

Calculation of surface leakage currents on high voltage insulators by ant colony algorithm-supported FEM

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Abstract: The weakness of the outer insulation at high voltages is the reduction of the surface resistance as a result of the environmental pollution yielding formation of flashover due to the surface leakage currents. In this study, it was shown how to calculate the surface leakage currents resulting in flashover in polluted insulators and therefore power cuts by means of the ant colony algorithm (ACA). For this purpose, first, field distribution on the sample insulator surface in question was defined by the Laplace equation ($\nabla^2 V = 0$). With the help of the finite element method (FEM), the Laplace equation was obtained as an equation with a complex coefficient as a complex dielectric coefficient was used in the problem, which was converted to a set of linear equations. The solution of this problem was performed by FEM. For this purpose, a 2D finite element mesh was constructed for the area in question and the voltages at the nodes of this mesh were calculated. The current value was then calculated by transferring these voltages to the open model (AR model) obtained from the 3D model of the insulator. The ACA was used in the current calculations. After certain values of the leakage current, dry bands formed on the surface where partial arcs occurred as a result of the increase in voltage drops. Accordingly, rapid variations occurred in the current values and the electric field strengths. These variations, appearing until the formation of an arc throughout the whole leakage current distance, were calculated gradually by the ACA. The results obtained were presented graphically.

Key words: High voltage insulator, pollution flashover, dynamic arc model, ant colony algorithm

1. Introduction

Surface flashover of polluted high voltage insulators is one of the most significant operation problems for transmission systems due to power cuts. Formation of surface flashover can be analyzed in two main parts [1–4]:

- Coverage of the insulator surface by a pollutant layer and ignition of pre-discharges in the dry pollution area formed due to the thermal energy of currents flowing through this conducting layer,
- Spread of pre-discharges along the polluted insulator surface.

Many studies have been done and many models were developed in order to determine the surface leakage currents on the polluted high voltage insulators. In spite of the presence of detailed field and laboratory studies

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[5,6], the main mechanism of the pollution flashover, which has a complex structure due to the existence of plenty of parameters related to pollution, has not been presented yet.

It was observed that the flashover voltage under service conditions depends on parameters like voltage polarity [7], type and size of the pollutant [3,8], irregular wetting, surface conductivity, wind, length, insulator profile and diameter [8], and thickness of the pollutant layer [9].

In the literature, two basic approaches are used to model the event of flashover on polluted surfaces. One of them is the formation of minimum voltage required to maintain the ignition of a partial and serial arc on the unabridged, polluted surface with varying length [3,7,10,11]. The other is the determination and application of a criterion for the spread of an arc along the wet insulator surface [3,4].

Solutions for insulator surface leakage currents and pollution resistance in series with the arc and pollution flashover problems have been sought by doing studies on the following issues: model and simulation studies to determine flashover voltage [11–16], computer package programs to analyze the potential and field distributions [3,10,12,13], artificial neural networks [10,17,18], fuzzy logic applications [19], the relation between leakage distance and pollution resistance [3], the variation of dry band resistance with time [11], and the effect of lightning impulse voltage and switching voltage [12].

Theoretical and experimental studies have shown that there is a critical leakage current value (I_{max}) above a threshold value at which the probability of flashover shows a sharp increase [20–22]. Verma [21] defined the current flowing in a half period before the flashover as the maximum peak leakage current. Holtzhausen and Du Toit [22] and Holtzhausen and Vosloo [23] suggested keeping the peak leakage current value below 25% of the I_{max} to minimize flashovers. In a condition where peak leakage current value exceeds the allowed value, flashovers occur, and it was determined that flashovers correspond to salinities between 50 kg/m³ and 60 kg/m³ [24].

It is not possible to make sure whether the flashover will happen or not by looking at the leakage current value [25]. However, the increase in leakage current value along the insulator surface means that the probability of flashover is high. First, leakage current increases quickly before flashover. When flashover occurs, short-circuit current is observed [26].

Leakage currents measured experimentally are grouped according to their amplitudes and waveforms. Jayasundara et al. [27] divided the insulator surface leakage currents into five categories as capacitive, resistive, nonlinear, discharge, and strong discharge. While capacitive-type leakage currents are approximately 25 μ A and have sinusoidal waveform, resistive-type leakage currents are between 100 μ A and 200 μ A and their waveforms are sinusoidal. Nonlinear-type leakage currents are a distorted form of resistive currents. Their values are close to 200 μ A, similar to resistive current. The amplitudes of the waveforms for discharge-type leakage currents are similar to that of the nonlinear type, i.e. around 200 μ A. Discharges of up to 600 μ A can be observed. The amplitude of the strong discharge type of leakage current varies between 0.5 mA and 2 mA and the discharge current rises up to 10 mA.

In most of the leakage currents present on insulators, there is a contribution of the DC resistance of the surface because high voltage insulators are used in the power frequency range (50–60 Hz). While skin effect and capacity are low and constant, variations occur only in the resistance component of the leakage current at this frequency. For this reason, in most of the studies concerning insulator characteristics, only the combination of surface resistance and leakage current were considered in the calculations [28].

Researchers examining the subject theoretically use different approaches to calculate the leakage current flowing on the insulator. In one of these approaches, the grounded side of the insulator is divided into thin and small sections. With the help of the pollutant thickness accepted for these sections, the current flowing on the layer is approximately calculated. All currents flowing through these small and thin sections are summed up and the current flowing to the grounded electrode through the insulator surface is determined [29]. This is one of the fundamental approaches defined as a suitable one for numerical calculation.

In this study, the surface leakage currents on insulators were calculated by using the ant colony algorithm (ACA). For this purpose, potential values of the nodes on the surface determined by finite element method (FEM) were defined by ant colonies. The calculation of flowing currents between all nodes was achieved as current flow from one point to another (ant motion) was defined by conductivity (the pheromone material left behind by ants during their motion).

2. Defining the problem and development of the algorithm

When the surface of the polluted insulators absorbs humidity in the air, the pollution layer becomes a conductor. When high voltage is applied to this insulator, leakage currents on the order of hundreds of milliamps flow on this surface. As a result of the joule effect created by these leakage currents, the humidity on the surface evaporates and thin dry bands form around the surface. It is already known that arc discharge occurs as a result of the formation and propagation of partial arcs formed by leakage current on these dry bands. Thus, the event ends with surface flashover.

In order to determine the flashover voltage by the help of insulator models, pollution resistance in series with an arc in the flashover equation should be calculated. For this, it is necessary to know leakage current on the insulator surface

First, potential and field strength distributions are calculated for the inside of the insulator and for the selected external area of the insulator by using the FEM. The following function can be given for the Laplace equation, which is valid for the area in question.

$$We = \int_S \rho_S \left[\left(\frac{\partial V}{\partial x} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 \right] dx.dy \tag{1}$$

Here, ρ_S is the surface conductivity. By minimization of this energy function, potential distribution for the studied area is obtained [30].

From node potentials determined according to FEM results, field strength values (ED) related to each triangular element used for the solution are calculated by using:

$$E_x = -\frac{\partial V}{\partial x} \tag{2}$$

and

$$E_y = -\frac{\partial V}{\partial y}, \tag{3}$$

as

$$ED = \sqrt{E_x^2 + E_y^2}, \tag{4}$$

where E_x and E_y are the components of the field strength in the x and y directions.

- After this step of the program, the ACA can be used to determine the amount, duration, and direction of the leakage current on the insulator. For this purpose, the AR model of the insulator is formed and the model is meshed by the FEM. Each node on the surface corresponds to the coordinates of the city in the traveling salesman problem. Thus, surface leakage currents mimicked ant motion and conducting the pollution layer deposited on the insulator is accepted as pheromone. Based on this approach, ants defined by the voltage of each node on the insulator surface move depending on the distance and the amount of pollution between nodes. In the ACA, the pheromone substance is distributed randomly along the path that the ants follow and its amount is updated by multiplying by the coefficient of evaporation to take the evaporation into account. Similarly, in the computer program, the pollution layer on the insulator surface is also distributed randomly. Meanwhile, the coefficient of evaporation is kept constant to express the reduction in the amount of pollutant occurring as a result of the formation of dry bands appearing due to heat effect caused by the flow of leakage currents. The conductivity is calculated from pheromone value and leakage current value is calculated by using conductivity and voltage difference values between the nodes [31].
- Field strength (E_{ARC}) of each node on the insulator surface is calculated by using the ACA. For nodes on the leakage area, the calculated E_{ARC} , which was obtained from the solution of the AR model, is compared with the ED value obtained from the solution of 2D FEM. If $ED > E_{ARC}$ at the nodes, an arc forms. For the condition of arc formation between any two points on the insulator surface, the voltage values of these two points are taken as the same ($V1 = V2$). This case will be used as an initial condition in the calculation, which will be carried out for the next step. For this, upon determination of arc formation through the discharge criterion, the condition of $V1 = V2$ should be included in the equation system. An easy way to do this is to use Lagrange multipliers [32].
- If $E_{ARC} \geq ED$, then the arc diminishes. The arc causes flashover if the arc length is equal to the leakage distance of the insulator for the condition of $ED > E_{ARC}$. If arc distance is shorter than leakage distance and arc-spreading criteria are fulfilled, then the dynamical variation in arc resistance is recalculated by using an open model and taking it into account in the corresponding equations. If the arc occurs at two or more points, feedback and processing steps are continuous until an arc occurs at all nodes on the leakage path.

The corresponding flowchart is given in Figure 1.

3. The results of the computer program

The algorithm of the program that was developed to apply the ACS to solve the pollution problem in insulators was written in MATLAB (License No. 161051).

As the U160 BL type of insulators were used in the experiments, finite element data belonging to these insulators were transferred to the computer and then necessary calculations and drawings were performed by the computer program prepared by MATLAB. The M value in the drawings represents a coefficient showing how many pieces each triangle will be divided into. Thus, it is a coefficient used to increase the number of triangular elements (Figures 2 and 3). Technical properties of a U160 BL insulator are given in Table 1.

Table 1. The properties of the U160 BL insulator.

Diameter (D)	Height (H)	Pin diameter (d)	Leakage length	Weight
280 mm	170 mm	20 mm	390 mm	8.8 kg

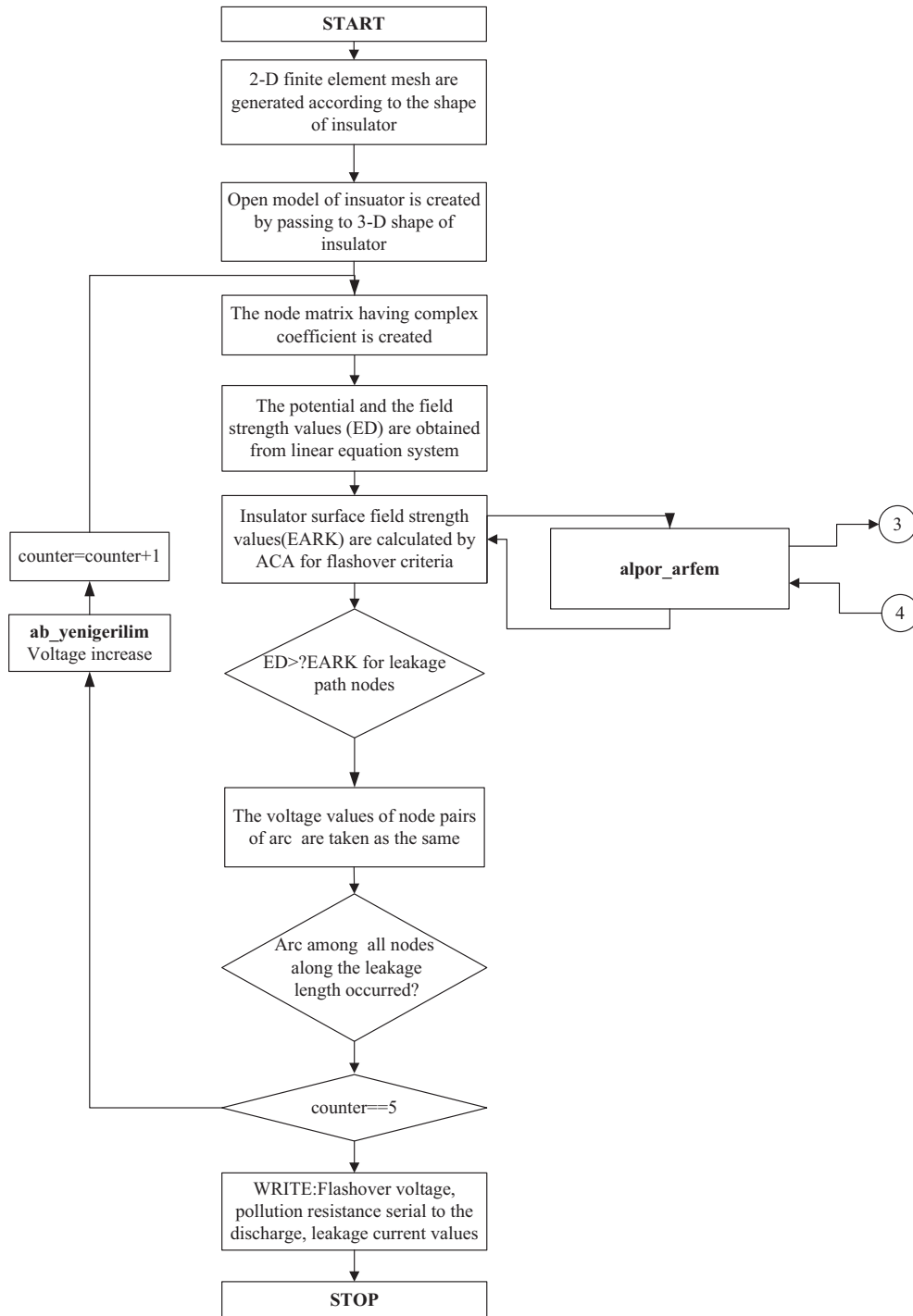


Figure 1. Flowchart of the program for the calculation of surface leakage current and flashover.

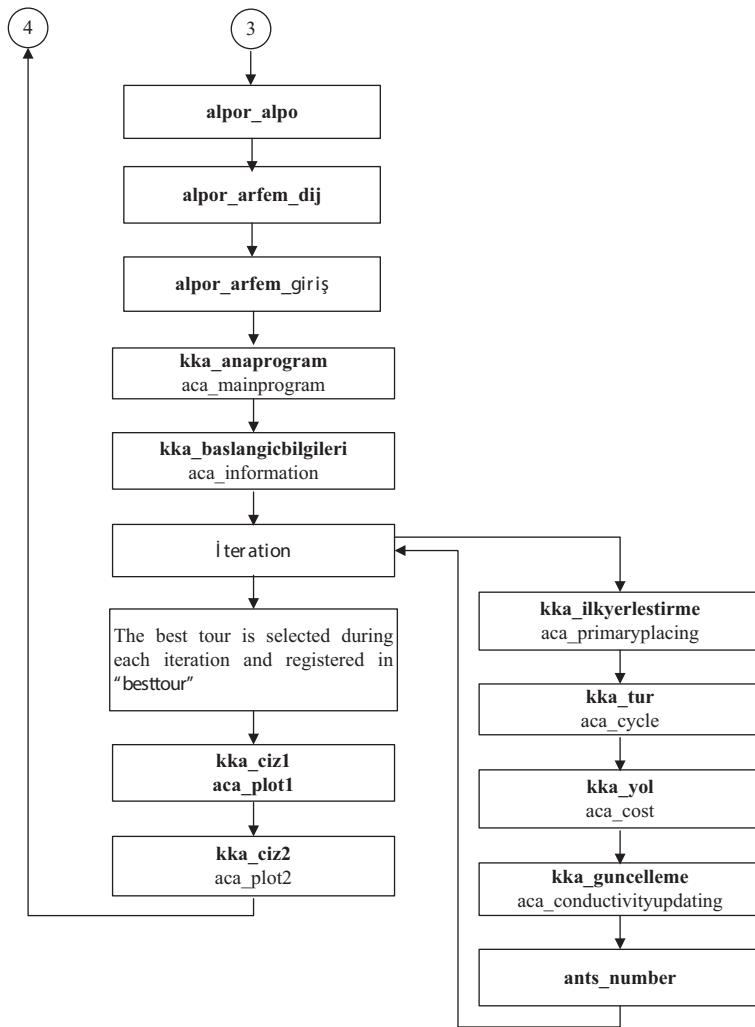


Figure 1. Continued.

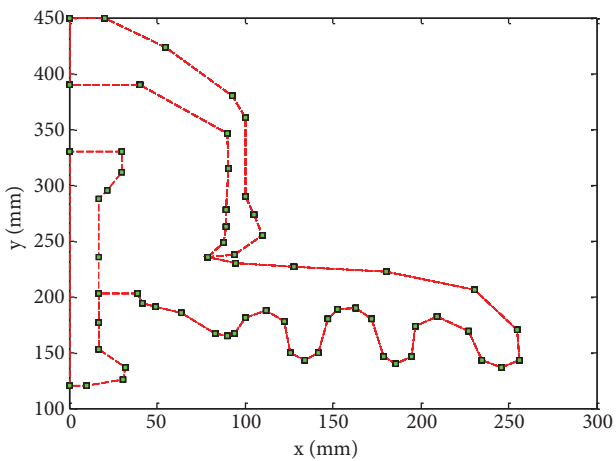


Figure 2. U160 BL insulator shape determined for $M = 1$ (half symmetry).

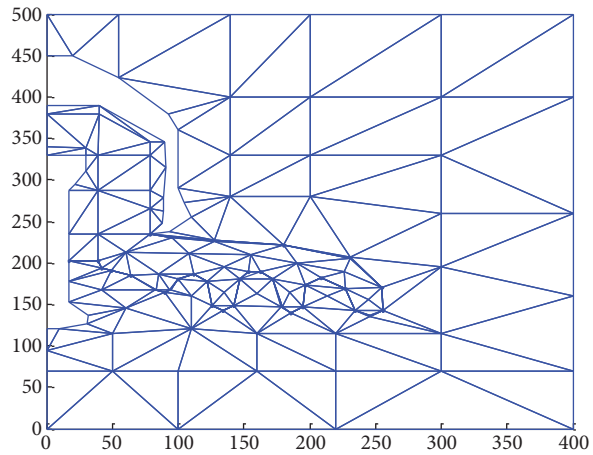


Figure 3. Finite element mesh generation of U160 BL insulator for $M = 1$.

The open model of the U160 BL insulator is given in Figure 4.

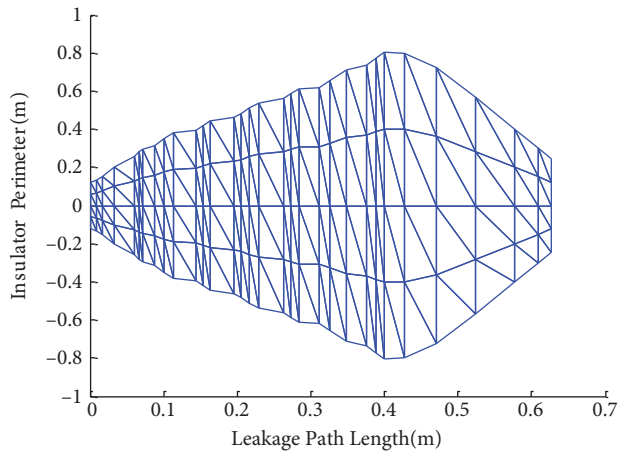


Figure 4. Open model (AR model) of U160 BL insulator.

Equipotential curves calculated for a clean insulator for $U = 5$ kV are given in Figure 5a. Equipotential curves calculated for $\sigma = 50 \mu S$ for $U = 5$ kV are given in Figure 5b.

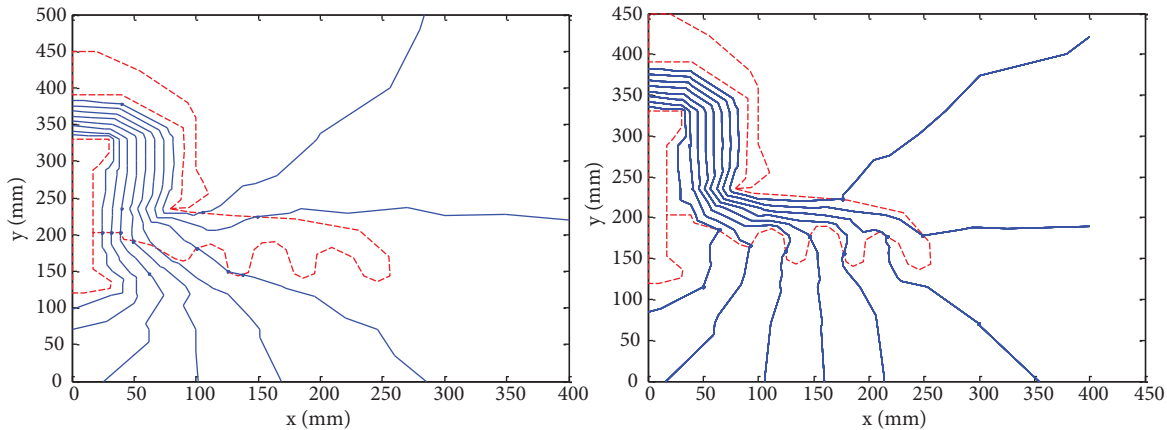


Figure 5. Equipotential curves of U160 BL insulator: (a) clean insulator, (b) surface conductivity $\sigma = 50 \mu S$.

In Figure 6, field strength variations throughout the leakage current for the clean insulator in question with surface conductivity value of $50 \mu S$ are shown. The curves were drawn for voltage values from 5 kV to 70 kV in 5 kV increments.

In Figure 6, it can be seen that the field strength at the initial values of the leakage (pin side) is quite high, while as the conductivity value increases, the field strength at the cap of the insulator increases to higher values. This can also be seen from Figure 5, such that equipotential curves are higher in number at the pin side in Figure 5a and the curve density shifts to the cap side in Figure 5b.

Figure 7 demonstrates the field strength variations throughout the leakage current for the clean insulator in question with surface conductivity value of $50 \mu S$. The curves were drawn for voltage values from 5 kV to 70 kV in 5 kV increments.

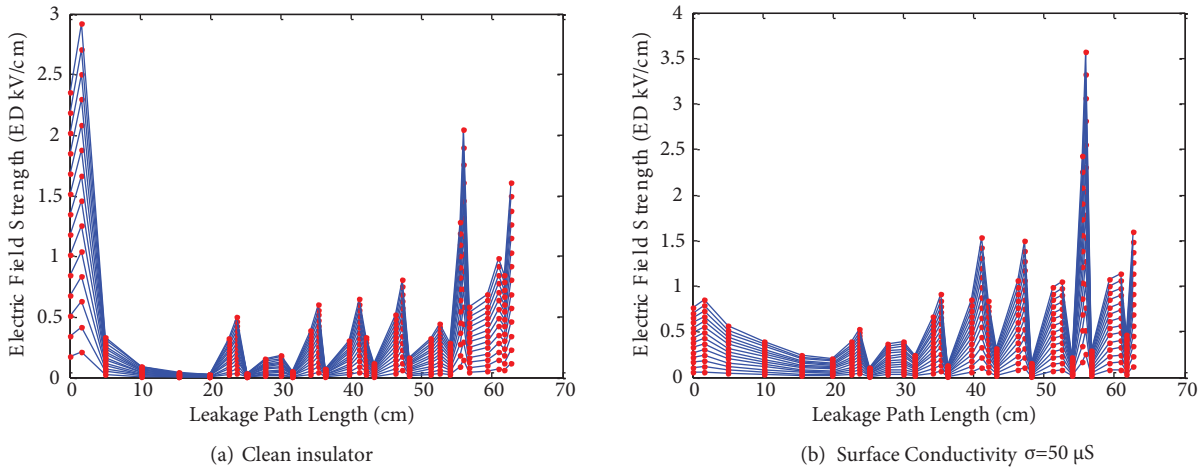


Figure 6. Variations of surface leakage length along the field strength for U160 BL insulator: (a) clean insulator, (b) surface conductivity $\sigma = 50 \mu\text{S}$.

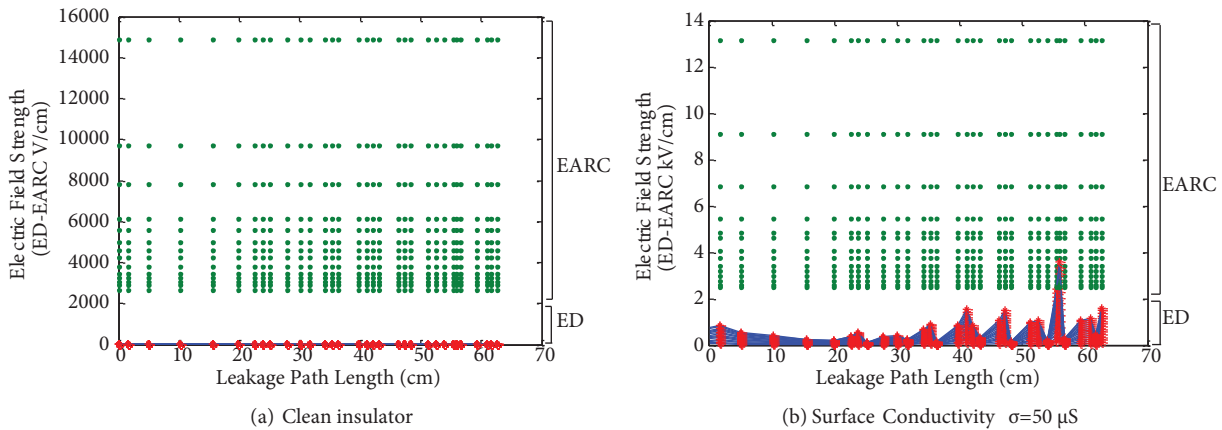


Figure 7. Variations of surface leakage length along the field strength for U160 BL insulator: (a) clean insulator, (b) surface conductivity $\sigma = 50 \mu\text{S}$.

Figure 7 shows ED and E_{ARC} values of the clean insulator having $50 \mu\text{S}$ surface conductivity starting from 5 kV to 70 kV in 5 kV increments (for 14 cycles). While the E_{ARC} values calculated by the ACA decrease at each step, ED values calculated by 2D FEM increase. Depending on the increase in the voltage or surface conductivity, surface discharges start to occur at points where $ED > E_{ARC}$. In Figure 7, it is observed that this condition holds starting from the cap of the insulator, and thus surface discharges start to occur in that area. When voltages are increased further, E_{ARC} values continue to decrease and ED values continue to increase, and thus arc formation appears at other points on the surface.

The surface leakage currents of insulators that have different surface conductivities were calculated by the computer program developed with the help of the ACA. The calculated current values are shown in Table 2.

4. The experimental study

The schema for the experimental set-up is shown in Figure 8. Two high voltage transformers, each one 50 kV, were connected in a cascade to obtain 100 kV voltage. The output voltage of the transformer was applied to

Table 2. The calculated surface leakage current values of the insulator at different surface conductivities using the computer program.

Applied voltage (kV)	Surface leakage current (mA)						
	2.03 μS	3.32 μS	8.55 μS	10.98 μS	13.45 μS	17.8 μS	226 μS
5	0.034	0.048	0.142	0.187	0.231	0.294	0.331
10	0.060	0.103	0.254	0.310	0.374	0.542	0.582
15	0.083	0.127	0.351	0.450	0.536	0.691	0.829
20	0.098	0.175	0.431	0.560	0.692	0.869	1.184
25	0.130	0.193	0.536	0.681	0.815	1.147	1.465
30	0.153	0.228	0.634	0.833	0.980	1.301	1.640
35	0.170	0.261	0.717	0.906	1.096	1.495	1.920
40	0.191	0.321	0.778	1.039	1.286	1.709	2.195
45	0.216	0.339	0.878	1.176	1.403	1.944	2.345
50	0.233	0.396	0.977	1.285	1.582	2.090	2.669
55	0.259	0.417	1.105	1.377	1.652	2.302	2.952
60	0.286	0.448	1.203	1.574	1.923	2.434	3.078
65	0.304	0.498	1.292	1.668	1.971	2.750	3.469
70	0.334	0.523	1.402	1.739	2.176	2.871	3.652

an insulator through a serial connected protective resistor of 875 k Ω . Waveforms related to surface leakage current were collected as information about voltage through a resistance of 500 Ω connected to the output of the insulator. An overvoltage protection was utilized to prevent any damage that could occur in measurement devices due to any failure in the system. When flashover occurs in the insulators, protective resistance connected to the secondary of the transformer is damaged and voltages dropped by 500 Ω increase to higher values. In this case, the overvoltage protector connected to the resistance in parallel shorts and protects both the oscilloscope and the data collection equipment (NI 6210). With the help of a voltage divider, the output voltage of transformer and current values can be monitored by the control unit.

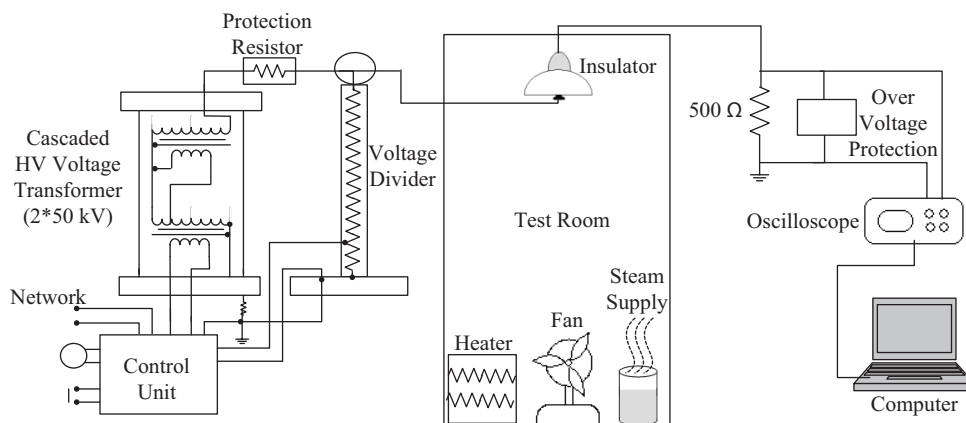


Figure 8. Experimental system.

A water heater was put into the test room to ensure the necessary humidity values for the experiments. Meanwhile, the temperature of the room was kept at the required level by the help of a heater. The homogeneous distribution of the heat and humidity in the room was achieved by a blower fan placed in the test room.

4.1. Preparation of the high voltage insulators for experiments

Tests of surface leakage current for a porcelain string insulator that has one unit was performed in the High Voltage Laboratory of the Department of Electrical and Electronics Engineering at Firat University by applying AA voltage. In order to measure flashover voltage, the cap of the insulator was connected to the ground and the pin of the insulator was connected to the AA high voltage power source. Artificial pollution was obtained by mixing NaCl with pure water. In the experiments, 7 different salt solutions, i.e. 0.2%, 0.4%, 0.6%, 1.0%, 1.2%, 1.6%, and 2.0%, were prepared. For example, in order to prepare the 1.2% salt solution, 1.2 g of NaCl was dissolved into 100 mL of water. Other solutions were prepared in a similar way. In order to distribute solutions on insulators homogeneously, a hanger system and insulators were hung on it. As-prepared salt solutions were sprayed separately on the surface of insulators homogeneously and left to dry. This process was repeated until all solutions were sprayed onto insulator surfaces. In this way, 7 different insulators each having different conductivity values were prepared. Meanwhile, in order to examine clean surface conditions, an insulator with a clean surface was used. Experiments were performed as soon as the pollution process was over.

4.2. Experimental results

First, the clean insulator was tested and energized through a protective resistor connected to the output of a high voltage transformer. Initially, with the application of 5 kV through a resistance of 500 ohm, waveform of the voltage was recorded by means of an oscilloscope and a computer through a data collection device. The peak and effective values of the surface leakage current were calculated by using the peak value of the voltage read from the oscilloscope. The shapes of the data collected by the computer were used by the MATLAB program. After that, the voltage value was increased by 5 kV at each step and leakage current values were recorded similarly. The same processes were repeated for each insulator having different amounts of pollution. By the experiments conducted, flashover and surface leakage current waveforms were investigated for clean and polluted conditions of the insulators.

Two methods can be used to identify the ESDD values of the insulators. The first method involves dividing the amount of the salt in the solution that was sprayed on the insulator surface by the surface area of the insulator. For example, 0.2 g of salt was dissolved into 100 mL of pure water to obtain 0.2% solution and this solution was sprayed onto the insulator surface. This means that 200 mg of salt was sprayed onto the insulator surface homogeneously. As the surface area of the insulator used in the experiments was equal to 2363 cm², the ESDD value was calculated by dividing 200 (mass of the salt) by 2363 (surface area of the insulator) and found as 0.084 mg/cm². The correctness of the data obtained by this method depends on the spraying of the salt solution on the insulator surface without a loss. As a small portion of the salt solution escapes to the air unintentionally, it is not possible to spray the whole solution on the insulator surface. For this reason, the calculation method was performed by the second method.

The processing steps of the second method are as follows: after the flashover experiment, the insulator surface was cleaned by spraying pure water. The volume and conductivity of the polluted water obtained from cleaning were measured. At the same time, its temperature value was also recorded. By using Eq. (5), conductivity values at different temperatures were converted to corresponding values at 20 °C.

$$\sigma_{20} = \sigma_{\theta} [1 - b(\theta - 20)] \quad (5)$$

The conductivity of the solution, which was formed by cleaning the insulator polluted by 0.2% salt solution, at 20 °C (σ_{20}) was measured by the conductivity meter and found as 3340 $\mu\text{S}/\text{cm}$. The volume of the solution

was also measured and determined as 110 cm³. When the unit of conductivity was converted from μS/cm to S/m, σ₂₀ was obtained as 3340.10⁻⁴ S/m.

The salinity of the solution (S_a) was determined by the help of the Eq. (6).

$$S_a = (5.7 \times \sigma_{20})^{1.03} \tag{6}$$

By inserting the σ₂₀ value into Eq. (6), the S_a value was calculated as 1.94. As a result, the density of the equivalent salt deposition was calculated by Eq. (7):

$$ESDD = (S_a \times Vol) / A, \tag{7}$$

where Vol is the volume of the solution and A is the surface area of the insulator. When all values are inserted into Eq. (7), the ESDD value is obtained as 0.082 mg/cm².

The difference between data obtained from these two methods comes from the insufficient spraying of the solution on the insulator surface. The second method is used for this reason.

Vol represents the volume of the solution (cm³) and A is the surface area of the cleaned surface (cm²). ESDD values corresponding to the salinity of the solution are given in Table 4.

Table 3. The obtained experimental values for the clean insulator.

θ (°C)	b
5	0.03156
10	0.02817
20	0.02277
30	0.01905

Table 4. The different values of ESDD.

Salinity (g/mL)	ESDD (mg/cm ²)
0.2	0.03
0.4	0.05
0.6	0.09
0.8	0.11
1.0	0.13
1.2	0.15

4.3. The test of the clean insulator

After cleaning with distilled water, the test insulator was placed into the test room for testing. The data obtained by applying an initial voltage of 5 kV for leakage current flowing on the insulator surface were recorded by means of an oscilloscope and a computer through a data collection device. Representations of the data collected by the computer were drawn using MATLAB, as seen in Figure 9.

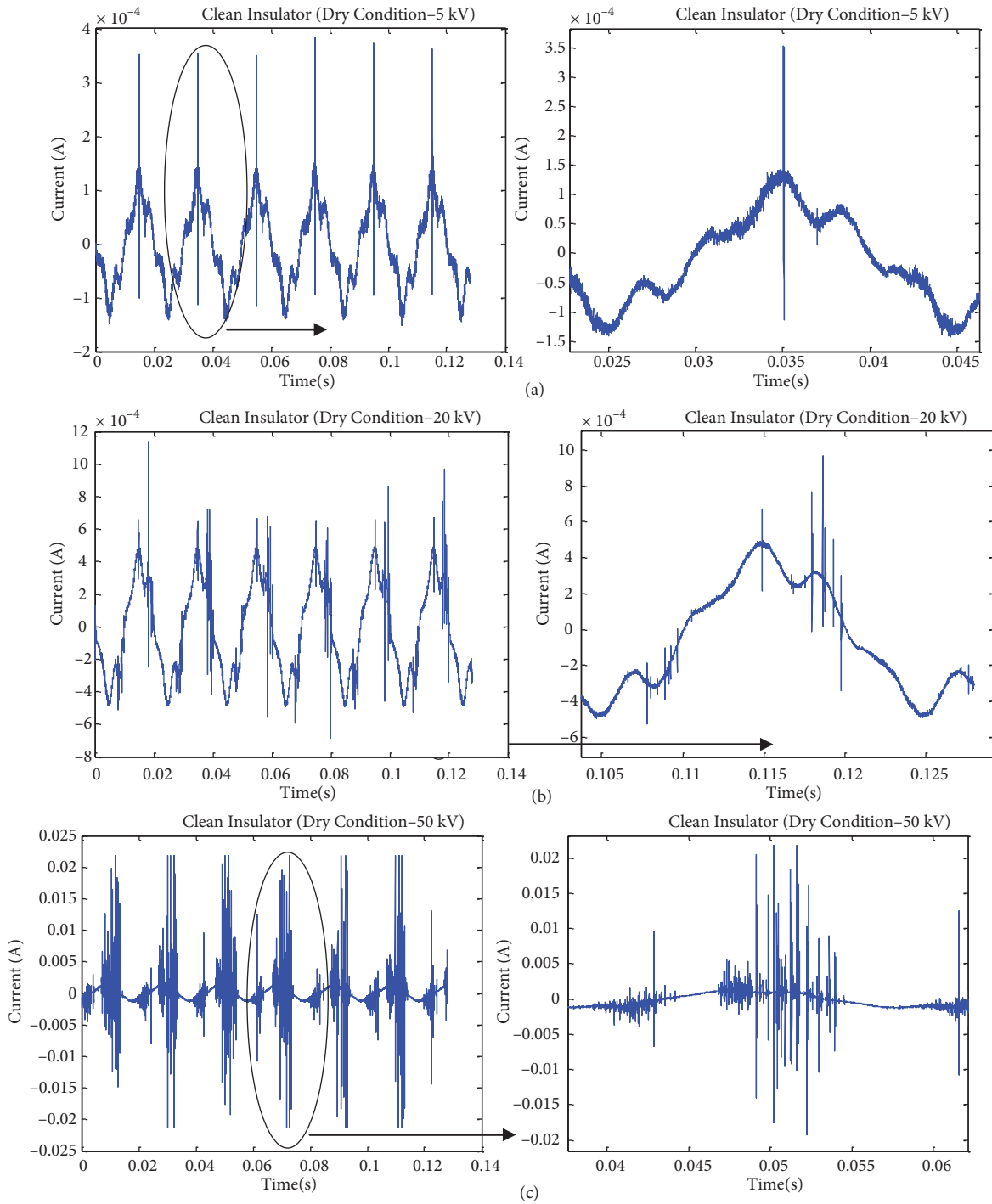


Figure 9. Leakage currents for clean insulator: (a) 5 kV, (b) 20 kV, (c) 50 kV.

4.4. Experiments for the pollutant layer with smooth distribution: leakage current for the insulator polluted by 1.0 g/100 mL NaCl

The values of leakage current at different voltage values for the insulator polluted by 1.0 g/100 mL NaCl are given in Figure 10.

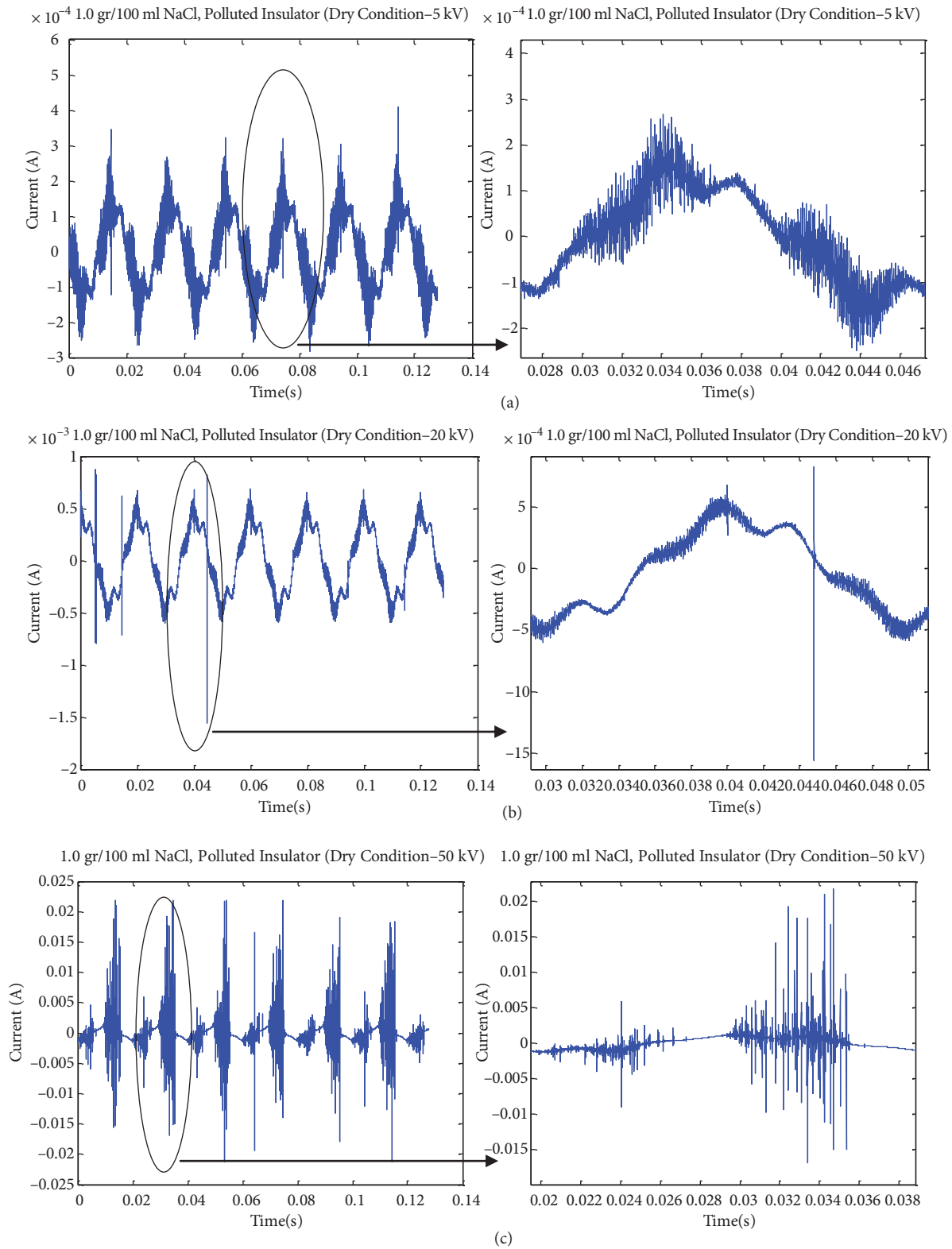


Figure 10. Leakage current for the insulator polluted by 1.0 g/100 mL NaCl: (a) 5 kV, (b) 20 kV, (c) 50 kV.

5. Comparison of experimental and theoretical results

Measured and calculated values of surface leakage current for the insulator with a conductivity of $10.98 \mu\text{S}$ polluted by 1.0 g NaCl are plotted in Figure 11. It shows the graphical representations of the leakage current values obtained for both conditions.

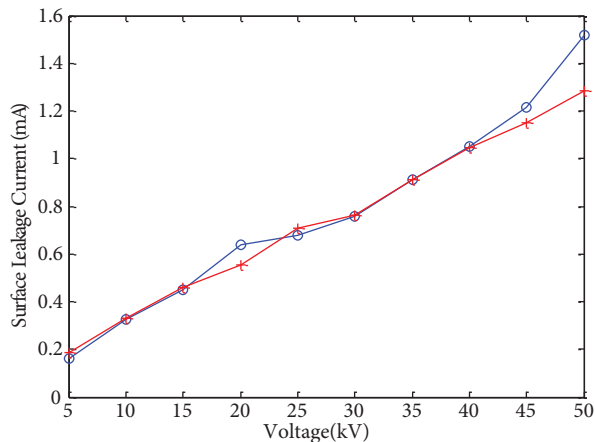


Figure 11. Measured and calculated current curves for insulator ($10.98 \mu\text{S}$ conductivity; o: measured values; +: calculated values).

6. Results

In this study, a new approach was proposed to identify surface leakage currents for the solution of pollution flashover on insulators, which is an important cause of breakdown in high voltage power lines. Leakage currents flowing on the insulator surface depend on the type and amount of the pollutant deposited on the insulator surface. In this study, leakage currents flowing on the insulator surface were mimicked by the movement of an ant and pollutant deposited on the insulator surface was accepted as pheromone substance. By using this approach, the motion of the ants from their present node to another one identified according to the voltage of each node on the insulator surface was directed depending on the amount of the pollutant and the distance between nodes. In the ACA developed, the pheromone substance was distributed randomly along the path that the ants followed and its amount was updated by multiplying by the coefficient of evaporation to take evaporation into account. Similarly, in the computer program, the pollution layer on the insulator surface was also distributed randomly. Additionally, the coefficient of evaporation was kept constant to express the reduction in the amount of pollutant occurring as a result of the formation of dry bands appearing due to heat effect caused by the flow of leakage currents. The conductivity was calculated from the pheromone value and the leakage current value was calculated by using conductivity and voltage difference values between the nodes.

In order to compare the correctness of the values calculated by means of a computer program obtained from theoretical studies, an experimental system was constructed. The results obtained from the computer program and those from the experimental study were evaluated comparatively.

In the studies conducted on pollution flashover on insulators, it is generally assumed that the pollution layer on the insulator surface is constant and calculations are performed accordingly. In fact, it is impossible that the pollution layer on the insulator surface be constant throughout the whole surface. For this reason, the amount of pollutant on the insulator surface was distributed randomly in the calculations performed by the ACA in order to improve the correctness of the modeling.

In the next studies, the coefficient of evaporation, which is used in the ACA to define the variation of pollution resistance on the insulator surface, will be defined as a function of heat energy, which is rising as a result of the leakage currents, instead of being accepted as a constant. This will help to evaluate the movements of leakage current on the insulator surface as well as the stages of flashover more correctly.

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