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Numerical Simulation of Leakage Current on Conductive Insulator Surface

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***Abstract**: The outdoor insulator is commonly exposed to environmental pollution. The presence of water like raindrops and dew on the contaminant surface can lead to surface degradation due to leakage current. However, the physical process of this phenomenon is not well understood. Hence, in this study we develop a mathematical model of leakage current on the outdoor insulator surface using the Nernst Planck theory which accounts for the charge transport between the electrodes (negative and positive electrode) and charge generation mechanism. Meanwhile the electric field obeys Poisson's equation. Method of Lines technique is used to solve the model numerically in which it converts the PDE into a system of ODEs by Finite Difference Approximations. The numerical simulation compares reasonably well with the experimental conduction current. The findings from the simulation shows that the conduction current is affected by the electric field distribution and charge concentration. The rise of the conduction current is due to the distribution of positive ion while the dominancy of electron attachment with neutral molecule and recombination with positive ions has caused a significant reduction of electron and increment of negative ions.*

***Keywords**: Leakage Current, Surface Discharge, Method of Lines technique*

I. INTRODUCTION

Today, high voltage systems are widely used for the various types of applications covering the industry and research applications due to the high demand [1]. One of the main issues in high voltage systems is the prevention of failure and losses in insulation. This part is used to prevent the flashover and short circuits between the live part of the systems and the grounded part [2]. For an outdoor application, an insulator is exposed to the environmental pollution like haze and dust. The dry condition of the pollution contaminant is not dangerous for the systems due to the small magnitude of leakage current (LC) flow on the insulator surface [3]. However, with the presence of the moisture like dew or rain that is mixed with the contaminant causes high flow of LC on the insulator surface. This is caused by the formation of discharge on the surface of the insulator.

Although the magnitude of the LC flow is quite small, the long term of LC flow due to the discharge activities may lead to the insulator degradation. The magnitude of LC flow increase will lead to the formation of dry-band condition and the evolution of arcing [4]. The arcing will lead to the flashover at the insulator and cause the breakdown. The flow of LC will cause the rise in temperature. Thus, due to the temperature increase, the carbonization process takes place and water vaporization occurs [5]. This condition will then cause the tracking and erosion of the outdoor insulator and finally the insulation breakdown.

Due to the discharge activities, LC will undergo different stages and produce different current waveforms. By the pattern of the LC waveforms and the magnitude of the LC, the surface condition of the insulator will be known. The surface condition of the insulator will be characterized as capacitive, resistive, and non-linear conditions [6]. Thereby, the measurement of LC is performed to evaluate the performance of the insulator in order to predict the flashover [4] and reduce the insulator breakdown [7]. In order to investigate the behaviour and discharge activities that cause the flow of LC, equivalent circuit models are commonly used [8],[9],[10]. However, all these models focus only on the LC patterns and flashover voltage. Yet, discussion on the phenomenological process of LC that involves charge transport and generation is lacking. In addition, there are researchers that use experimental test set-up to investigate the insulator performance. This experimental set-up is time-consuming and need high cost and special equipment [3]. By understanding this physical process, it will help in the design consideration of the insulator used. The numerical simulation is done in order to study the effect of surface discharge to the insulator surface.

In this research, 1 dimensional model of leakage current on contaminated surface of artificially polluted insulation is analysed. This model considers the physical description of surface discharge activities on the insulator including free charge transport and generation mechanism. The Nernst-Planck theory has often been used to develop the diffusion-migration model for free charge carriers in diluted electrolyte whereas Poisson's equation describes the electric field distribution on the contaminated surface of insulator. The method of line (MOL) technique that is accounted for finite different method was used to solve the mathematical model.

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Then, the numerical simulation results of charge carrier (which are positive ions, negative ions and electron) density, electric field distribution and leakage current were analysed and compared to the size of dimensionless parameters that had been calculated.

II. MATHEMATICAL MODEL OF LEAKAGE CURRENT

A. *The Conservation Equations of Charge Carrier*

The equations described the physical model of the surface discharge formation which eventually led to the flow of leakage current including the charge conservation equations, the Nernst-Planck theory and potential equation, the Poisson's equation. The charge conservation equations can be written as:

$$\frac{\partial N_i}{\partial t} - \nabla . J_i = G_i - R_i \qquad (1)$$

where the suffices, $i = p, n, e$ denote the species of free charge carrier (p -positive ion, n -negative ion and e-electron). N_i is the concentration of each charge carrier and J_i is the conduction current density due to the concentration gradient, electric field potential and the velocities of the charges. The right side of equation (1) is the generation rate G_i discussed in Section B and recombination rate R_i discussed in Section C.

The charge conservation equation in the left side of equation (1) is accounted by Nernst Planck theory that has been used to explain the charge behavior in various systems such as biological membranes of protein channel in [11], membranes of neuron cell [12], and electrolytic liquids [13]. The conduction current density in equation (1) could be expressed as [14]:

$$J_i = -D_i \nabla N_i \pm N_i \mu_i \left|\vec{E}\right| + N_i v_i \qquad (2)$$

where D_i is the diffusion constant, μ_i is the mobility of charge, $\left|\vec{E}\right|$ is the electric field and v_i is the velocity of charge in fluid. The first term of the current density equation (2) describes the ion transport due to the diffusion of ions and concentration gradient, the second term describes the migration of the charges influenced by an electric field and the third term explains how the charges move caused by the fluid convection. The surface discharge activities which lead to the formation of leakage current is assumed to be dominated by conduction currents. This is due to the influence of the high electric field and the effect of the concentration gradient. Thus, in this model, only the diffusion term and migration term are considered. The convection term is neglected because the contamination flow rate is assumed constant.

Meanwhile, the Poisson's equation is used to describe the electric field distribution on the insulator surface due to the presence of the free charge carriers and can be expressed as:

$$\nabla . \left(-\varepsilon_0 \varepsilon_r \left|\vec{E}\right|\right) = \left(N_p - N_n - N_e\right) q N_A \qquad (3)$$

where ε_r is permittivity of free space charge and ε_0 is relative permittivity.

The sum of integral of total current density determines the conduction current on the insulator surface. The conduction current equation can be written as:

$$I = Fb \int \left(J_p + J_n + J_e\right) dA \qquad (4)$$

where F is a Faraday's constant and b is volume per unit area of the insulator.

B. Charge Generation Mechanisms

In the modelling of leakage current on the contaminated surface of the outdoor insulator, the charge generation is explained by electric field dependent molecular ionization. Electric field dependent molecular ionization is a direct ionization mechanism where an electron is extracted from a neutral molecule which donates an electron and a positive ion. The model of charge generation mechanism by molecular ionization in high electric potential field has been used in modelling the liquid dielectric streamer in transformer oil (see works in [15][16][17]). Furthermore, the modelling of dielectric breakdown is described by Zener theory [18] which correlates the tunnelling electron in solid with molecular ionization mechanism in the presence of high electric field. Hence, the charge carrier generation mechanism rate G_i in equation (1) is written as [15]:

$$G_i = \alpha_I \left|\vec{E}\right| \exp\left(-\frac{\beta_I}{\left|\vec{E}\right|}\right) \qquad (5)$$

where $\alpha_I = \frac{q^2 \mathrm{n}_0 a}{h}$ and $\beta_I = \frac{\pi^2 m^* a \Delta^2}{q h^2}$. Note that q is the electronic charge, $\left|\vec{E}\right|$ is the electric field vector, m^* is the effective electron mass, a is the molecular separation distance, Δ is the molecular ionization potential, h is the Planck's constant and n_0 is the density of ionizable charge.

The charge generation mechanism term G_i for positive ion, negative ions and electron can be simplified as:

$$G_i = \begin{cases} G_i \left|\vec{E}\right|, & \text{for } i = p, e \\ 0, & \text{for } i = n \end{cases} \qquad (6)$$

The generation rate accounted only for positive ion and electron because during the field dependent molecular ionization, a neutral molecule extraction generates only positive ion and electron[18]. There is no charge generation mechanism term G_i for negative ion but in the real liquids, the free electrons will be attached to the neutral molecule, causing the formation of negative ions [15].

C. Recombination and Electron Attachment

All Besides charge generation in the dielectric system, free charge carrier also undergoes ion recombination when it interacts between charges and the surrounding media. Three possibilities of ion recombination are electron-positive ion recombination, positive-negative ion recombination and electron attachment.

To account for this behaviour, Langevin's relation is used (see works in [15][19]) which explains the recombination factor based on the mobility of charge carriers in the electric field [20] and it takes the form

$$K_{rpn} = \frac{q(\mu_p + \mu_n)}{\varepsilon\varepsilon_0} \tag{7}$$

$$K_{rpe} = \frac{q(\mu_p + \mu_e)}{\varepsilon\varepsilon_0} \tag{8}$$

where K_{rpn} and K_{rpe} is the notation of recombination coefficient of positive-negative ion and electron-positive ion, respectively. Here q is an elementary charge. The recombination rate R_i can be expressed as:

$$R_{pn} = N_p N_n K_{rpn} \tag{9}$$

$$R_{pe} = N_p N_e K_{rpe} \tag{10}$$

Additionally, the combination of electron with neutral molecules must be considered as such combination would form a negative ion. It can be modelled by an attachment time (EA) constant that describes the lifetime of energetic electron in a dielectric. The EA constant accounts for the electron attenuation length, the mobility of electron and electric field strength. The electron attachment rate, EA can be expressed as:

$$EA = \frac{N_e}{\tau_a} \tag{11}$$

D. Boundary Conditions at high voltage and ground electrodes

The boundary conditions for the model:

- Charge Transport Continuity equations (1): Zero normal flux at both electrodes

$$\hat{n}(\nabla N_i) = 0 \tag{12}$$

- Poisson's equation (3): A supply DC voltage V_0 is set at the high voltage electrode ($x = 0$). In the meantime at the ground voltage ($x = d$), the voltage is zero

$$\text{At } x = 0; \quad \hat{n}(V) = V_0 \tag{13}$$

$$\text{At } x = d; \quad \hat{n}(V) = 0 \tag{14}$$

where $x = d$ is the distance between electrodes.

III. NON-DIMENSIONALIZATION

In order to reduce the difficulty while doing the simulation, all the charge continuity equation and Poisson's equation are solved by using a non-dimensional framework. The appropriate scaling parameters to obtain the dimensionless equations are as follows:

$$V^* = \frac{V}{V_0} \qquad \nabla^* = \nabla d \qquad \mu_i^* = \frac{\mu_i}{\mu_p} \tag{15}$$

The time scale for the leakage current flow with the surface discharge activities was defined as:

$$t^* = \frac{V_0 \mu_p}{d^2} t \tag{16}$$

while the time scale for electron attachment can be defined as:

$${\tau_a}^* = \frac{\mu_p V_0}{d^2} \tau_a \tag{17}$$

Thus, we obtain the dimensionless parameters:

$$\begin{gathered} \Gamma = \frac{RT}{FV_0} \qquad {\alpha_I}^* = \frac{d^3 F}{\mu_p \varepsilon\varepsilon_0 V_0} \alpha_I \\ {\beta_I}^* = \frac{d}{V_0} \beta_I \quad {N_i}^* = \frac{d^2 F}{\varepsilon\varepsilon_0 V_0} N_i \\ {J_i}^* = \frac{d^3 F}{\varepsilon\varepsilon_0 {V_0}^2 \mu_p} J_i \quad I^* = \frac{d^3}{L\varepsilon\varepsilon_0 {V_0}^2 \mu_p} I \\ {K_{rpe}}^* = {K_{rpn}}^* = \frac{K_{rpn}\varepsilon\varepsilon_0}{F\mu_p} \end{gathered} \tag{18}$$

where, α_I is the pre-exponential term charge generation $\alpha_I = \frac{q^2 \mathrm{n}_0 a}{h}$ and β_I is the exponential term of charge generation $\beta_I = \frac{\pi^2 m a \Delta^2}{q h^2}$ and * sign is for non-dimensional parameter in the equations. The dimensionless model from the equation (1) – (4) can be written as follow:

$$\begin{aligned} \frac{\partial {N_p}^*}{\partial t^*} = \nabla^*.{J_p}^* + {\alpha_I}^* |\nabla V^*| \exp\left(-\frac{{\beta_I}^*}{|\nabla V^*|}\right) \\ - {N_p}^* {N_e}^* {K_{rpe}}^* - {N_p}^* {N_n}^* {K_{rpn}}^* \end{aligned} \tag{19}$$

$$\frac{\partial {N_n}^*}{\partial t^*} = \nabla^* {J_n}^* + \frac{{N_e}^*}{{\tau_a}^*} - {N_p}^* {N_n}^* {K_{rpn}}^* \tag{20}$$

$$\begin{aligned} \frac{\partial N_e}{\partial t} = \nabla^*.{J_e}^* + {\alpha_I}^* |\nabla V^*| \exp\left(-\frac{{\beta_I}^*}{|\nabla V^*|}\right) \\ - {N_p}^* {N_e}^* {K_{rpe}}^* - \frac{{N_e}^*}{{\tau_a}^*} \end{aligned} \tag{21}$$

$$\nabla^*.(\nabla^* V^*) = \left({N_p}^* - {N_n}^* - {N_e}^*\right) \tag{22}$$

$$I^* = \int_0^1 ({J_p}^* + {J_n}^* + {J_e}^*)\, dx \tag{23}$$

where ${N_p}^*$, ${N_p}^*$ and ${N_p}^*$ are the positive ion, negative ion, and electron dimensionless concentration respectively. ${J_p}^*$, ${J_n}^*$ and ${J_e}^*$ are the positive ion, negative ion and electron dimensionless conduction current density respectively and can expressed as:

$${J_p}^* = (\Gamma {\mu_p}^* \ \nabla^* {N_p}^*) + \left({N_p}^* {\mu_p}^* \ \nabla^* V^*\right) \tag{24}$$

$${J_n}^* = (\Gamma {\mu_n}^* \ \nabla^* {N_n}^*) - ({N_n}^* {\mu_n}^* \ \nabla^* V^*) \tag{25}$$

$${J_e}^* = (\Gamma {\mu_e}^* \ \nabla^* {N_e}^*) - ({N_e}^* {\mu_e}^* \ \nabla^* V^*) \tag{26}$$

The dimensionless boundary conditions for equations (20) – (26) can be written as:

- Flux of ions:

$$\hat{n}(\nabla^* {N_i}^*) = 0 \tag{27}$$

where the suffices, $i = p, n, e$ indicate the species of free charge carrier (positive ion, negative ion and electron).

- The electric potentials:

$$\text{At } x^*.d = 0; \quad {}^{\wedge}_{n}(V^*V_0) = V \tag{28}$$

$$\text{At } x^*.d = d; \quad {}^{\wedge}_{n}(V^*V_0) = 0 \tag{29}$$

A. Size of Dimensionless Parameter

In equation (25) – (27), Γ gives the ratio of the thermal voltage to the typical voltage drop across cell, ${\alpha_I}^*$ and ${\beta_I}^*$ are the dimensionless parameter for the pre-exponential and exponential term for charge generation mechanism respectively. ${K_{rpe}}^*$ and ${K_{rpn}}^*$ are the dimensionless parameter for the recombination coefficient.

The size of each of dimensionless parameters is estimated based on the values listed in Table-I. The estimated size of dimensionless parameters are as follows:

$$\begin{gathered} \Gamma = 6.38 \times 10^{-6} \qquad {\alpha_I}^* = 3.029 \times 10^{22} \\ {\beta_I}^* = 2.034 \times 10^{4} \\ {K_{rpe}}^* = {K_{rpn}}^* = 1.57 \qquad {\tau_a}^* = 1.174 \times 10^{-8} \end{gathered} \tag{30}$$

From the size of the key dimensionless parameters, the value of Γ is extremely small (10^{-6}). Hence, the simulation can be approximated by neglecting the diffusion term of the conduction current density equation (${J_p}^*$, ${J_n}^*$ and ${J_e}^*$) in equations (25) – (27) in the mathematical simulation. This approximation is appropriate as the previous study of streamer development [29],[30] only considered the migration term in their modelling. The size of the dimensionless parameter ${\tau_a}^*$ is significantly small hence the term $1/{\tau_a}^*$ in equation (12), is relatively large (10^7).

B. Numerical Procedure

The mathematical model of equation (20) – (29) are then be solved with respective dimensionless parameters (31) using finite difference method (FDM). This method is universally applicable to solve linear and non-linear problems [31]. For example, it was used by Flavell et. al. in modelling of ion transport in ion channels [32]. In the electro diffusion problem using Nernst-Planck and Poisson equations, Jasielec et. al. applied a numerical procedure of method of lines (MOL) technique by discretising the derivatives using implicit finite difference method [33]. MOL is a technique that approximates the spatial derivatives in the partial differential equation (PDE) algebraically using finite difference approximations [34]. This technique transforms the complex system PDE into a series of coupled ordinary differential equations (ODEs).

The resulting system of ODEs are then solved using standard time integration method '*ode15s*' in MATLAB. '*ode15s*' performs an implicit linear multistep formulas which makes it a good solver in solving stiff problems [35].

Table- I: Parameter values of electrolyte.

Term	Descriptions	Value	Units	References
R	Gas constant	8.31440	$Jmol^{-1}K^{-1}$	[21]
T	Temperature	2.9615×10^2	K	[22]
F	Faraday's constant	9.64853×10^4	$C\ mol^{-1}$	[21]
τ_a	Time constant	2×10^{-7}	s	[23]
$m*$	Effective electron mass	9.109×10^{-32}	kg	[21]
Δ	Molecular ionization energy	6.4087×10^{-19}	J	[23],[24]
α	Molecular separation distance	3.1×10^{-10}	m	[23]
d	Distance between two electrodes	5×10^{-2}	m	[22]
q	Charge	1.6022×10^{-19}	C	[25]
h	Planck's constant	6.626×10^{-34}	$J.s$	[25]
C	Concentration of free charge carrier	1.6603×10^3	$mol\ m^{-3}$	[26]
n_0	Density of ionisable species	1.6603×10^3	$mol\ m^{-3}$	[26]
μ_p	Mobility of positive ion	3.5×10^{-7}	$m^2s^{-1}V^{-1}$	[23]
$\mu_n = \mu_e$	Mobility of negative ion and electron	2×10^{-7}	$m^2s^{-1}V^{-1}$	[23]
NA	Avogadro's number	6.023×10^{23}	mol^{-1}	[21]
ε_0	Relative permittivity	8.85×10^{-12}	$F\ m^{-1}$	[21]
ε	Permittivity of water	80		[26],[23]
k	Boltzmann constant	1.3807×10^{-23}	$m^2\ kg\ s^{-2}\ K^{-1}$	[21]
K_{rpn}=K_{rpe}	Relative recombination	7.49651×10^7	$m^3s^{-1}mol^{-1}$	[27]
D_p	Diffusion of positive ion	8.93195×10^{-9}	$m^2\ s^{-1}$	[28]
$D_n = D_e$	Diffusion of negative ion and electron	5.10397×10^{-9}	m^2s^{-1}	[28]
V_0	Initial voltage	2.4×10^3	V	[22]

IV. RESULTS AND DISCUSSION

The numerical simulation results analyzed the positive ion concentration, negative ion concentration, electron concentration, electric field distribution and conduction current. The axis x^* in Fig. 2 until Fig. 5 is the dimensionless distance between two electrodes where $x^*= 0$ is at high voltage electrode and $x^*= 1$ is at ground electrode. Fig. 1 shows the comparison of numerical simulation with experimental conduction current. It can be seen that the numerical simulation compares reasonably well to the experimental data. The electric field distribution affects the conduction current which varies depending on the electric field distribution and charge concentration similarly stated in equation (24). The rise of the conduction current by the time increasing is due to the distribution of positive ion over other charge carriers on the insulator surface. Thus, this positive ion distribution influences the electric field distribution and then causes the increase of the conduction current (see Fig. 3).

Fig. 2 shows dimensionless electric field distribution along the insulator surface. The result shows that the electric field is higher in the region near to high voltage electrode. This is because the surface discharge activities occur more strongly in this region compared to the region near to ground electrode.

The formation of the electric field distribution is strongly related with the generation of free charge carriers [37]. The positive ions generation from the field molecular ionization as shown in Fig. 3 and negative ion generation from the electron attachment as shown in Fig.4 contribute to the formation of free space charge. This free space charge then leads to the electric field distribution on the insulator surface.

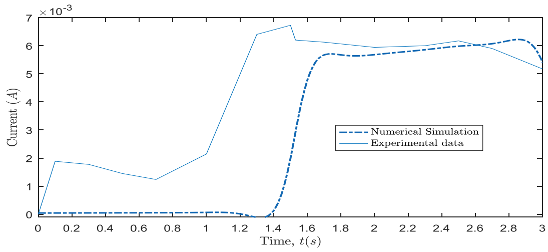

Fig. 1: The comparison of numerical simulation of the model with the experimental data.

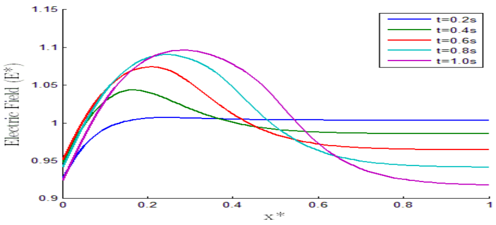

Fig. 2: Dimensionless electric field distribution

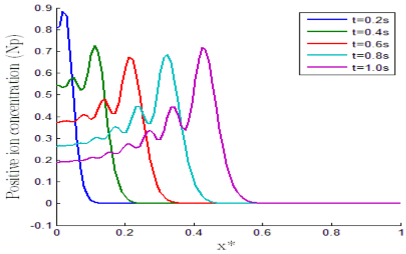

Fig. 3: Dimensionless positive ion concentration across the dimensionless distance of electrodes.

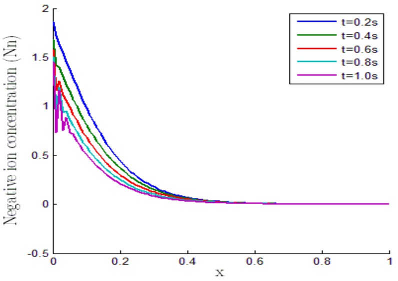

Fig. 4: Dimensionless negative ion concentration across the dimensionless distance of electrodes.

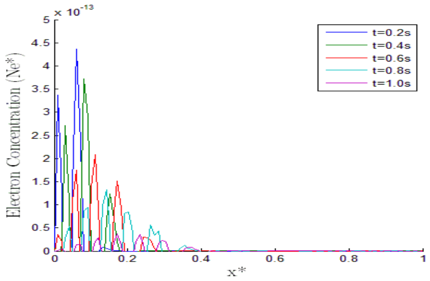

Fig. 5: Dimensionless electron concentration across the dimensionless distance of electrodes.

The size of dimensionless parameters is shown in equation (1). This size of the dimensionless parameter is used to predict the dominant role that contributes to the charge generation. Thus, for the dimensionless equation (20) – (22), the assumption is made that the electron attachment is the dominant factor of the surface discharge on the insulator surface.

The electron concentration profile is extremely small as time increases as shown in Fig. 5. This is due to the electron attachment to the neutral molecule and recombination with the positive ions. As the electron attachment is dominant, theses result showed that the concentration of electron was reduced by the electron attachment to the neutral molecules that produced more negative ions.

V. CONCLUSION

In conclusion, the mathematical model of leakage current on the contaminated surface with the presence of surface discharge are discussed. Then, the dimensionless framework of the mathematical model is proposed to reduce the numerical difficulties and the dimensionless parameters are presented physically. Then, the numerical procedure of non-dimensionalization

framework is compared with the simulation result. From the simulation results, it shows that the behaviour of the ions concentration is correlated with the assumption made using dimensionless parameters. Therefore, the simulation results of the mathematical model can be predicted from the dimensionless size parameters. The behaviour of leakage current, electric field distribution and concentration of ions are analysed. The model compares reasonably well to the experimental conduction current, therefore can benefit to understand the leakage current behaviour on the conductive insulator surface.

The result shows that the electric field is higher in the region near to high voltage electrode. This is because the surface discharge activities occur more strongly in this region compared to the region near to ground electrode. The positive ions from the molecular ionization and negative ions generation have strongly contributed towards the formation of free space charge which then leads to electric field distribution. These findings can contribute to better understanding of the phenomenon of leakage current on conductor surface.

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