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Effect Analysis of Pollutant Distribution on the Flashover Performance of Porcelain and Composite insulator using Finite Element Method

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ABSTRACT

The paper presents the investigation of flashover performance on porcelain and composite insulators by using the finite element-based method. The main focus of this study was to investigate the performance of insulators when operated under pollution since pollution is the leading factor of flashover phenomenon. In terms of the pollution configuration, different methodologies were proposed according to the nature of the insulating material. For porcelain insulators, the assumption based on previous research is that pollution accumulates as a conductive layer covering the surface of the insulator. In contrast, the composite insulator will have particulate matter to indicate the formation of a pollution layer on the insulator surface as the hydrophobic property would provide additional resistance to contamination. The simulation was conducted in finite element-based method software by applying different types of pollution configurations to porcelain and composite insulator surfaces. Evaluation of the simulation results will be based on the evaluation of electric field strength across the insulators surfaces. By comparing the electric field profiles across the insulator's surfaces, the flashover performances of the insulators can be determined. Based on the evaluation results, the composite insulator shows better performance under pollution conditions, providing a more stable operation and stands as a more economical replacement for porcelain insulators to ensure the sustainability and reliability of the power system.

Keywords: Electric field; Flashover; Finite element method; Insulator; Pollution

1. Introduction

Insulation is crucial in a power transmission system to withstand the overvoltage conducted through the system while maintaining efficient power delivery. In terms of an electrical transmission system, insulators are required to resist the high voltage potential in between the conductors

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and the unexpected lightning strikes to maintain the stability of the electrical system. Generally, any properly designed insulator is expected to withstand the voltages within the insulator specification. However, the presence of pollutants has affected the insulation performance and greatly contributes to the occurrence of flashover phenomena. Distinct outdoor ambient will expose the insulator to different pollutants, for example, salt deposits in coastal areas, ice accumulation in cold climate regions, or dust and dirt in dusty environments. In conjunction with factors such as humidity, ambient temperature and UV radiation, the insulating properties are significantly affected and limited to some extent. Therefore, an insulator is required to possess characteristics such as pollutant resilience, and chemical and heat resistance to operate under different conditions. Therefore, correct material selection is essential to maximize the cost efficiency and cost effectiveness in insulator design.

The most common insulator used in power transmission and distribution is the porcelain insulator, while composite the insulator serves as an alternative. The composite insulators became an alternative option due to their performance under pollution conditions, and their lightweight, easy handling and installation. A composite insulator performs better under pollution conditions compared to porcelain or glass insulators due to the hydrophobic properties of its surfaces which sustain the pollutants to dissolve and deposit as a pollution layer [1-6]. However, research regarding the flashover performance between porcelain and composite insulators corresponding to the material characteristic and pollutant distribution is limited. While practically proven that the pollution flashover gradients of composite insulator outperformed both glass insulator and porcelain insulator [1], other research focused on proposing a mathematical model to predict the flashover performance of insulators under different conditions [7-10]. The majority of flashover model research in the field of pollution has relied on the Obenaus mathematical model to determine the remaining resistance on the pollution layer that is connected to the arc [11]. Therefore, the residual resistance varies as an important parameter that will significantly affect the results. Consequently, the parameters are strictly referenced under different conditions, which contribute to the complexity of analyzing and predicting the flashover voltage. Nevertheless, there are very limited resources that have direct comparison between flashover performance of composite insulator and porcelain insulator as a practical flashover test requires a vast investment [12, 13].

In this paper, the formation of pollutants due to the nature of the material is the main focus that distinguishes the flashover performance difference between porcelain insulators and composite insulators. Pollutants are assumed to accumulate and deposit on the porcelain insulator, while the composite insulator is polluted by the presence of particulate matter. The analysis is conducted through the finite element-based software simulation, where different parameters such as relative permittivity and electrical conductivity are referenced as the representatives of different materials to carry out the simulation.

2. Methodology

The study involving the flashover of contaminated insulators is highly associated and deduced from Obenaus model [14] over the past decades. As an empirical model, the Obenaus model has contributed greatly to the development of flashover study, which is with and mainly classified under the AC/DC model and into static or dynamic models. In this study, the flashover process is expressed by an ideal DC model referencing the Obenaus model.

2.1 Flashover model

Fig. 1 illustrates a simple flashover model by neglecting the complex geometry of insulators. The flashover process is represented by an electric arc in series with the residual resistance of the insulator. The electric arc is defined by a voltage-current relationship, which is used to express the flashover voltage:

$$U = AXI^{-n} + R(x)I, \qquad (2.1)$$

where U is the applied voltage to the insulator; the electric arc (Earc), is represented by AXI^{-n}; A and n are the arc constants that vary with the arc characteristic and insulator type; X is the length of the arc; I is the current that flows through the surface of the insulator and $R(x)$ represents the resistance of the pollution layer.

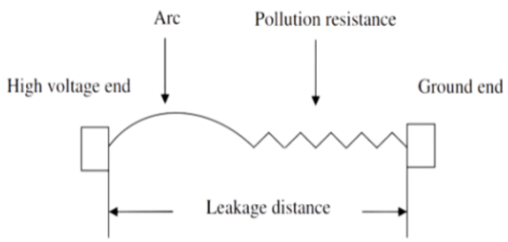


Fig. 1. Obenaus model [9].

While the Obenaus model is used to predict the flashover voltage, the Hampton criterion is also helpful in determining the condition for the arc to propagate. An arc can only propagate along the contaminated insulator when the electric field along the arc path is higher than the arc gradient, which can be expressed by Hampton condition: Ep > Earc, where Ep is the electric field of pollution layer and Earc is the voltage gradient of the arc.

2.2 Finite element based software

In this study, Finite Element Based Software, COMSOL Multiphysics, was primarily used to investigate the electric field differences when different pollutant distributions are applied [15]. A simple porcelain insulator and composite insulator were modelled in software and two different physics were applied to obtain the electric field, which are electrostatic and electric current. The differences between the two physics are the computation and the parameters required in the simulation. For electrostatic, relative permittivity is used to define the insulator whereas electric current uses electrical conductivity instead. In short, there are two different simulations conducted to study the electric field distribution with respect to different pollutant distributions, where different computations are implemented based on the physics applied. All simulation is conducted in steady state condition as all parameters involved are pre-defined based on various research.

2.3 Electrostatic

In electrostatic simulation, the model is processed with Poisson's or Laplace equation to compute the result. The equation is solved numerically to obtain the electric potential or electric field in the system; the corresponding equations applied are shown below:
Electric Potential is computed in Eq. (2.2)

$$E = -\nabla V, \qquad (2.2)$$

which represents the relationship between the electric field (E) and the electric potential (V) in a given space. With the aids of Gauss's Law, the electrostatic field is expressed in Eq. (2.3)

$$-\nabla \cdot (\varepsilon \nabla V - P) = \rho, \qquad (2.3)$$

where ε is the permittivity of vacuum, P is the electric polarization vector and ρ is the space charge density.

2.4 Electric current

In electric current simulation, the result is computed through the application of continuity equation and Ohm's law. The continuity equation describes the conservation of electric charge, while Ohm's law relates the current density to the electric field and conductivity of the medium. The equations are solved numerically to obtain the electric current and electric potential in

the system; the corresponding equations applied are shown below:
The continuity is expressed in Eq. (2.4):

$$-\nabla \cdot J = -\frac{\partial \rho}{\partial t}, \tag{2.4}$$

Ohm's law is expressed in Eq. (2.5):

$$J = \sigma E, \tag{2.5}$$

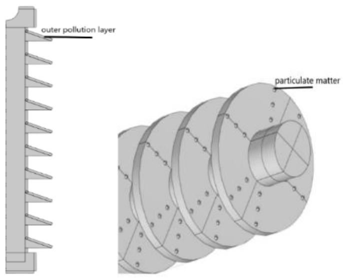
where J is the electric current density; ρ is the charge density; σ is the electrical conductivity of the medium and E is the electric field.

2.5 Test condition and process

Study regarding the flashover process has always been challenging as the phenomenon is a complex process that involves multiple physical and chemical processes, which enable the analysis to be conducted in different aspects and further increase the complexity. In this study, the main focus will be placed on the effect of pollutant distribution to the flashover performance, while the different pollutant distributions are considered as the results of the insulator material's nature. In the case of a porcelain insulator, it is more susceptible to pollutants as water droplets tend to remain longer on the surface of porcelain, forming a pollution layer that will lead to flashover phenomena. In contrast, a silicone rubber composite insulator consists of better pollutant resistance due to the hydrophobic property that repels the water droplet. Therefore, it is assumed that the pollutant is accumulated as particulate matter on a silicone rubber insulator.

The pollutant distribution of porcelain insulator and composite insulator are illustrated in Fig. 2 below, where the pollutant of porcelain insulator is set to a pollution layer of 5mm thickness while the particulate matters are set to be a sphere of 1.5 mm radius.

The simulation will be conducted by supplying 33kV to the insulator and the insulator is surrounded by an air layer. Due to the limitation of the software used, different parameters cannot be simulated at the same time and the simulation will be conducted in terms of electrostatic and electric current. The peak value of electric field will be collected and used as the prime factor to determine the flashover performance, whereby a higher electric field increases the chances for flashover to occur and vice versa. This statement is made by complying to the definition of electrical breakdown, where an insulating material will lose its insulating property when the electric field generated by an applied voltage surpasses the dielectric strength of an insulating material. While referencing to the Obenaus model, a simple flashover model will be applied and Hampton condition will be neglected. Similarly, the insulator will only be defined as a sole material as the main focus is to determine the effect of pollutant distribution to the flashover performance.



(a) (b)

Fig. 2. (a) Pollutant distribution of porcelain insulator; (b) Pollutant distribution of silicone rubber insulator.

A brief flowchart is shown in Fig. 3 to demonstrate the process of the simulation. First, the porcelain and composite insulators are modelled and defined independently based on their material. Secondly, the user is required to choose the physics to conduct the simulation, which also can be defined prior the modelling process. After the computation method is chosen, the mesh command is initiated to determine the element size for the FEM computation. Once the setup is finished, the simulation will be conducted to calculate the results of voltage potential and the electric field distribution. Lastly, the electric field values are recorded as a reference to predict the flashover performance.

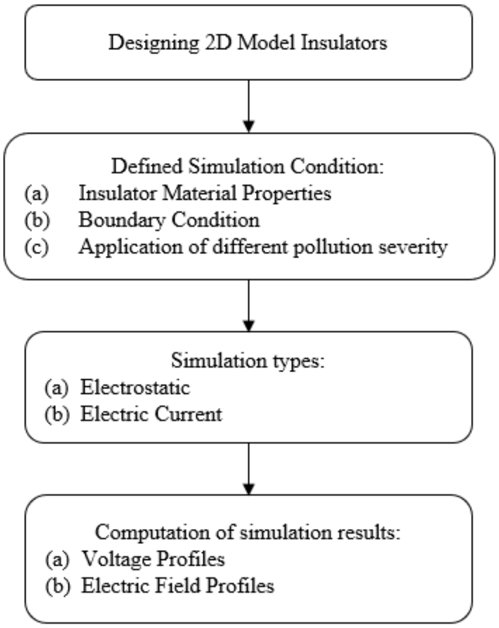


Fig. 3. Flowchart of finite element analysis.

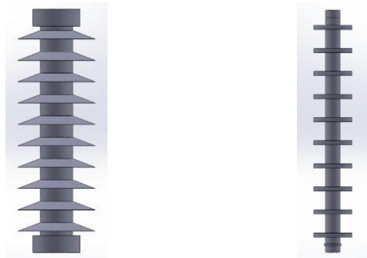
In Table 1, parameters used to define the materials are listed; all of the listed parameters are referenced from the research papers [16-20]. For the presence of pollutant, sodium chloride was used as the pollutant and the electrical conductivity was defined under the condition of 0.025mol/lit.

Table 1. Parameters defining the material.

Material	Relative permittivity	Electrical Conductivity (S/m)
Porcelain	7	1×10^{-12}
Silicone rubber	3.5	1.25×10^{-13}
Pollutant (NaCl)	6	0.28
Air	1	1×10^{-15}

2.6 3D Modeling of Porcelain Insulator and Composite Insulator

The insulators were designed by referencing to the real-world products. The modelling and the details are illustrated in the Fig. 4 and Table 2 below:



(a) (b)

Fig. 4. 3D model of (a) porcelain insulator and (b) composite insulator.

Table 2. Modelling specification of porcelain insulator and composite insulator.

Material	**Porcelain insulator**	**Silicone rubber**
Creepage distance	1330mm	1240mm
Core diameter	76mm	38mm
Number of sheds/disks	10	10
Diameter of shed	180mm	96mm
Distance between shed	30mm	50mm
Total length	570mm	640mm

3. Result and Discussion

The insulators were simulated in finite element-based software under the conditions listed in the previous section. While exposed to the air and stressed under 33kV, the insulators were simulated under different contaminated conditions referencing to their characteristics. In COMSOL Multiphysics, the boundary conditions are limited in electrical related simulation as the ambient environment is considered as ideal when carrying out the simulation. In this case, boundary conditions are defined as the material’s property and voltage applied to the terminal, which is shown in Figs. 5-6.

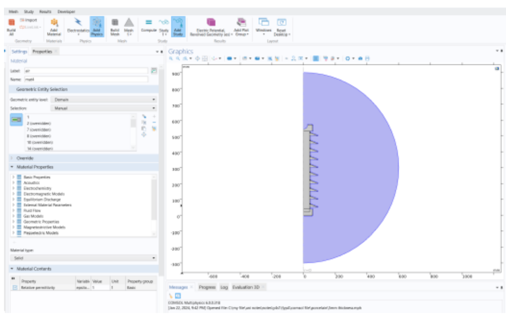


Fig. 5. Air layer property.

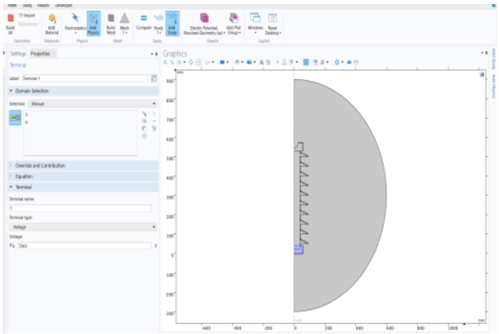


Fig. 6. Voltage Terminal Domain.

The analysis will be conducted by comparing the electric field of the insulator when it is unpolluted and when the pollutant is applied. By referencing the electric field of an unpolluted insulator, the electric field differences are obtained and used as the prime factor to predict the flashover performance of the insulators.

Fig. 7 illustrates the computational domain of a polluted porcelain insulator.

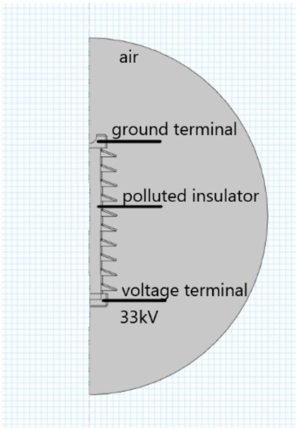


Fig. 7. Computational Domain.

3.1 Electric field strength analysis of porcelain insulator

Assuming that the pollutant will form as a conductive layer covering the porcelain insulator, three pollution sectors were suggested to be the main study focus to determine the impact of pollutant distribution: the top, the core (body and shed) and the bottom. The electric field values collected from the contaminated insulator were then compared with the value of the unpolluted insulator to obtain the electric field increment. In Table 3, the maximum electric field value in respect to the pollutant distribution is shown. The simulation was conducted with the purpose to study which sector of an insulator was more susceptible to the pollution by referencing the change of electric field value.

In the electrostatic simulation, it was observed that pollutant surrounding the core and the voltage terminal will have a significant impact on the electric field strength when compared to other sectors. In contrast, the electric field remained unchanged when the pollutant was applied to the ground terminal, which is acceptable since the contaminant did not block the path of the current flow. The insulator was considered to be in high pollution level when it was evenly polluted, which has shown the largest electric field increase of 29.19% when compared to the unpolluted insulator.

In the electric current simulation, which refers to electrical conductivity for the computation, the electric field strength varied drastically ranging from minimum 13.49% to maximum 549.89%. It was observed that pollutant covering the core will greatly affect the electric field strength when compared to other sectors. When the analysis was conducted independently in respect to the polluted sector, the pollutant covering the body sector has the greatest impact on the electric field distribution while the pollutant located at the voltage terminal(bottom) and the sheds has the minimum impact on the electric field distribution. However, the latter results were assumed to be inaccurate as the role of these two sectors was to withstand the intense electric field from the insulator. The resulting error was assumed to be the massive disparity of the electrical conductivity between the insulator (1x10^{-12}S/m) and the pollutant (0.28 S/m). As a result, the sector with a larger surface area, such as the body, was stressed under intense electric field strength, while the other sectors with smaller surface area, such as the sheds, were partially excluded from the electric field computation.

Table 3. Simulation result of porcelain insulator.

Polluted Section	Electric field peak value (V/m) Electrostatic	Electric current
Unpolluted	2.09×10^5	9.34×10^4
Evenly polluted	2.70×10^5	6.07×10^5
Top and bottom polluted	2.38×10^5	2.51×10^5
Top only	2.09×10^5	2.45×10^5
Bottom only	2.32×10^5	1.17×10^5
Body and shed(core)	2.34×10^5	5.76×10^5
Body only	2.12×10^5	4.75×10^5
Shed only	2.24×10^5	1.06×10^5

3.2 Electric field strength analysis of composite insulator

By having particulate matter as the pollution source, the pollutant distribution was replaced with pollution severity instead as results indicated that pollutant taking form of particulate matter has minimum impact on the electric field behavior. Three levels of pollution severity are proposed and represented by the number of particulate matters, starting with 60 particulate matters in low pollution level and increasing 60 per level. The particulate matters were considered to be uniformly distributed on the shed of the insulator. In Table 4, the electric field strength corresponding to different pollution severity was collected under electrostatic simulation and electric current simulation.

In the electrostatic simulation, the electric field increased from the range of maximum 13.51% to minimum 10.89%. In contrast, the electric field varied drastically in electric current simulation, which ranged from a maximum 63.97% to a minimum 20.54%. Based on the results shown in Table 4, the particulate matter was assumed to have limited impact on the change of electric field. In the electrostatic simulation, the electric field tended to increase slowly despite the pollution level increase. The same results were also obtained from the electric current simulation, whereby the electric field changed slowly in medium and low pollution levels.

Table 4. Simulation result of composite insulator.

Pollution severity	Electric field peak value (V/m) Electrostatic	Electric Current
Unpolluted	4.96×10^5	2.97×10^5
High	5.63×10^5	4.87×10^5
Medium	5.51×10^5	3.68×10^5
Low	5.50×10^5	3.58×10^5

3.3 Result analysis

In this section, the analysis will be conducted in terms of electric field differences between the porcelain insulator and composite insulator. Based on the summary in Table 5, it was noticeable that the electric field changes drastically in an electric current simulation, which is reasonable since the pollutant and insulators have a huge disparity in terms of the electrical conductivity. By referring to the electric value change, it was observed that the porcelain insulator was more susceptible to pollution as the electric value increased drastically. Therefore, the pollution style will affect an insulating property significantly, since the pollution style taking form as a covering layer has greater impact on the change of electric field. Subsequently, a hydrophobic property can help improve a flashover phenomenon greatly, as the resulting electric field will be lower if the pollutant accumulates as particulate matter. Thereby, a simple conclusion can be drawn that a porcelain insulator is more susceptible to pollution when compared to a composite insulator.

Table 5. Comparison of Electric Field Increment.

Simulation Type	Maximum percentage increase of electric field when exposed to high pollution level	
	Porcelain insulator	Composite insulator
Electrostatic	29.19%	13.51%
Electric Current	549.89%	63.97%

4. Conclusion

In this paper, a simple static DC model was used to study the effect of pollutant distribution on the flashover performance, where the pollutant style was assumed to be different due to the nature of the insulator's material. The results indicated a pollution cover would significantly affect the flashover performance of an insulator, whereas pollution taking form as particulate matter would only affect performance slightly. It can be concluded that a composite insulator with hydrophobic will perform better under certain polluted conditions. Nonetheless, the variant of pollutant is the limitation of this study as both porcelain and composite insulators are susceptible to different pollution sources. In short, the results have shown that a porcelain insulator was more susceptible to pollution while a composite insulator will perform better under pollution. Therefore, it is suggested that a composite insulator will be a better insulator to operate under pollution, providing a more stable operation and stand as a more economical replacement for porcelain insulators.

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