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Investigation of Insulator Performance Under Artificial Contaminants

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Abstract: There are three types of insulators, namely glass, ceramic, and polymer. Although polymers have hydrophobic properties that make them superior to other materials. However, in its application, ceramic and glass insulators are still used because they are cheaper. Environmental conditions around the work location of the insulator greatly affect its performance. Areas with high levels of pollution will result in the insulator being damaged quickly. The effect of seawater and fly-ash contaminants on the three types of insulators is discussed in this study. Experimental approaches and FEM (Finite element method) based simulations have been carried out. Pollution levels in seawater contaminants were standardized using ESDD (Equivalent Salt Deposit Density). Meanwhile, the level of pollution in fly-ash contaminants is standardized using NSDD (Non-soluble deposit density). Simulations and experiments were carried out at four levels of contamination, namely light, medium, heavy and very heavy. Then the simulation and test results are compared. The greater the ESDD and NSDD values, the greater the leakage current.

Keywords: Finite element method (FEM), fly ash contaminant, insulator, leakage current, sea water contaminant

1. Introduction

Polymer insulators are the development of glass and porcelain insulators that have hydrophobic properties. This hydrophobic nature is able to prevent the accumulation of water contaminants on the surface. However, glass and porcelain insulators are still used today because their price are cheaper than polymer insulators. In glass and porcelain insulators, water contaminants settle on the surface. This results in lower resistance. While at the top of the insulator is still dry, so the resistance is much greater. This results in a flashover phenomenon that can damage the insulator. Meanwhile, polymer insulators with hydrophobic properties cause local flashover. Because not the entire surface will experience a decrease in resistance [1]. Therefore, research on the effect of contaminants is still a very important concern for the development of insulators.

In [2], the author analyzed the effect of acid rain contaminants in the industrial environment on polymer insulators [2]. Acid rain represents the level of contamination in industrial areas caused by combustion residues in power plants and other production processes. Meanwhile, Huafeng Su et al [3] analyzed the effect of the combination salt contaminants and combustion products (fly ash) from the generator on glass, porcelain, and polymer insulators. This represents the environmental conditions in the power plant area located in the coastal area. However, they did not analyze the effect of contamination level on leakage current comprehensively.

Leakage current characteristics can be obtained by experimental and simulation approaches. The measurement of leakage current in glass, porcelain and polymer insulators on the level of salt contamination has been studied [4-6]. However, no one has compared the effect of the level of salt contamination on the three types of insulators on the

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leakage current by experimental approach. For the simulation approach, there are two commonly used methods, namely equivalent circuit-based simulation and finite-element method (FEM). Several studies have carried out the characterization of leakage currents in porcelain, glass and semiconducting glazed insulators based on equivalent circuit-based simulations. The contaminant analyzed is salt water [7-9]. In addition, several studies have conducted FEM simulations to determine the effect of contaminants on insulators [10-23]. However, most of these studies only analyzed polymeric insulators against certain types of contaminants, such as ice [12], salt water [16, 17], and water [20-22]. In [24], the author analyzed the effect of pollutant salt and fly ash on the polymer surface. From the pollutant salt and fly ash, the pollutant fly ash shows higher value of leakage current compared to the pollutant salt. The super heavy NSDD (1.2933) composed of fly ash (2500 mg) and the super heavy ESDD (0.5197) composed of salt (1000 mg) dissolved in water (50 mL). The value of leakage current in NSDD and ESDD at 20 kV voltage level is 6.03 mA and 5.43 mA, respectively. However, investigation about both contaminant effects on three various insulators less attract attention.

Based on these conditions, this study was carried out to determine the effect of salt and fly ash contaminants on the surface of glass, porcelain, and polymer insulators. In the study, two approaches were used, FEM-based simulation and experimental approaches. Simulations and experiments were carried out at four levels of contamination on the types of seawater and fly ash contaminants, namely light, medium, heavy and very heavy. Through a simulation approach, the comparison of the distribution of the electric field and the leakage current in each condition is analyzed. Meanwhile, through an experimental approach, the value of the leakage current is obtained in each condition. Furthermore, the comparison of the value of the leakage current between the simulation and experimental results was analyzed.

2. Simulation Method & Experimental Setup

2.1 Insulator Specification

The size of the polymer insulator design is adjusted to the actual size of the polymer insulator. The specifications and construction of the insulator can be seen in Table I and Figure 1.

Table 1 - Specification of insulator used

Specification	Polymer Insulator	Glass Insulator	Porcelain Insulator
System Voltage (kV)	20	20	20
Rated Voltage (kV)	24	24	24
Arching Distance (mm)	272	146	580
Minimum Creepage Distance (mm)	713	240	300
Insulator Fittings	Cap, Base	Pin	Pin
Material : Shed, Shank	Silicon Rubber	Tempered / Toughned Glass	Porcelain
Height (mm)	330	180	240
Weight (kg)	2.45	3.6	1.5 - 3.8 kg

Fig. 1 - Visualization of the insulator used (image does not represent actual size)

2.2 Modeling and Simulation

Insulator modeling is done in three dimensions. On the top side is a conductor with a diameter of 1 cm. The conductor represents the actual state at the time of operation. The 0.5 mm thick layer of contaminants was added to the surface of the insulator. The air around the insulator was added.

Insulator simulation was carried out with the help of finite-element method (FEM) based software. The parameters used for the simulation include relative permittivity and electrical conductivity. The required parameter values, including polymer components, supporting iron, air, and conductors, are shown in Table II. Meanwhile, the electrical conductivity parameter values for seawater and fly ash contaminants were varied based on the level of contaminants shown in Table III.

2.3 Experimental Setup

The leakage current test is carried out after all preparations of the pre-conditions of the insulator have been completed. This leakage current test uses the step voltage method. This method is one of the methods used to measure the leakage current of equipment, one of which is an insulator. This test method is carried out by gradually increasing the voltage and then observing the change in the value of the leakage current. In this study, the voltage used is high-voltage AC. The test circuit is shown in Figure 2.

The insulator mounted on the support pole is connected to a voltage source that an AC high-voltage generator has generated. The conductor that has been installed on the top side of the insulator represents a live conductor cable. At the bottom of the insulator, support is connected to the ground. A resistor module with a value of 1000 ohms is connected in series with the ground. A voltmeter is connected in parallel with a resistor to measure the voltage. This leakage current test uses the step voltage method, with the voltage levels used 20 kV, 22 kV, 24 kV, 26 kV, 28 kV, and 30 kV. The test was repeated five times as a validation of the test data.

Table 2 - Value of conductivity and permittivity of insulators

Material	Relative Permittivity	Electrical Conductivity (S/m)
Polymer	4.3	1 x 10^-12
Glass	8	9 x 10^-9
Porcelain	5.7	1 x 10^-14
Support Iron	1.0	5.9 x 10^7
Aluminium Conductor	2.2	3.69 x 10^7
Air	1	1 x 10^-14

The electrical conductivity of the contaminants is measured using AMTAST PE02 Conductivity Meter. The contaminants is dissolved in water and the contaminated water is measured using AMTAST PE02 Conductivity Meter.

The contaminated water conductivity is influenced by the Total Dissolved Solid (TDS). The higher the value of TDS, the higher the value of the electrical conductivity.

Table 3 - Conductivity value based on contamination level

No.	Contamination Level	Composition	ESDD / NSDD (mg/cm^2)	Electrical Conductivity (S/m)
Polymer Insulator				
1	Seawater - Light	2 g/L	0.0520	2.63 x 10^-4
2	Seawater - Medium	4 g/L	0.1039	2.76 x 10^-4
3	Seawater - Heavy	9 g/L	0.2339	3.14 x 10^-4
4	Seawater - Very Heavy	20 g/L	0.5197	3.51 x 10^-4
5	Fly Ash - Light	115 mg	0.0598	1.76 x 10^-4
6	Fly Ash - Medium	380 mg	0.1975	1.93 x 10^-4
7	Fly Ash - Heavy	1100 mg	0.5717	2.30 x 10^-4
8	Fly Ash - Very Heavy	2500 mg	1.2993	2.82 x 10^-4
Glass Insulator				
9	Seawater - Light	1.04 g/L	0.0520	0.10 x 10^-4
10	Seawater - Medium	2.07 g/L	0.1039	0.14 x 10^-4
11	Seawater - Heavy	4.65 g/L	0.2339	0.20 x 10^-4
12	Seawater - Very Heavy	10.37 g/L	0.5197	0.24 x 10^-4
13	Fly Ash - Light	104 mg	0.0520	0.09 x 10^-4
14	Fly Ash - Medium	394 mg	0.1970	0.07 x 10^-4
15	Fly Ash - Heavy	1143 mg	0.5720	0.05 x 10^-4
16	Fly Ash - Very Heavy	2600 mg	1.303	0.04 x 10^-4
Porcelain Insulator				
17	Seawater - Light	2.7 g/L	0.0520	0.85 x 10^-4
18	Seawater - Medium	5.2 g/L	0.1039	0.95 x 10^-4
19	Seawater - Heavy	12 g/L	0.2339	1.15 x 10^-4
20	Seawater - Very Heavy	27 g/L	0.5197	1.25 x 10^-4
21	Fly Ash - Light	156 mg	0.0598	1.0 x 10^-4
22	Fly Ash - Medium	514 mg	0.1975	1.20 x 10^-4
23	Fly Ash - Heavy	1488 mg	0.717	1.30 x 10^-4
24	Fly Ash - Very Heavy	3381 mg	1.2993	1.35 x 10^-4

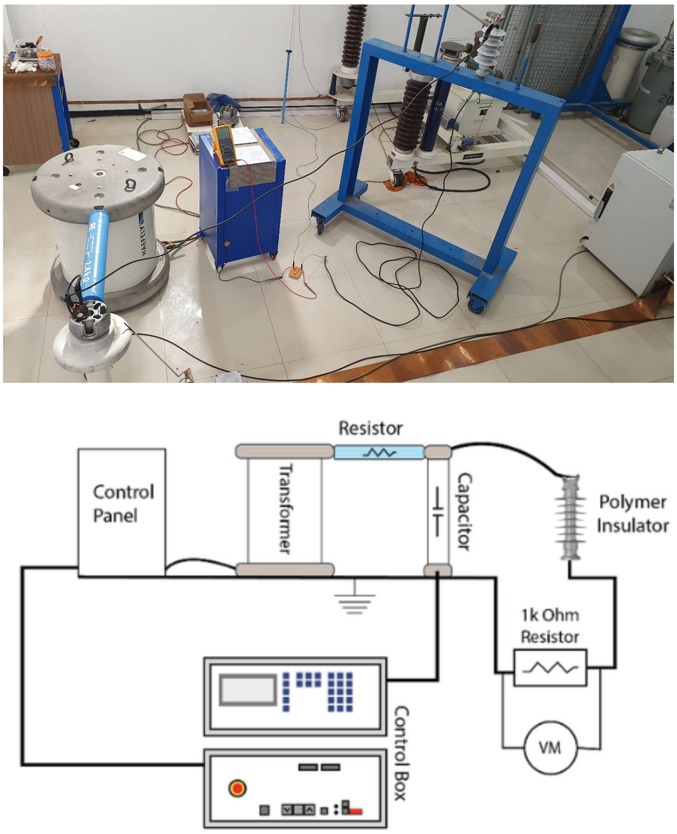


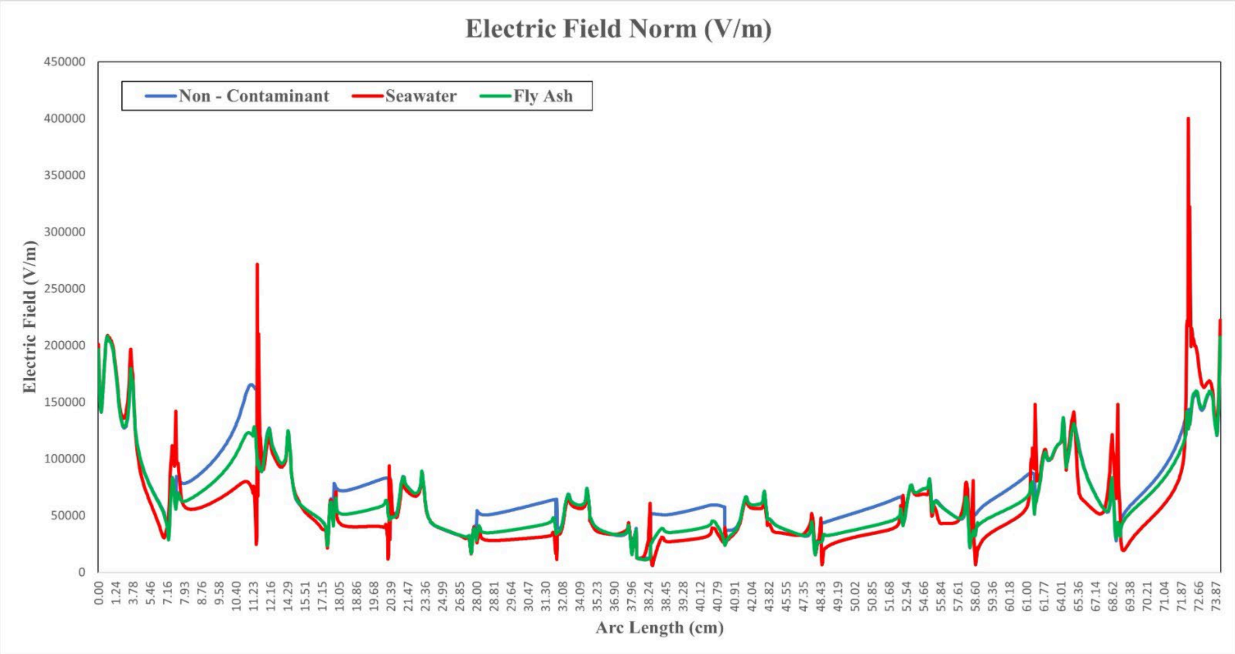
Fig. 2 - Experimental setup for leakage current measurement

3. Results and Analysis

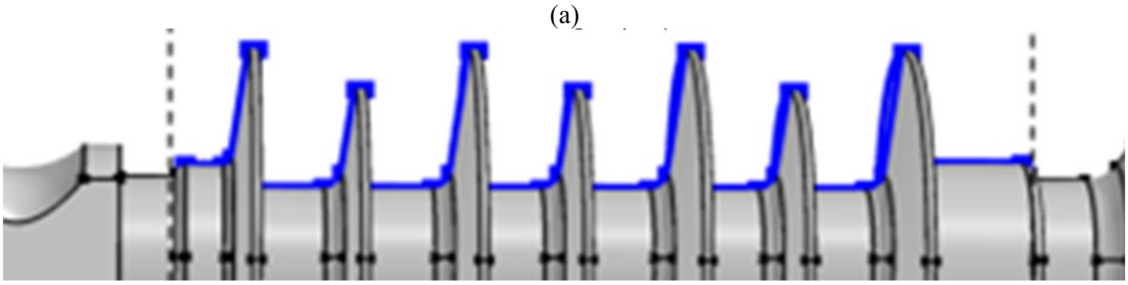
3.1 Electric Field Distribution

The blue and red lines are the distribution of the electric field on the insulator without any contaminants and the electric field distribution of the salt-contaminated insulator, as shown in Figure 3a. The green line is the electric field distribution of the fly ash-contaminated insulator. The results show that the electric field graph of the insulator without contaminants looks more sloping and does not appear to produce steep increases and decreases. Each graph of the electric field of the contaminant polymer insulator appears to have a graph that fluctuates and has an extreme shape. The peak pattern formed is always above the chart without any contaminants. In addition, the peak formed is also seen to dip sharply upwards. Meanwhile, the valley pattern formed is always below the chart without contaminants. In Figure 3a, the insulator without contaminants results in a maximum electric field value of 0.207 × 10^6 V/m, while for salt and fly ash contaminants, the maximum value is 0.4 × 10^6 V/m and 0.208 × 10^ 6 V/m. It shows that the higher the value of the dielectric constant of a contaminant, the higher the distribution of the electric field on the glass insulator. In Figure 3b. the insulator fin marked by blue line is the arc length. In Figure 4 and 5 the arc length is the same as shown in Figure 3b. the arc length ramps across the insulator fin.

In Figure 4, the results show that the electric field graph of the insulator without contaminants looks more sloping and does not appear to produce steep increases and decreases. The insulator without contaminants results in a maximum electric field value of 0.056 × 10^6 V/m, while for salt and fly ash contaminants, the maximum value is 0.36 × 10^6 V/m and 0.55 × 10^6 V/m.



(a)



(b)

Fig. 3 - (a) Electric field distribution on polymer insulators (b) creepage distance visualization

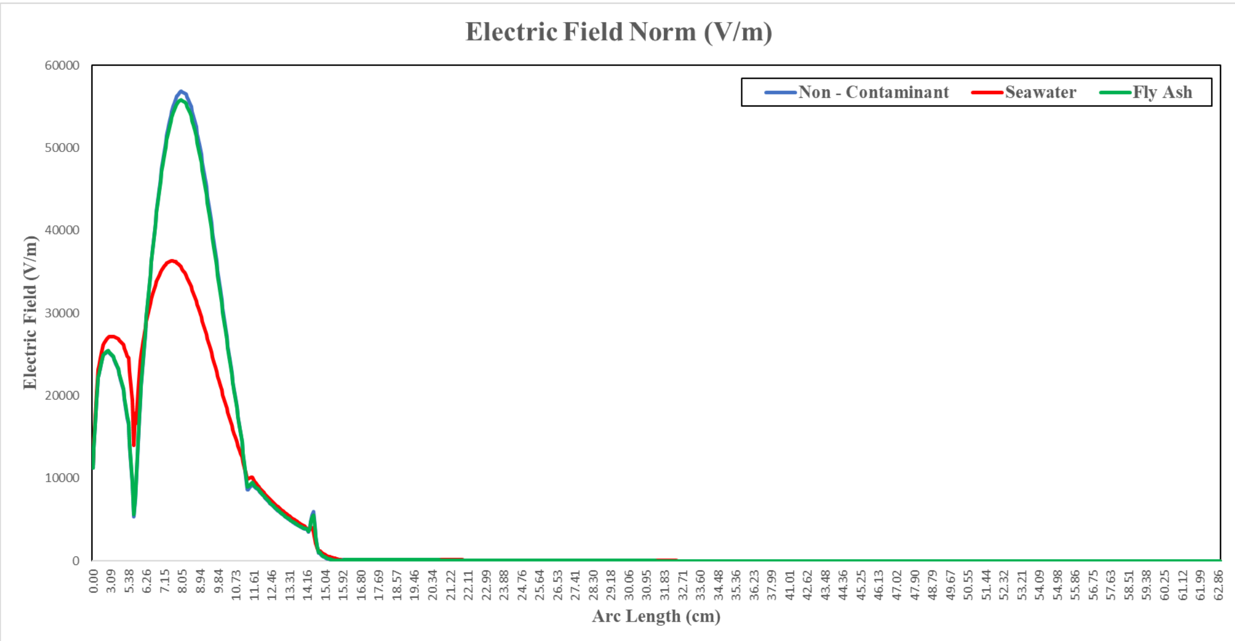


Fig. 4 - Electric field distribution on glass insulators

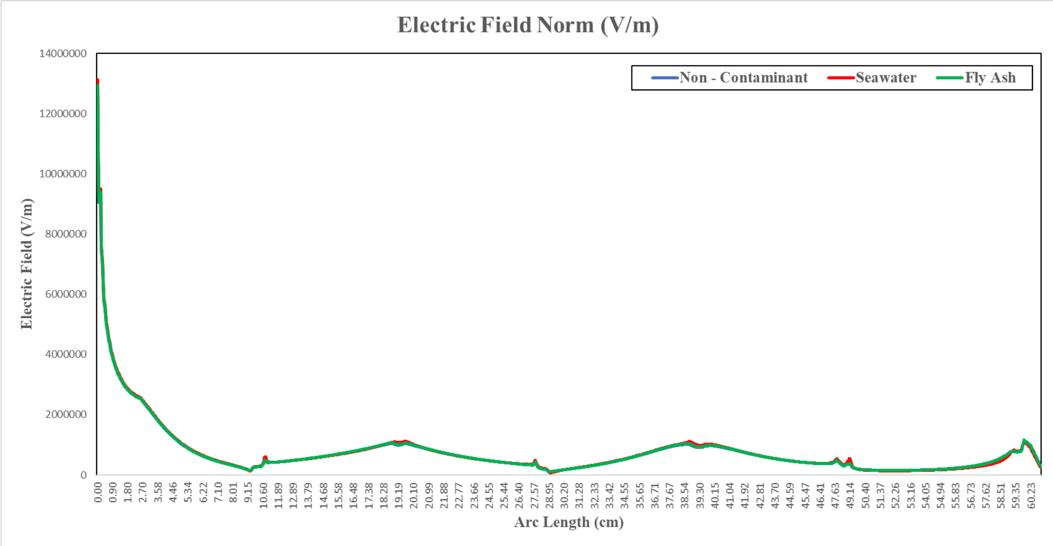


Fig. 5 - Electric field distribution on porcelain insulators

The simulation results show that the electrical field graph of the insulator without contaminants is the lowest, followed by salt contaminants, and fly ash contaminants are the highest. It can be seen that the porcelain insulator without contaminants has an increase and decrease in the value of the electric field, which is not extreme. In contrast, the porcelain insulator with fly ash contaminants has the most extreme increase and decrease in the value of the electric field. The results of the analysis of the electric field of porcelain insulators without contaminants and porcelain insulators with salt and fly ash contaminants are shown in Figure 5 and the highest is fly ash contaminants.

3.2 Polymer Insulator

The leakage current simulation results show that each simulated contaminant's leakage current value impacts increasing the leakage current. In the simulations results at a voltage level of 20 kV, the value of leakage current without contaminants is 0.07721 mA. At the same voltage level, the leakage current value of the fly ash and seawater contaminants are 0.09442 mA and 0.09818 mA.

From experiment results at a voltage level of 20 kV, the leakage current value for clean insulators, fly ash and seawater are 0.07424 mA, 0.08892 mA and 0.0890 mA, respectively. The comparison between the simulation results and the leakage current test on polymer insulators is shown in Table IV and Table V. The mean values are 0.00363 mA (fly ash) and 0.00649 mA (seawater). The standard deviation values for fly ash and seawater contaminants are 0.001114 and 0.00253, respectively. The data on seawater contaminants on polymer insulators has the most significant data deviation.

3.3 Glass Insulator

In the simulation results at a voltage level of 20 kV, the value of leakage current for clean condition, seawater and fly ash contaminants are 0.22039 mA and 0.26811 mA as shown in Table VI and Table VII.

From the experimental results at a voltage level of 20 kV, the leakage current value is 0.186 mA (clean condition), 0.194 mA (fly ash contaminants) and 0.266 mA (seawater contaminants). The mean values for fly ash and seawater contaminants are 0.01411 mA and 0.00649 mA.

Table 4 - Comparison of leakage current values between simulation results and experiments on polymer insulators (Seawater pollutants)

Seawater Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.077	0.087	0.097	0.106	0.115	0.123	0.074	0.084	0.093	0.101	0.110	0.118
Light	0.088	0.097	0.106	0.116	0.125	0.135	0.083	0.093	0.103	0.111	0.118	0.125
Medium	0.090	0.100	0.108	0.118	0.127	0.137	0.085	0.094	0.104	0.114	0.121	0.130
Heavy	0.094	0.103	0.112	0.122	0.131	0.142	0.088	0.097	0.106	0.116	0.125	0.134
Very Heavy	0.098	0.107	0.116	0.129	0.136	0.147	0.089	0.098	0.107	0.117	0.126	0.135

Table 5 - Comparison of leakage current values between simulation results and experiments on polymer insulators (Fly-ash pollutants)

Fly-ash Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.077	0.087	0.097	0.106	0.115	0.123	0.074	0.084	0.093	0.101	0.110	0.118
Light	0.087	0.096	0.105	0.113	0.121	0.130	0.083	0.093	0.103	0.111	0.118	0.125
Medium	0.090	0.098	0.107	0.116	0.124	0.133	0.085	0.094	0.104	0.114	0.121	0.130
Heavy	0.092	0.101	0.110	0.118	0.127	0.135	0.088	0.097	0.106	0.116	0.125	0.134
Very Heavy	0.095	0.103	0.112	0.120	0.129	0.139	0.089	0.098	0.107	0.117	0.126	0.135

Table 6 - Comparison of leakage current values between simulation results and experiments on glass insulators (Seawater pollutants)

Seawater Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.220	0.242	0.264	0.287	0.309	0.331	0.186	0.21	0.24	0.27	0.296	0.332
Light	0.235	0.259	0.282	0.306	0.329	0.353	0.228	0.258	0.292	0.326	0.364	0.394
Medium	0.245	0.269	0.294	0.318	0.343	0.367	0.238	0.266	0.292	0.322	0.356	0.384
Heavy	0.259	0.285	0.311	0.336	0.362	0.388	0.254	0.28	0.308	0.336	0.37	0.394
Very Heavy	0.268	0.295	0.322	0.349	0.375	0.402	0.266	0.29	0.326	0.352	0.384	0.41

Table 7 - Comparison of leakage current values between simulation results and experiments on glass insulators (Fly-ash pollutants)

Fly-ash Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.220	0.242	0.264	0.287	0.309	0.331	0.186	0.21	0.24	0.27	0.296	0.332
Light	0.233	0.256	0.279	0.303	0.326	0.349	0.212	0.242	0.27	0.298	0.328	0.364
Medium	0.228	0.251	0.274	0.296	0.319	0.342	0.21	0.252	0.284	0.306	0.328	0.346
Heavy	0.223	0.246	0.268	0.290	0.313	0.335	0.2	0.218	0.248	0.28	0.31	0.34
Very Heavy	0.221	0.243	0.265	0.287	0.309	0.331	0.194	0.22	0.244	0.27	0.304	0.334

The standard deviation values for fly ash and seawater contaminants are 0.009501 and 0.01124, respectively. It can be concluded that the data on seawater contaminants on glass insulators has the largest data deviation.

3.4 Porcelain Insulator

The leakage current simulation results show that each simulated contaminant's leakage current value impacts increasing the leakage current. In the simulation results at a voltage level of 20 kV, the value of leakage current without contaminants is 0.09372 mA. For contaminated insulators, the leakage current is 0.16631 mA (seawater) and 0.18226 mA (fly ash) as shown in Table VIII and Table IX.

From experiment results at a voltage level of 20 kV, the leakage current value without contaminants is 0.103258 mA. At the same voltage level, the leakage current value of fly ash contaminants is 0.18966 mA. The measured leakage current value for salt contaminants with the same voltage level is 0.1843 mA. The mean values for fly ash and seawater contaminants are 0.01981 mA and 0.01541 mA. The standard deviation values for fly ash and seawater contaminants are 0.007409 and 0.00629, respectively. It indicated that the fly ash contaminant data on porcelain insulators has the most significant data deviation.

Table 8 - Comparison of leakage current values between simulation results and experiments on porcelain insulators (Seawater pollutants)

Seawater Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.094	0.106	0.114	0.125	0.135	0.143	0.103	0.116	0.124	0.135	0.145	0.153
Light	0.114	0.122	0.133	0.145	0.158	0.175	0.162	0.173	0.194	0.214	0.233	0.241
Medium	0.126	0.139	0.145	0.156	0.175	0.188	0.174	0.195	0.202	0.225	0.236	0.244
Heavy	0.153	0.163	0.182	0.209	0.227	0.245	0.186	0.204	0.225	0.245	0.266	0.284
Very Heavy	0.166	0.175	0.198	0.217	0.256	0.273	0.190	0.216	0.238	0.257	0.278	0.299

Table 9 - Comparison of leakage current values between simulation results and experiments on porcelain insulators (Fly-Ash pollutants)

Fly-ash Contamination Level	Applied Voltage (kV)											
	20	22	24	26	28	30	20	22	24	26	28	30
	Simulation Results (mA)						Experimental Results (mA)					
Clean	0.094	0.106	0.114	0.125	0.135	0.143	0.103	0.116	0.124	0.135	0.145	0.153
Light	0.133	0.152	0.168	0.185	0.206	0.226	0.162	0.173	0.194	0.214	0.233	0.241
Medium	0.160	0.169	0.178	0.196	0.217	0.234	0.174	0.195	0.202	0.225	0.236	0.244
Heavy	0.173	0.182	0.197	0.217	0.237	0.265	0.186	0.204	0.225	0.245	0.266	0.284
Very Heavy	0.182	0.195	0.214	0.235	0.251	0.277	0.190	0.216	0.238	0.257	0.278	0.299

Based on the experimental results with clean conditions, the smallest and largest values of leakage current are polymer insulators and glass insulators. If sorted by insulator size, the biggest and smallest are polymer and glass insulators, respectively. It can be expected that the value of the leakage current is affected by the creepage distance, due to the difference of the insulator size. Meanwhile, the comparison of leakage current values between seawater and fly ash contaminants is less significant in polymer and porcelain insulators. However, in glass insulators, it is known that the leakage current value in seawater contaminants is greater than other contaminants at the same level of contamination. But the greater the level of contamination, the smaller the value of the leakage current. It seems this is caused by fly ash contaminants on the glass insulator being lifted and sticking to the test electrode; thus, the dielectric strength of the glass insulator increases.

It can be shown that the trends from simulation results have a good agreement with experimental results. It can be drawn that the greater the contamination level, the greater the electrical conductivity value. Therefore, the level of leakage current is affected by electrical conductivity value.

4. Conclusion

In this paper, the effect of two contaminants (fly ash and seawater) on three types of insulating materials (polymer, glass, and porcelain) on the characteristics of electric field distribution and leakage current has been carried out. The purpose of comparing the two contaminants is to observe which of the contaminants produce the higher leakage current on different types of insulators. The dielectric strength of each insulator with different contaminant is also observed. The characteristics are obtained from the FEM-based simulation and experimental results. Based on the simulation and experimental results, it is known that the value of the leakage current is affected by the creepage distance of an insulator. In addition, seawater contaminants have a higher conductivity so that the leakage current is higher.

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