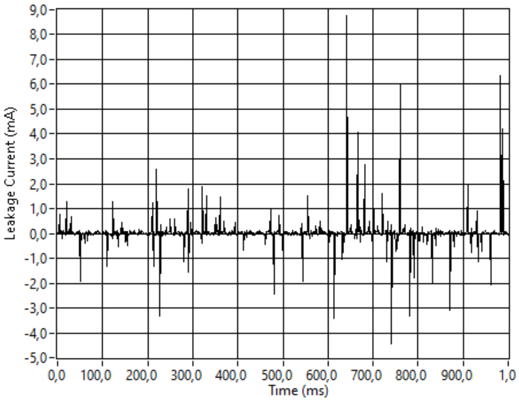
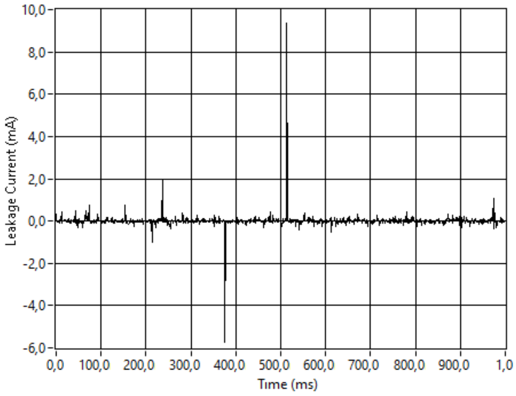


(a)



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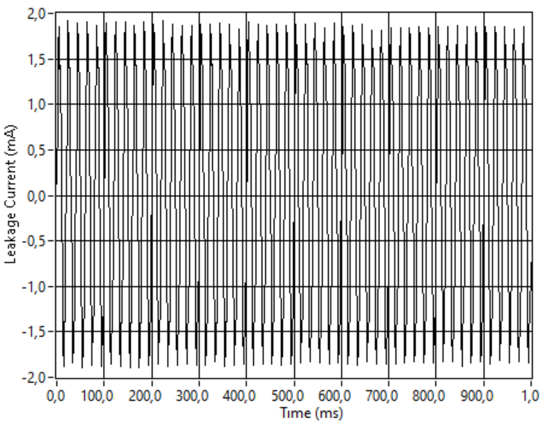

(c)

Figure 6. Leakage currents obtained under 20 kV voltage for ıced (a) porcelain, (b) glass, (c) silicone insulator with a conductivity of 4000 µS/cm.

Figure 7 shows the leakage currents with a voltage of 20 kV applied to the iced porcelain, glass, and silicon insulators for a conductivity of 4000 µS/cm near melting

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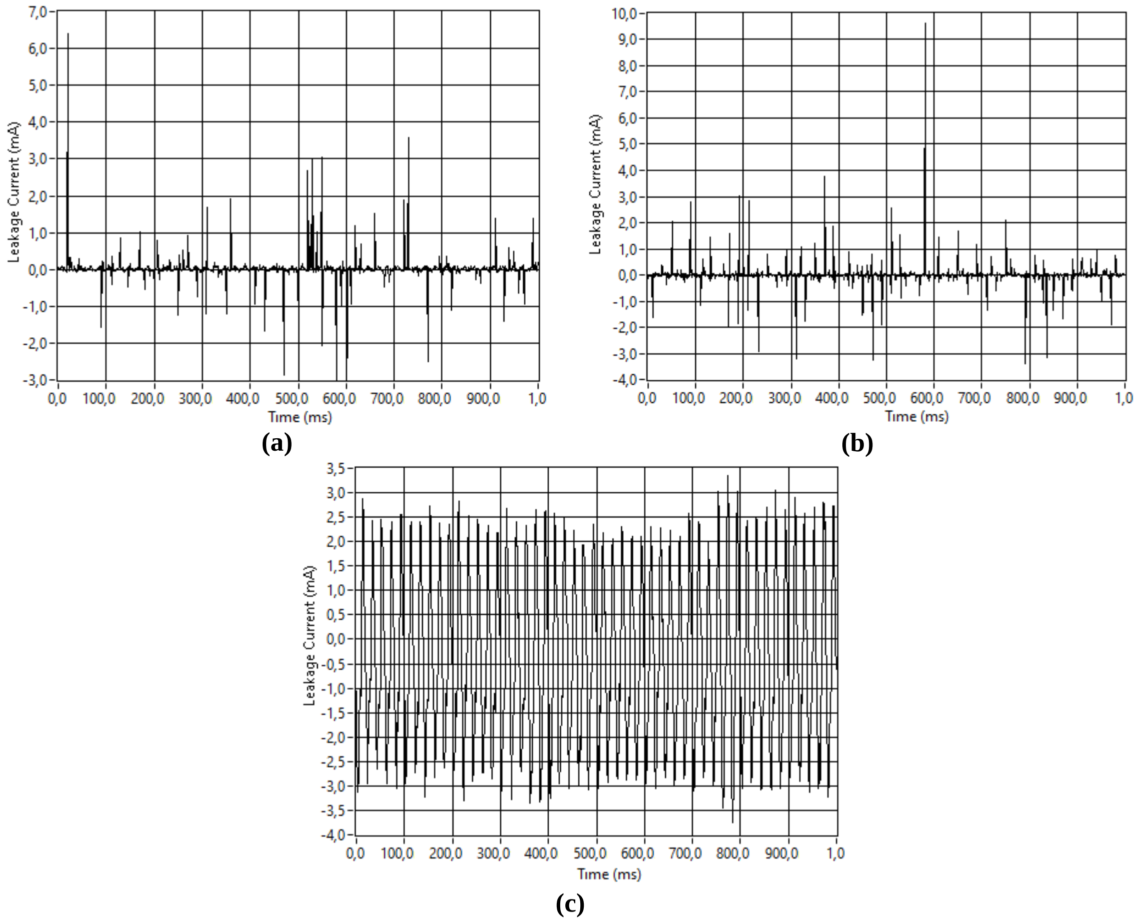

Figure 7. For an iced (a) porcelain, (b) glass, (c) silicone insulator with a conductivity of 4000 µS/cm, the leakage currents obtained under a voltage of 20 kV just before the ice liquefies.

Leakage currents partially increase with the liquid conductivity in the porcelain insulator. This is due to the fact that the resistance is inversely proportional to the surface conductivity, as can be seen in equation (4). An increase in surface conductivity will reduce the resistance of ice, and with a decrease in resistance, the leakage current will increase. As can be seen from the instantaneous jumps in the graphs, partial arcs were formed on the insulator surface along with increasing the applied voltage when the liquid conductivity was 4000 µS/cm, and the length of these arcs was longer than in low conductivity cases.

Leakage currents in the glass insulator have approached 25 mA levels from time to time. With the increase in liquid conductivity, arcs were formed on the insulator surface. Compared to the porcelain insulator, the glass insulator is more sensitive to increasing the conductivity and applied voltage.

Leakage currents in the silicon insulator did not exceed 4 mA. In general, the leakage current did not exceed the levels of 0.4 mA at 5 kV, 0.8 mA at 10 kV, 1.2 mA at 15 kV, and 2 mA at 20 kV. However, at a conductivity value of 4000 µS/cm, it approached the level of 4 mA at the moment when the ice began to melt on the insulator surface. According to the glass and porcelain insulators, the insulator that is least affected by liquid conductivity is the silicone insulator. However, since the leakage path length of the silicone insulator used in the experiments is much longer than that of the glass and porcelain insulators, it would be more accurate to compare the glass and porcelain insulators among themselves.

The relationship between leakage currents of porcelain, glass, and silicone insulators and conductivity is shown in Figure 8.

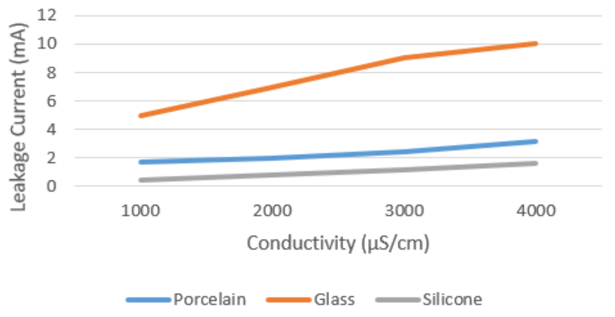

Figure 8. Relationship between conductivity and leakage current of porcelain, glass, and silicone insulators.

The amplitude of the leakage current increases with the increase in conductivity in all three types of insulators. The increase in leakage current with conductivity is most observed in the glass insulator, while the least affected element is the silicon insulator.

With the artificial icing used in the study, the leakage currents also differ, since the ice that the cabin will accumulate on the insulator surface may differ according to the ice that naturally accumulates on the insulator surface. However, the examination of leakage currents at December intervals of 100 milliseconds reduced this situation as much as possible. Considering the continental climate and high regions of our country, it is the insulators that are one of the transmission and distribution line elements where the most failures occur. For this reason, the icing event is one of the issues that needs to be studied in more detail. But there are almost no studies on this topic in our country. This study will guide future studies.

4. Conclusion and Suggestions

Wind, air pressure, pollution, temperature, humidity, etc., which are effective against the icing event in insulators and the flashover event with them, have been studied in many studies in which environmental events have been simulated. The studies carried out focused more on the voltage value at which the flashover occurred, and the flashover event in insulators could not be completely solved. In this study, taking into account the icing situation along with pollution, leakage currents were studied in detail for very short time intervals, and more data were obtained.

Liquid conductivity is an important parameter in the effect of icing events on surface leakage currents in insulators. Increasing the conductivity of the liquid is very effective in losing the insulating property of the iced insulator surface. When the sensitivity of leakage currents to liquid conductivity is compared in porcelain and glass insulators, it is concluded that glass insulators are more affected than porcelain.

When designing the insulators, taking into account the icing level and the pollution level according to the climatic conditions of the region and the mechanical properties, such as the material from which they are made, will help to reduce the problems that may occur due to pollution and icing.

In our country, which is covered with seas on three sides, the conductivity of the liquid formed on the insulator surface increases with the effect of sea water along with humidity and precipitation. The impact of natural events on the environment on Earth is being felt more and more with increasing global warming. Together with this, considering the geographical situation of our country and the rural areas where the continental climate is intense, the failures caused by icing and the conductivity of the iced liquid in the insulators are quite high. It is possible to minimize the effects of adverse conditions that will occur. In future studies, signal processing or image processing techniques can be used more effectively together with artificial intelligence techniques, which are one of the most popular topics today. With the early warning system, the occurrence of malfunctions can be prevented by timely intervention with the insulators.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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