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Evaluation of Electromagnetic Fields on Polluted Polymer Insulator under Lightning Impulse Current

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***Abstract*—This paper presents a simulation study of a polluted insulator under a direct lightning impulse current. The pollution condition was considered and divided into two cases which are partial and full pollution. Under those conditions, the electromagnetic profiles of the insulator were evaluated. In the study, six points of measurement recognised as the weak points of the insulator were introduced to be evaluated. Meanwhile the electric field and magnetic field values at the points were related to the common discharge and damage of polymer insulators. It was found that the pollution condition effectively influenced the electric field and magnetic field profile. A significant difference in the electric field value indicated at least 65.15 % in both cases. For the magnetic field, at least a 10.9 % percentage difference was recorded.**

Keywords-Electromagnetic field; polymer insulator; lightning impulse current; polluted insulator; surface discharges

I. Introduction

Recent trends show a large demand for polymer insulators from the power industries due its superior performance against rugged conditions. In addition, the use of polymer insulators economically reduces the cost of manufacture, handling and installation due to the decrease in labour work because polymer insulators are lightweight and durable compared to heavy and easy-to-chip porcelain insulators. Comparatively, polymer insulators need less maintenance compared to others due to their high performance when polluted and a hydrophobic characteristic that allows a washing effect during rain.

To emphasise, the washing effect depends on the rain, which makes the effect unreliable throughout the year. During the season with no rain, the pollution and airborne conductive particles accumulate on the insulator surface, hence reducing the surface resistivity [1]. By this means the surface conductivity increases and the electrical performance of insulator may change accordingly. Most studies on polluted insulators have proved that an electrical breakdown of an insulator occurs due to reduced performance as a result of pollution [2-4]. Also, electrical discharges have been recorded to appear on the surface of a polluted insulator during its normal operation, commonly recognised as partial discharges, dry-band discharges and corona discharges [5, 6].

In most research, the formation of contaminants is assumed to covers all parts of the insulator. Salt fog and artificial pollution tests were revised in IEC 60060 and IEC 60507 as a guide to apply a full pollution condition on an insulator surface. However in the real application, the possibility of surface pollution to be partially polluted is higher with regard to the wind movement, insulator placement and weather conditions.

Note that different profiles of pollution may provide for a different electrical performance of the insulator. Therefore in this study, a partially polluted insulator was considered in comparison with a fully polluted insulator. In both cases of pollution, NaCl is assumed to be the contaminant to represent conductive pollution.

In tropical countries, a lightning strike is always the most likely threat to an electrical system either directly or indirectly. Concerning overhead lines, the Malaysian electrical provider, Tenaga Nasional Berhad (TNB) claims that lightning causes power interruption in more than 50 % of the total system failures every year [7]. In addition, the Indonesian electrical companies also claim about 90 % of outages in their 20 kV system are caused by lightning [8].

Research on effect of lightning to the high voltage electrical system has been carried out extensively across the globe. Literature [9] has focused on the influence of lightning channel tortuosity on electromagnetic field coupling and the induced voltage in a medium voltage (MV) distribution line.

Meanwhile, the study described in [10] conducted experimental work using a short tail impulse voltage on a composite insulator in a MV distribution line. It was evident that a short tail impulse (1.2/4 μs) gave a higher breakdown voltage compared to a standard lightning impulse (1.2/50 μs). However the real component of the lightning was the impulse current. Only limited studies have considered the impulse current recently. Also, a direct lightning strike should be considered due to the harmful effects such as experienced in Indonesia, where a porcelain type insulator fractured when hit by a direct lightning strike [11].

By focusing on the distribution system, many damaging effects on the system would be an issue if a direct strike took place, especially to an insulator of which the withstand capabilities have been compromised by pollution.

Therefore, a FEM has been used in this study to simulate a 10 kV polymer insulator to investigate the effect of pollution on the electrical performance of an insulator under a lightning impulse current.

II. ELECTROMAGNETIC FIELD

It is important to realise that the high electric field can cause damage as follows:

i. Develop an electrical discharge on the surface material of the insulator under both dry and wet conditions which leads to surface deterioration,
ii. Leads to internal discharge activity inside the core and the polymer material which could result in both electrical and mechanical failure,
iii. Produces radio noise and interference.

High electric fields appear to cause corona discharges when the surface electric fields exceed a threshold value which is 0.5-0.7 x 10^6 V/m [12, 13]. Commonly, this type of discharge can easily be found near to the metal end fittings as the electric field is found to be highest in those areas [14, 15]. Meanwhile, partial discharge (PD) could occur either inside or outside the insulation material during a high electric field to cause cracks and erosion [16]. Likewise, dry-band discharges occur on the surface of the insulator during the formation of water layers and dry areas caused by heat (evaporation).

The magnetic field is associated with the leakage current on the insulator. It should be mentioned that the magnetic field is produced when discharges take place. Also, based on previous research, evaluation of the magnetic field can be useful to monitor discharge activities regardless of the location of the discharge [16]. On the other hand, a small magnetic field with a threshold of 11.57 kA/m could increase the evaporation rate of moisture and water on the insulator surface [17]. Similarly, it can be used to predict the temperature profile of the insulator.

III. EVALUATION OF ELECTROMAGNETIC PROFILE ALONG AN INSULATOR

Simulations were carried out using software based on the finite element method (FEM) that is commercially available for electromagnetic simulation named high frequency structural simulator (HFSS). HFSS is the industry standard software for analysis of 3-D, full-wave electromagnetic fields designed with high accuracy and advanced solvers that are derived from the differential form of Maxwell's equations.

A. Parameters of Polymer Insulator

This study considers a 10 kV polymer insulator with an alternate size of shed. Measurements for the simulation model were adapted from the real insulator as shown in Fig. 1 whereby the specification is indicated in Table 1.

Fig. 1. A real 10 kV polymer insulator

TABLE I. INSULATOR DIMENSIONS

Part of Insulator	Dimension
Shed diameter (mm)	148/118
Shed-to-shed spacing (mm)	50
Structure Height (mm)	250
Min Nominal Creepage distance (mm)	420

For measuring the electromagnetic fields, six points were introduced on insulator surface as shown in Fig. 2 with regard to the critical points presented in [14, 15, 18, 19].

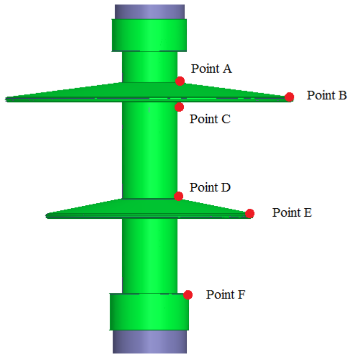

Fig. 2. Location of measurement points

B. Surface Pollution of Polymer Insulator

Contaminants of insulators can be categorised as two types, namely active and inert pollution. According to the IEC standard [1], active pollution is known as permanently conductive pollution, while inert pollution may become conductive when it absorbs water. Examples can be found in Table II.

TABLE II. EXAMPLES OF SURFACE CONTAMINATION

Surface Contaminant	Example
Active Pollution	NaCl, $NaSO_4$, MgCl, fly ash, SO_2, SO_3, NO_x, metallic deposits, bird droppings, acid rain, wet cement, agricultural material
Inert Pollution	Clay, Kaolin

The micro particles of the above contaminants can easily spread out into the air which can finally end up on the insulator surface. In this study, NaCl was selected to represent an active pollution as NaCl pollution is a common pollution on an insulator, especially when located in a country surrounded by the sea such as Malaysia. However, some assumption as the following should be made in order to model the pollution on insulator surface:

i. The insulator washing effect is neglected, therefore the pollution will build up on insulator surfaces in the form of a thin layer.
ii. The consistency of pollution is considered to be uniform across the layer.
iii. The physical and chemical characteristics of materials are not considered while only electrical parameter is taken into account (limitation of the FEM software).

Two cases were considered for the simulation as case A and case B (i.e. partially polluted and fully polluted insulator respectively) as shown in Fig. 3 below. The reason for the case selection was as discussed in the introduction. The pollution applied was as a layer with a thickness of 0.163 mm defined by [20] which is categorised as light pollution.

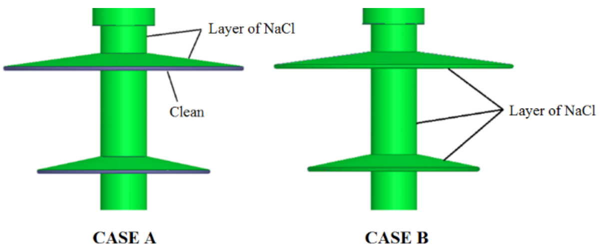

Fig. 3. Formation of pollution of Case A and Case B, partially and fully polluted insulator.

The pollution in case A covered all the polymer part of the insulator except for the lower surface of the shed which represented 70 % of the overall surface. However for case B, 100 % of the polymer surface was covered. It is worse case to have fully polluted insulator, but in reality partial polluted insulator is observed.

C. *Modelling of Polymer Insulator under Lightning Conditions*

The insulator was simulated under a non-standard lightning impulse current at a peak of 30 kA as shown in Fig. 4. Note that the current peak was selected based on the average first return stroke current of lightning [21, 22].

In this model, the line conductor was connected to the upper fitting of the insulator while the bottom fitting was connected to the cross-arm (420 × 75 × 10 mm). The excitation (Fig. 4) was set at the conductor model assuming a direct strike on the conductor.

Meanwhile, moist air parameters were set for the surrounding area assuming a foggy or wet condition. In the study, the air condition was extended 30 mm away in all directions from the insulator which is reasonable to minimise the simulation time. To run the simulation, a high-end PC with 4 x 3.2 GHz and 24 GB memory was used.

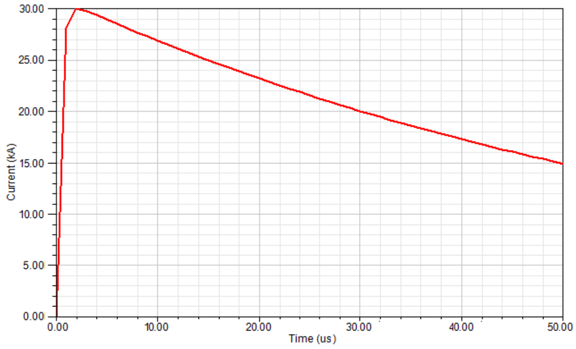

Fig. 4. Lightning impulse current

The important parameters used in this study are presented as Table III below.

TABLE III. FEM MODEL INFORMATION

Part Material	Relative permittivity (ε_r)	Relative Permeability (μ_r)	Volume Conductivity (σ) S/m
Fitting Aluminium	1	1.000021	3.8×10^{7}
Sheds Silicone	3	1	1×10^{-17}
Core Fiberglass	5	1	1×10^{-12}
Cross-arm Steel	1	1	2×10^{6}
NaCl Pollution	81	1	4.85
Moist Air Condition	1.0008	1.0000004	5×10^{-14}

In addition, the full drawing of the FEM model is as shown in Fig. 5 in which the area of air is extended 300mm away from the insulator.

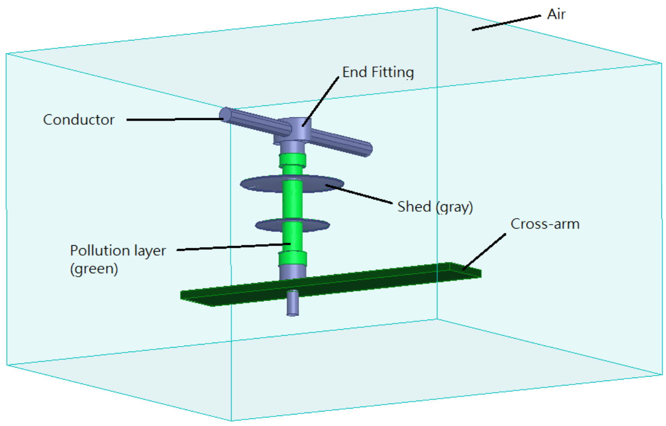

Fig. 5. Full FEM model

IV. RESULTS AND DISCUSSION

From the simulation works, the electrical performance of the insulator under pollution and lightning conditions was evaluated. EMF profiles were depicted in the form of a contour plot at each of measurement points discussed in the previous section. In addition, the max and mean values of the EMF were summarised in two sets of tables.

Note that the metallic parts (end fittings) of the insulator were neglected from the results and assumed to perfectly cater with the effect of the EMF while only the polymer dielectric is of concern.

A. Electric Field

Theoretically, an electric field is formed on the surface of an insulator when the insulator dielectric material tends to maintain its electrical properties during a high current. Based Fig. 6 and Fig. 7, it shows the formation of electric fields during the current peak for case A and case B respectively. Based on field plot in Fig. 6, a high intensity of the electric fields can be found at the shed edges. Despite of that, analysis along the length of insulator also reveals that electric fields are mostly concentrated nearer to both end fittings.

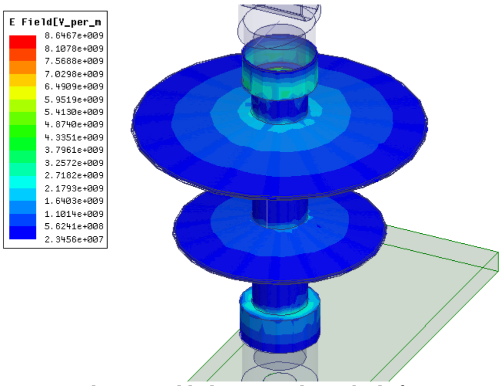

Fig. 6. Electric Field plot on insulator sheds for case A

The same trend can be observed for case B in Fig. 7 in which stronger electric fields were found at the shed edges. It is apparent that the area of high electric field is the intersection point of two or more materials. Comparatively, a more intense electric field can be observed in case B compared to case A.

The edges would appear to have greater chance for partial discharge (PD) to occur. If there was a cavity or a manufacturing defect in those areas, an internal PD might occur inside the material. Meanwhile, an external PD might occur at the metal-insulator intersection which is closest to point A and F (see Fig. 2). According to [23, 24], both types of PD denote the same type of discharge known as a Townsend electron avalanche which can develop into a streamer and sparks that often observed in many insulator tests.

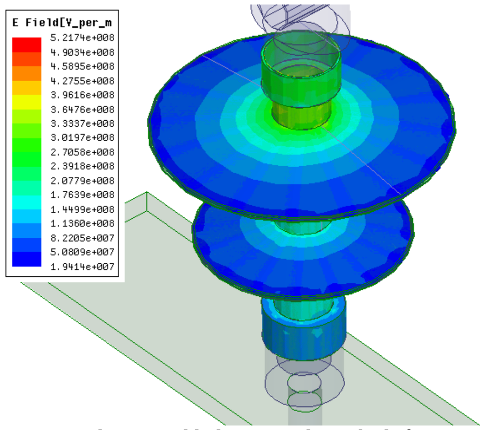

Fig. 7. Electric Field plot on insulator sheds for case B

Table IV shows the maximum value of the electric field during a lightning event for both case studies. Remarkably, the shed edges at points A, C, D and F show high values of electric field compared to points B and E that lie on the shed. Under those circumstances, those points are most likely to have greater stress.

A tremendous difference (about 97.8 %) of the electric field value can be observed at point A of the fully polluted insulator compared to the partially polluted insulator. Also, other points show percentage difference of at least 65.2 %.

TABLE IV. ELECTRIC FIELDS FOR CASE A AND CASE B

Point of measurement	**Electric Fields (E) MV/m**			
	Case A		**Case B**	
	Max	***Mean***	***Max***	***Mean***
Point A	202.19	180.11	1983.00	1682.00
Point B	14.43	12.86	41.41	35.03
Point C	36.33	32.37	208.54	177.00
Point D	43.75	3.90	146.28	124.14
Point E	1.49	1.33	69.78	59.01
Point F	30.60	27.24	114.42	96.92

It is important to realise that the results indicate the value of the electric fields higher than threshold value of 0.5-0.7 x 10^6 V/m which corona discharges could appeared [12, 13]. This discharge will consequently degrades the polymer sheds due to heat, ozone and UV radiation produced due to ionisation of material and the air.

B. Magnetic Field

Particularly, magnetic fields were generated when a leakage current flows on the insulator. Similarly, a magnetic field can also be recognised as a by-product of the discharges. By monitoring the trend of the magnetic fields of an insulator, the leakage current and discharges can be estimated.

Fig. 8 and Fig. 9 show the magnetic fields for case A and case B respectively. It was observed that the magnetic field for both cases focused on the upper part of the insulator, nearer to the fitting. Meanwhile, based on Fig. 8, the upper shed of the insulator has a higher magnetic field compared to the other sheds which means greater current flows on the upper shed which also means the material was thermally high. Simultaneously, wet pollution on the upper shed will dry up faster.

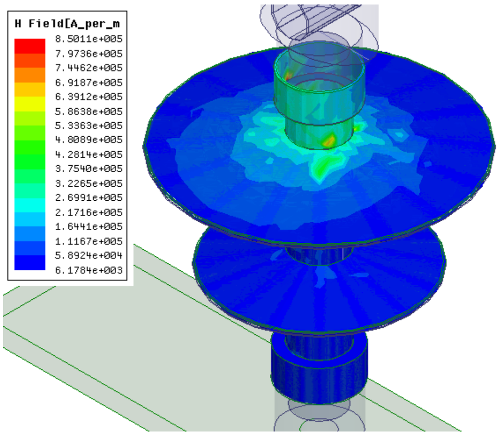

Fig. 8. Magnetic Field plot on insulator sheds for Case A

Based on Fig. 9, magnetic fields were observed to be distributed almost evenly along the insulator length. This behaviour was found to be different to Fig. 8 in which the magnetic field was focused at the upper shed. This could be due to the separation between the upper pollution shed and the other part of the pollution which limits the leakage current to flow across the surface.

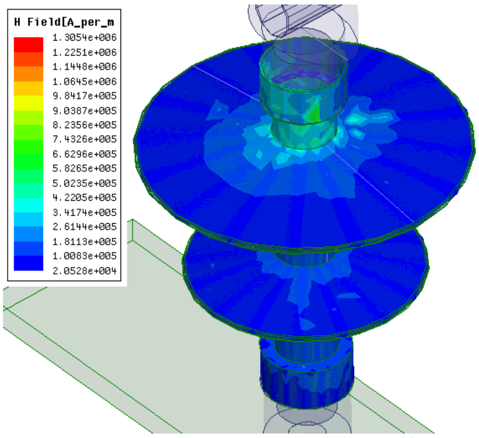

Fig. 9. Magnetic Field plot on insulator sheds for case B

Based on Table V, the magnetic field at point A for case A was significantly larger than the other points. The highest percentage difference between case A and case B was obtained at point A which indicated 86.7 %. Meanwhile the lowest recorded difference was at point F with 10.9 % of difference.

For case B, the magnetic field was well spread along the insulator. Consequently, there were no focused magnetic fields as in case A recorded in case B. With this in mind, the heat would be distributed evenly across the insulator.

TABLE V. MAGNETIC FIELDS FOR CASE A AND CASE B

Point of measurement	**Magnetic Fields (H) kA/m**			
	Case A		**Case B**	
	Max	***Mean***	***Max***	***Mean***
Point A	253.14	209.26	33.76	29.00
Point B	16.68	13.82	7.99	6.93
Point C	15.76	12.94	64.05	54.24
Point D	12.27	10.13	83.96	71.30
Point E	12.66	10.48	6.83	5.91
Point F	24.64	20.10	27.66	23.69

The magnetic field can also have a great effect when the pollution composition consists of ferromagnetic material. Ferromagnetic pollution can be commonly found in industrial dust for instance iron oxides and Cu, Fe, Pb, Zn, Cd, V, Cr, Co, Ni and Cu which occur in fly ash of coal combustion [25].

The field plot shown in Fig. 10 indicates the current density for case A. A high density of current can be observed at the upper side of the insulator which proves the discussion of Fig. 7.

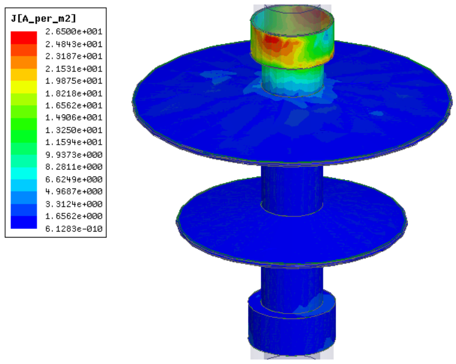

Fig. 10. Current density for case A

To summarise, pollution formation can have an effect on the electrical performance of a polymer insulator. Also, by using this simulation method, designers can easily detect the potential location for discharges to occur and estimate the leakage current with consideration of different pollution locations.

V. CONCLUSION

In this study, the electromagnetic performance of a 10 kV polymer insulator was evaluated by using 3D FEM-based software. By considering partial and full pollution on the insulator surface, a direct lightning impulse current was applied. Six critical points were highlighted for evaluation.

From the study, it was found that an insulator with full pollution has a higher electric field intensity compared to a partially polluted insulator which represents at most 97.8 % of difference. In addition, a significantly high electric field (1983.00 MV/m) was recognised at the shed edges nearer to the end fittings as mentioned in a previous study. Also, this study has confirmed the location of common damage to the insulator.

In addition, the magnetic field along the partially polluted insulator was found to focus on the upper shed, from which it can be concluded that there was intense current density in those areas. Consequently, heat will be concentrated and thus degrade the insulation material. For the fully polluted insulator, the magnetic field was almost evenly distributed along the insulator. Comparatively, at most 86.7 % and at least 10.9 % of difference was recorded between the magnetic fields for both cases of pollution.

For the most part, the electric and magnetic fields at the points highlighted in the study should be concerned whereby further study should be undertaken to minimise these values in order to maintain the insulator performance. Also, maintenance should be conducted to minimise the occurrence of pollution by comprehensive washing over all directions of the insulator. As realised in this study, even partial pollution can also result in destructive consequences.

However, this study only summarised the insulator performance under a typical current waveform which is non-standard waveform. Indeed, a comparative study on the insulator performance between non-standard and standard current waveforms should be done in the future.

Respectively, the results presented in this paper are legitimate for the polymer insulator in power distribution due to the use of the distribution polymer insulator. However, it should be noted that the trends obtained throughout the study also can be used to understand or predict the performance of polymer insulator in power transmission.

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