STRING EFFICIENCY ANALYSIS OF 132-kV HIGH SUSPENSION INSULATORS USING 2D FINITE ELEMENT METHOD MAGNETICS

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Abstract: Suspension insulator is needed to prevent leakage current flow to earth through the support tower in high voltage transmission. However, the potential distribution and electric field across each insulator in a string is non-uniform, which causes flash over and excessive heat that shortens the lifespan of the insulators and lowers string efficiency. The potential difference at the bottom unit is inversely proportional to string efficiency. A higher string efficiency, which can be attained using capacitance grading, assures a longer lifespan of the insulator. The purpose of this paper is to study the voltage distribution and string efficiency of a 12-disc glass suspension insulator (model LXWP4-70) at 132 kV using 2D Finite Element Method Magnetics (2D FEMM) software with and without capacitance grading method. The 2D FEMM was used to determine the potential distribution as well as the static capacitance of each string insulator and to calculate the string efficiency. One of the string insulator disc dimensions was measured at the High Voltage Lab of the University Malaya. The results showed that the string efficiency has improved from 64% to 76% due to capacitance grading.

Keywords: *String insulator, suspension insulator, electric field, potential distribution, string efficiency*

1. INTRODUCTION

Insulator strings are the main components used to provide safe insulation between line support and high voltage transmission lines (Ali et al., 2018). They prevent leakage current to flow from the overhead transmission lines to earth through the support tower. It can be used to electrically isolate the conductor from the support tower. The string efficiency is an important consideration in suspension-type of insulator strings (Figure 1) because it is an indicator of the potential or voltage distribution along the string (Tonmitr et al., 2015). The greater the string efficiency, the more uniform is the voltage distribution across the capacitor discs. The string efficiency of 100% represents an ideal case in which the voltage across each capacitor disc has exactly the same value. But in reality, 100% string efficiency is impossible to attain due to the presence of shunt capacitance and other reasons. It can only be improved as close to 100% as possible (Mehta & Mehta, 2004). The defining formula for the string efficiency (Tonmitr et al., 2015) is given in Equation (1).

$$\text{String efficiency } = \frac{\text{Total voltage across string insulator}}{\text{number of insulator} \times \text{voltage across nearest disk}} \times 100\% \quad (1)$$

Figure 1. Example of a suspension-type string insulator.

The 2D planar Finite Element Method Magnetics (FEMM) software (Baltzis, 2010) is used to simulate the potential distribution and electric field along the string insulator. The suspension type insulator with model number LXWP4-70 (Figure 2) having IEC and ANSI standard of U70BP/146 was selected for this study. The specifications of this type of insulator were used for modeling a string insulator having 12 discs. In this project, the high voltage of 132 kV was applied to the conductor side of the string insulator. The model of the string insulator with 12 identical discs has been developed to withstand 132 kV, since each insulator can withstand 11 kV of voltage (Kontargyri et al., 2004). The electric stress across the disc that is nearest to the conductor exceeds three to five times that of the other insulators, which may lead to insulator surface breakdown or flash over to occur. Hence, calculations and simulation methods were carried out to study the voltage distribution of each insulator and determine the string efficiency (Mehta & Mehta, 2004).

1.1 String insulator parameters

The parameters of the LXWP4-70 model of the suspension-type string insulator used for 2D simulation are shown in Figure 3. The values of these parameters are:

a) Diameter of insulator:	25.6 cm
b) Spacing:	15 cm
c) Thickness of insulator:	1 cm
d) Diameter of outer pin:	3.2 cm
e) Diameter of inner pin:	1.5 cm
f) Cap height:	9 cm

Figure 2. Model of LXWP4-70 glass suspension insulator.

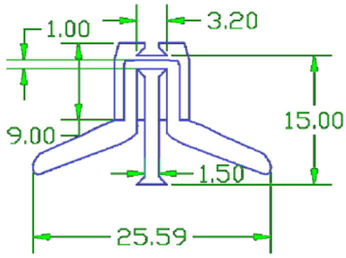

Figure 3. Parameters of model LXWP4-70 insulator for 2D simulation.

In this project, the shape of the creepage was ignored in designing the simulation model of the suspension insulator. Creepage tends to increase the distance along the insulator surface between the metal cap and the pin at each end of the insulator. That means, the longer the creepage distance, the more the insulator is able to minimize the leakage current from electrical conductor line to earth. Hence, it is not necessary to include a creepage shape in the drawing of the model. The simulation of the string insulator was performed in a clean and non-polluted environment to prevent insulators breakdown or damage. The insulator can easily break down and become conductive due to the decrease in the dielectric strength caused by the pollution level on the insulator surface. The leakage current can only exist when the insulator is damaged. The model of the 12-disc string insulator was drawn using DraftSight (Santos, 2013; Jayathilake & Shantha, 2015), which is an engineering drawing software similar to AUTOCAD. After that, the model was saved as DXF file and imported to FEMM software for simulation.

2. METHODOLOGY

The geometric dimension of the model of the 12-disc suspension insulators is shown in Figure 4. It indicates the length of the steel tower, which is 200 cm, and the distance of the cross arm between steel tower and the metal caps, which is 25 cm. Moreover, the distance from the reference point to each of the 12 discs ranges from 0 to 180 cm.

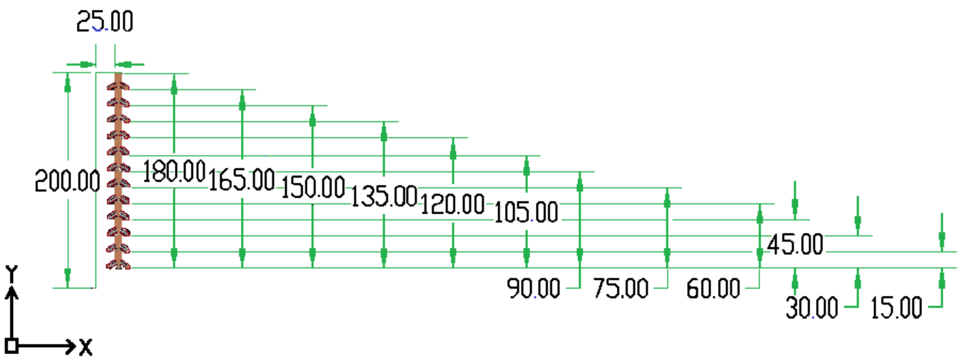

Figure 4. Model of 12-disc suspension-type string insulator used for simulation by FEMM software 2.0.

2.1 Simulation procedure

In 2 dimensions, the voltage of 132 kV is applied at the bottom unit of the metallic pin by using the boundary condition. This 2D model is simulated in high voltage of 132 kV one phase voltage of a 3-phase transmission line. The metal cap of top unit is assigned as earth or 0V (Kontargyri et al., 2004). The glass suspension insulator consists of three main parts: the metal pin and cap, glass, and cement. The relative permittivity of glass and cement are 4.7 and 4.5, respectively. The 2-dimensional model of glass suspension insulator is represented as Figure 5.

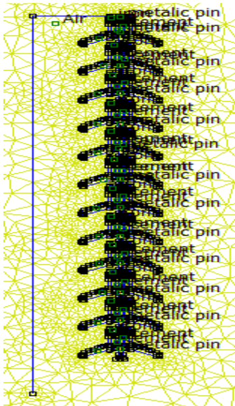

Figure 5. Model of the 12-disc insulators showing the metal (cap, pin), glass, cement as block label; horizontal line (support tower) and vertical line (cross arm) as earth; lowest part of segment defined as 132 kV conductor.

To perform the simulation, a button is pressed to run the mesh generator. The solver automatically gives the command to the mesh generator to update from within FEMM. While the mesh is running, the model is loaded into memory and displays underneath the defined nodes, segment and block such as cement, glass, and metal (pin and cap). Then the potential distribution along the string is portrayed as shown in Figure 6.

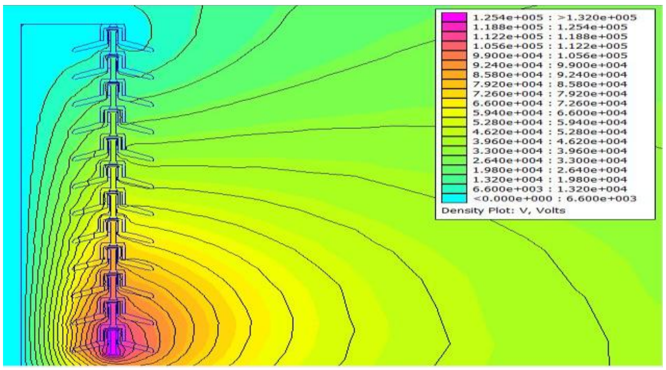

Figure 6. Model of the 12-disc glass insulator after simulation; different colors indicate plots of different range of density, V, measured in volts.

2.2 Equations for voltage distribution calculation

A simple method to calculate the voltage distribution and string efficiency can be devised by using the Kirchhoff's current law. According to Kirchhoff's current law ("Mechanical Design of Overhead Lines," 2015), the total current flow to a node is equal to the total current flow out. The sum of currents flowing in and out is zero as shown in Figure 7. The following sign convention is used for the flow of current:

a. Current flowing toward a junction is positive (+).

b. Current flowing away from a junction is negative (−).

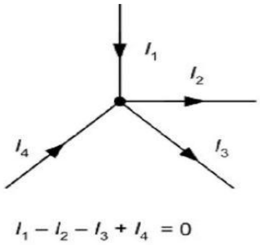

Figure 7. Kirchhoff's current law states that the sum of currents flowing in and out is zero.

Figure 8 shows the circuit diagram of the 12-disc suspension insulators. The conductor line is located at the bottom unit of the insulators. The charging currents flow from the bottom unit, I_{12}, to the top unit, I_1, of the insulator. The respective self-capacitance and shunt capacitance are indicated as C and C_s. The points A to K are the junctions or nodes into which charging currents flowing in and away from.

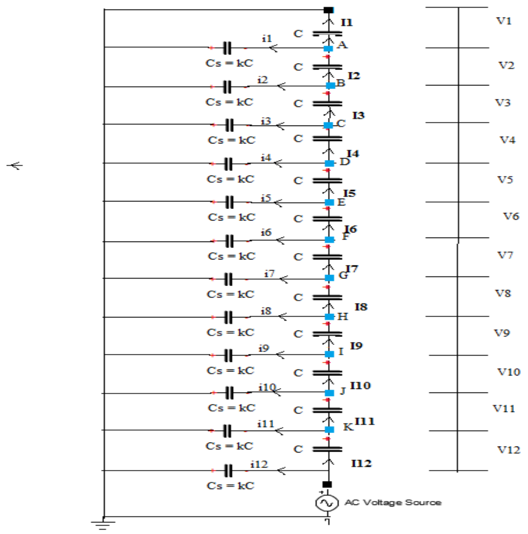

Figure 8. Kirchhoff's current law applied on the junction and the direction of charging current flow through the 12 insulators.

The following is a sample computation for string efficiency assuming there are only 3 suspension insulators as shown in Figure 9. The procedure can be extended to any number of suspension insulators. Let

k = shunt capacitance /self-capacitance, F
ω = angular frequency, rad/sec
f = frequency, Hz (Note: $f = 50$ Hz in Malaysia)

where

$$\omega = 2\pi f \tag{2}$$

Apply Kirchhoff's current law at node A,

$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1\omega kC$$
$$V_2 = V_1(1+k) \tag{3}$$

Next, apply Kirchhoff current law at node B,

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega kC$$
$$V_3 = V_2 + (V_1 + V_2)k$$
$$V_3 = V_1(1+k) + \big(V_1 + V_1(1+k)\big)k = V_1k + V_1(1+k)^2$$
$$V_3 = V_1[k + (1+k)^2]$$
$$V_3 = V_1(1 + 3k + k^2) \tag{4}$$

Let the voltage between the conductor and the earth be V_T, then

$$V_T = V_1 + V_2 + V_3. \tag{5}$$

The string efficiency is given by

$$String\ efficiency = \frac{V_T}{3V_3} \times 100\%$$

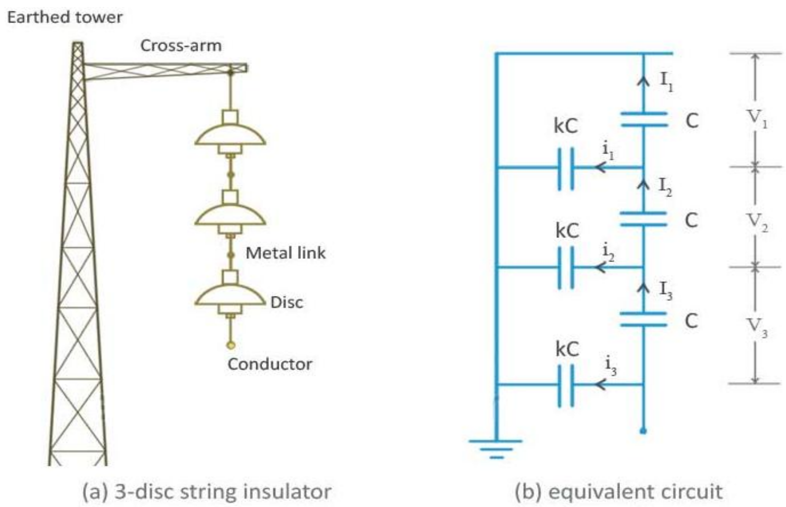

Figure 9. A three-disc string insulator and its equivalent circuit.

Based on the previous derivation, it can be shown that the string efficiency and voltage distribution with the presence of k, which is the ratio of shunt to self-capacitance, can be found through Kirchhoff's current law.

3. RESULTS AND DISCUSSION

3.1 Simulation result

In 2 dimensions, the voltage of 132 kV is applied at the bottom unit metallic pin by using the boundary condition. The 2D model is simulated in high voltage of 132 kV one-phase voltage of 3-phase transmission line. The metal cap of the top unit, which makes contact to the cross arm and support tower, are assigned as earth or 0V. The 2-dimensional model of glass suspension insulator after simulation was previously shown in Figure 6. The voltage across each insulator without capacitance grading is shown in Table 1.

Table 1. The voltage distribution of 12 insulators without capacitance grading.

Voltage distribution	**V12**	**V11**	**V10**	**V9**	**V8**	**V7**
Voltage across each unit (V)	17150.7	14796.9	13285.8	12118.6	11113.6	10361.5
Voltage distribution	**V6**	**V5**	**V4**	**V3**	**V2**	**V1**
Voltage across each unit (V)	9674.8	9164.93	8799.8	8617.74	8416.03	8499.48

Based on the electric stress of the lowest unit insulator, the string efficiency can be identified as shown in Figure 10.

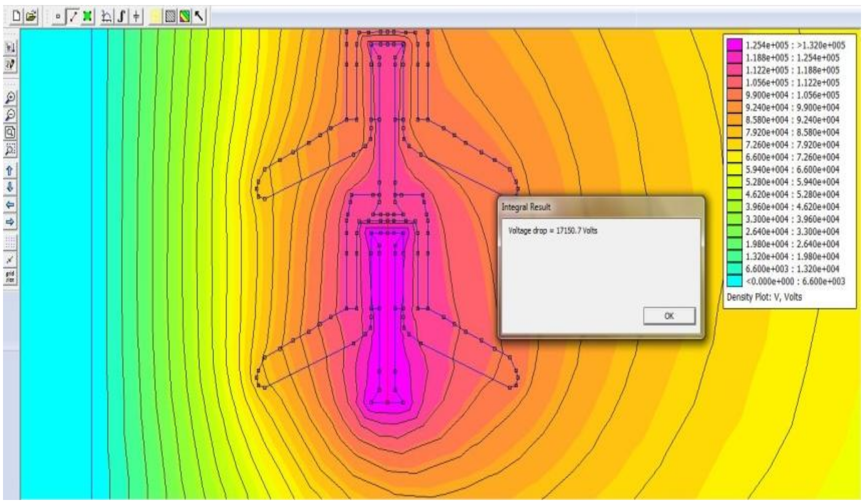

Figure 10. Stimulation result that shows the voltage across the lowest unit of insulator.

As shown in Figure 10 above, the simulation result indicates that the value of the voltage drop across the lowest bottom unit of the insulator result is 17150.7 volts, that is, $V_{12} = 17150.7$ volts. Hence, the string efficiency based on the simulation is

$$\text{String efficiency } = \frac{132 \text{ kV}}{12 \times 17150.7} \times 100\% = 64.137\ \% \quad (6)$$

On the other hand, the voltage across each insulator with capacitance grading is shown in Table 2.

Table 2. The voltage distribution of 12 insulators with capacitance grading.

Voltage distribution	**V12**	**V11**	**V10**	**V9**	**V8**	**V7**
Voltage across each unit (V)	14433.4	13512	12691	11768	11195	10520
Voltage distribution	**V6**	**V5**	**V4**	**V3**	**V2**	**V1**
Voltage across each unit (V)	10062.9	9576.52	9314.08	9272.17	9624.14	10029

When capacitance grading is applied, the voltage across the insulator nearest disc is $V_{12} = 14433.4$ volts. Hence, the string efficiency based on the simulation is

$$\text{String efficiency } = \frac{132 \text{ kV}}{12 \times 14433.4} \times 100\% = 76.212\ \% \quad (7)$$

This shows an improvement of around 12.075 % in string efficiency.

3.2 Voltage distribution and electric field plot

The electric field along the 12-disc suspension insulators from the metal pin of the bottom unit insulator as the reference point at the position zero (0 cm to the cross arm), which is attached to the iron cap, to the top unit insulator located at a position of 180 cm relative to the reference point, is shown as a graph in Figure 11.

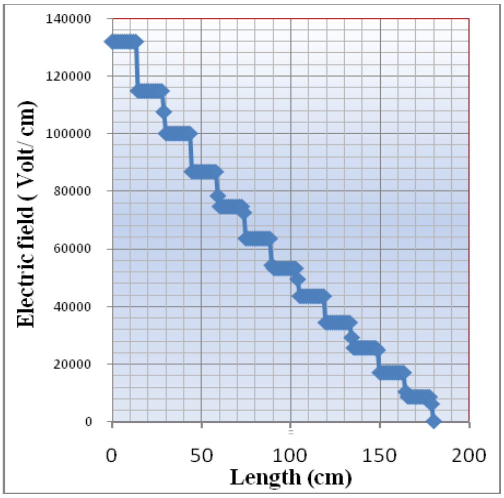

Figure 11. Graph of the electric field from reference point to top within the 12 insulators.

3.3 Shunt and self-capacitance calculation based on simulation

The shunt capacitance C_s is formed between the support tower, which is considered as earth, and each of the metallic caps and pins with the air gap as insulator. Each of these 12 shunt capacitors is connected in parallel. The vertical straight line shown in Figure 12 placed beside the string of 12 insulators represents the support tower defined as earth, which is at 0V. The voltage applied to the conductor at the bottom unit insulator is specified as 132 kV. In order to determine the shunt capacitance, the air is identified in this model of simulation as insulator while the cross arm is assumed to have no capacitance. The result of simulation indicated that the total flow of charge received by the support tower as shown in the conductor properties box is $Q_T = 5.11444 \times 10^{-8}$ coulombs.

The total capacitance resulting from the shunt capacitances connected in parallel is

$$C_T = 12C_s \tag{8}$$

We shall use the following formula to compute the shunt capacitance C_s:

$$Q_T = C_T V_T \tag{9}$$

With the total voltage, $V_T = 132$ kV, we have

$$5.11444 \times 10^{-8} = (12C_s)(132{,}000).$$

Hence, the shunt capacitance in Farad (F) is,

$$C_s = 3.2288 \times 10^{-14} \text{ F} \tag{10}$$

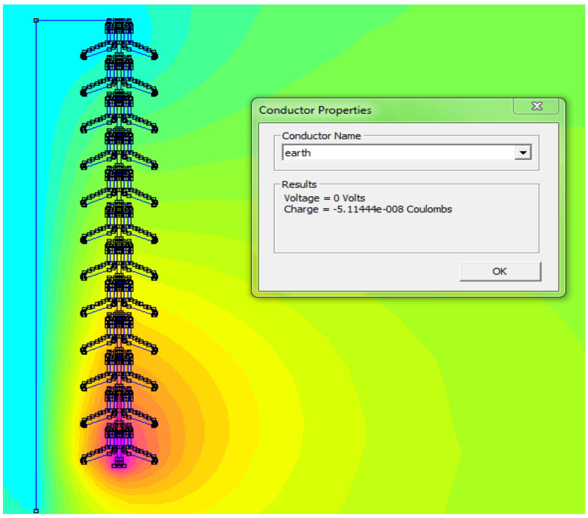

Figure 12. The conductor properties box shows the result of the total charge flow to the support tower as earth with air as insulator.

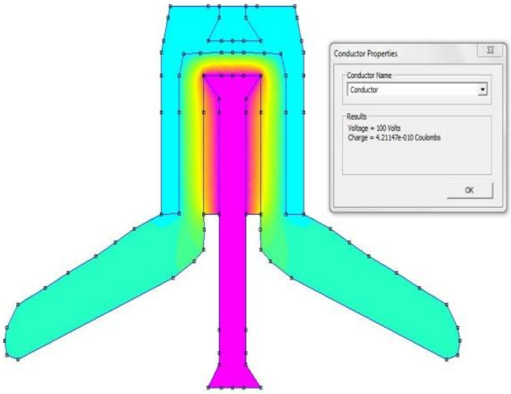

Figure 13. Conductor properties box showing the result of total charge flow through the 12 insulators to the horizontal line at the top of the first unit defined as earth.

Based on Figure 13, the capacitor C is one of the other 12 identical insulators before applying the grading method. When a voltage of $V = 100$ volts is applied to the lower part (pin) while the upper part (iron cap) as ground is at 0 V, the total charge flow emitted from the lower part (pin) to ground is $Q = 4.21147 \times 10^{-10}$ coulombs (C). We can compute the self-capacitance using the formula:

$$Q = CV \tag{11}$$

This gives,

$$4.21147 \times 10^{-10} = C(100).$$

Hence, each self-capacitance is $C = 4.21147 \times 10^{-12}$ Farad.

This paper discussed the 2-dimensional modeling of 12-disc suspension insulators, as well as, determined the string efficiency and voltage distribution of this string of insulators. The comparison between simulation result based on finite element method (Bathe, 2007) analysis and the result obtained through formulation based on Kirchhoff's current law were presented. The 12-disc glass insulator used for 132 kV overhead transmission lines is simulated. In order to construct an accurate result, the shunt and self-capacitance have to be identified based on simulation. Then the ratio of shunt to self-capacitance is used for the formulation.

3.4 Derivation of voltage distribution based on shunt and self-capacitance

The derivation method is used here to determine the voltage distribution and string efficiency. After that, the comparison is carried out between simulation result based on finite element method analysis and formulation result based on Kirchhoff's current law (Dhalaan & Elhirbawy, 2003; Kontargyri et al., 2006; Bandyopadhyay, 2006) as applied to the circuit diagram presented in Figure 6.

The ratio of shunt capacitance to self-capacitance, k, is defined as:

$$k = \frac{shunt\ capacitance}{self-capacitance} \tag{12}$$

Substituting the value of the shunt capacitance and the value of the self-capacitance as determined above, we obtain

$$k = \frac{3.2288 \times 10^{-14}}{4.21147\ \times 10^{-12}} = 0.00767$$

We shall now determine the voltage distribution of the 12-disc string insulator by applying Kirchhoff's current law to the different junctions or nodes labeled as A, B, C, D, E, F, G, H, I, J, and K. In the subsequent computations, we shall use $k = 0.00767$ and substitute this value in the formula. Applying the Kirchhoff's current law to:

<u>Node A:</u>

$$I_2 = I_1 + i_1$$
$$V_2\omega C = V_1\omega C + V_1\omega kC$$
$$V_2 = V_1 + kV_1$$

$$V_2 = (1+k)V_1 \tag{13}$$

Hence,

$$V_2 = 1.00767\, V_1$$

<u>Node B:</u>

$$I_3 = I_2 + i_2$$
$$V_3\omega C = V_2\omega C + (V_1 + V_2)\omega kC$$
$$V_3 = V_2 + k(V_1 + V_2)$$
$$V_3 = (1+k)V_1 + (V_1 + (1+k)V_1)k$$
$$V_3 = (1 + 3k + k^2)V_1 \tag{14}$$

Hence,

$$V_3 = V_2 + k(V_1 + V_2)$$
$$V_3 = 1.00767\, V_1 + 0.00767(V_1 + 1.00767\, V_1)$$
$$V_3 = 1.02307V_1$$

In general, we note that the current I_m at the mth node is computed in terms of the current I_{m-1} and the current i_{m-1} at the previous $(m-1)$th node. That is,

$$I_m = I_{m-1} + i_{m-1} \tag{15}$$

Moreover, we note that the voltage V_m at the mth node, can be computed in terms of the first $(m-1)$ voltages using the recursive formula:

$$V_m = V_m + k\sum_{i=1}^{m-1} V_i \tag{16}$$

We can use this observation and formula to guide us and simplify the succeeding calculations. The results were as follows:

Node C:

$$I_4 = I_3 + i_3$$
$$V_4\omega C = V_3\omega C + (V_1 + V_2 + V_3)\omega kC$$
$$V_4 = V_3 + k(V_1 + V_2 + V_3)$$
$$V_4 = (1 + 3k + k^2)V_1 + k(V_1 + (1+k)V_1 + (1 + 3k + k^2)V_1)k$$
$$V_4 = (1 + 6k + 5k^2 + k^3)V_1 \tag{17}$$

Hence,

$$V_4 = V_3 + k(V_1 + V_2 + V_3)$$
$$V_4 = 1.02307V_1 + 0.00767(V_1 + 1.00767\,V_1 + 1.02307V_1)$$
$$V_4 = 1.0463V_1$$

In the following calculations, we shall mostly use the recurrence formula mentioned above and omit some details to shorten the computations.

Node D:

$$I_5 = I_4 + i_4$$
$$V_5 = V_4 + k(V_1 + V_2 + V_3 + V_4)$$
$$V_5 = 1.0463V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1)$$
$$V_5 = 1.077571V_1$$

In general,

$$V_5 = (1 + 10k + 15k^2 + 7k^3 + 7k^4)V_1 \tag{18}$$

Node E:

$$I_6 = I_5 + i_5$$
$$V_6 = V_5 + k(V_1 + V_2 + V_3 + V_4 + V_5)$$
$$V_6 = 1.077571V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1)$$
$$V_6 = 1.1171069V_1$$

In general,

$$V_6 = (1 + 15k + 35k^2 + 28k^3 + 9k^4 + k^5)V_1 \quad (19)$$

Node F:

$$I_7 = I_6 + i_6$$
$$V_7 = V_6 + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6)$$
$$V_7 = 1.1171069V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1)$$
$$V_7 = 1.16521V_1$$

In general,

$$V_7 = (1 + 21k + 70k^2 + 84k^3 + 45k^4 + 11k^5 + k^6)V_1 \quad (20)$$

Node G:

$$I_8 = I_7 + i_7$$
$$V_8 = V_7 + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7)$$
$$V_8 = 1.16521V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1)$$
$$V_8 = 1.22225V_1$$

In general,

$$V_8 = (1 + 28k + 126k^2 + 210k^3 + 165k^4 + 66k^5 + 13k^6 + k^7)V_1 \quad (21)$$

Node H:

$$I_9 = I_8 + i_8$$
$$V_9 = V_8 + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8)$$
$$V_9 = 1.22225V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1 + 1.22225V_1)$$
$$V_9 = 1.28867V_1$$

In general,

$$V_9 = (1 + 36k + 210k^2 + 462k^3 + 495k^4 + 286k^5 + 91k^6 + 15k^7 + k^8)V_1 \quad (22)$$

Node I:

$$I_{10} = I_9 + i_9$$
$$V_{10} = V_9 + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9)$$
$$V_{10} = 1.28867V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1 + 1.22225V_1 + 1.28867V_1)$$
$$V_{10} = 1.36497V_1$$

In general,

$$V_{10} = (1 + 45k + 330k^2 + 924k^3 + 1287k^4 + 1001k^5 + 455k^6 + 120k^7 + 17k^8 + k^9)V_1 \quad (23)$$

<u>Node J:</u>

$$I_{11} = I_{10} + i_{10}$$
$$V_{11} = V_{10} + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9 + V_{10})$$
$$V_{11} = 1.36497V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1 + 1.22225V_1 + 1.28867V_1 + 1.36497V_1)$$
$$V_{11} = 1.451739V_1$$

In general,

$$V_{11} = (1 + 55k + 495k^2 + 1716k^3 + 3003k^4 + 1820k^5 + 680k^6 + 120k^7 + 153k^8 + 19k^9 + k^{10})V_1 \quad (24)$$

<u>Node K:</u>

$$I_{12} = I_{11} + i_{11}$$
$$V_{12} = V_{11} + k(V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9 + V_{10} + V_{11})$$
$$V_{12} = 1.451739V_1 + 0.00767(V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1 + 1.22225V_1 + 1.28867V_1 + 1.36497V_1 + 1.451739V_1)$$
$$V_{12} = 1.54964V_1$$

In general,

$$V_{12} = (1 + 66k + 715k^2 + 3003k^3 + 6435k^4 + 8008k^5 + 6188k^6 + 3060k^7 + 969k^8 + 190k^9 + 21k^{10} + k^{11})V_1 \quad (25)$$

The total voltage across the string of insulators is,

$$V_T = V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9 + V_{10} + V_{11} + V_{12}$$
$$V_T = V_1 + 1.00767V_1 + 1.02307V_1 + 1.0463V_1 + 1.077571V_1 + 1.1171069V_1 + 1.16521V_1 + 1.22225V_1 + 1.28867V_1 + 1.36497V_1 + 1.451739V_1 + 1.54964V_1$$
$$V_T = 14.314V_1$$

In general,

$$V_T = (12 + 286k + 2002k^2 + 6435k^3 + 11440k^4 + 12376k^5 + 8568k^6 + 3876k^7 + 1140k^8 + 210k^9 + 22k^{10} + k^{11})V_1 \quad (26)$$

Based on derivation, V_T is the phase voltage, which is the line voltage to earth. Since $V_T = 132$ kV, we have

$$V_T = 14.314V_1 = 132{,}000.$$

It then follows that

$V_1 = 9221.74$ V
$V_2 = 1.00767V_1 = 1.00767\ (9221.74) = 9{,}292.47$
$V_3 = 1.02307V_1 = 1.02307\ (9221.74) = 9{,}434.49$
$V_4 = 1.0463V_1 = 1.0463\ (9221.74) = 9648.71$
$V_5 = 1.077571V_1 = 1.077571\ (9221.74) = 9937.07$
$V_6 = 1.1171069V_1 = 1.1171069(9221.74) = 10301.67$
$V_7 = 1.16521V_1 = 1.16521\ (9221.74) = 10745.26$
$V_8 = 1.22225V_1 = 1.22225\ (9221.74) = 11271.27$
$V_9 = 1.28867V_1 = 1.28867\ (9221.74) = 11883.78$
$V_{10} = 1.36497V_1 = 1.36497\ (9221.74) = 12587.40$
$V_{11} = 1.451739V_1 = 1.451739\ (9221.74) = 13387.56$
$V_{12} = 1.54964V_1 = 1.54964\ (9221.74) = 14290.38$

The string efficiency based on calculations is:

$$String\ efficiency\ = \frac{14.314\ V_1}{12 \times 1.54964V_1} \times 100\% = 76.975\ \%$$

On the other hand, the string efficiency based on simulations with capacitance grading is given in Equation 7 as 76.212 %. Comparison gives a percentage error of:

$$Percentage\ Error\ = \frac{76.975 - 76.212}{76.975} \times 100\% = 0.991\ \%$$

Discrepancies between simulation and theoretical values of the string efficiency can be attributed to several factors. The first factor is the inaccuracy in estimating the actual value of the shunt capacitance. The second factor is the presence of the metallic cross arm, which affects the overall capacitance between the steel tower and the metal caps. The third factor is the numerical error introduced by rounding-off numbers to 4 or 5 decimal places, which affected the accuracy of the result.

Table 3. Calculation result obtained from derivation for the voltage distribution of 12 insulators of the circuit diagram of Figure 6.

Voltage distribution	**V12**	**V11**	**V10**	**V9**	**V8**	**V7**
Voltage across each unit (V)	14290.38	13387.56	12587.40	11883.78	11271.27	10745.26
Voltage distribution	**V6**	**V5**	**V4**	**V3**	**V2**	**V1**
Voltage across each unit (V)	10301.67	9937.07	9648.71	9434.49	9292.47	9221.74

4. CONCLUSIONS

In this paper, we considered the 132 kV 12-disc string insulators and determined its voltage distribution as well as string efficiency through calculations and 2D planar simulations using the FEMM software for finite element analysis. The theoretical calculation of the voltage distribution across each unit of the insulators proved to be useful in determining the string efficiency and for verification of simulation results. At the end of the project, we obtained the voltage distribution and maximum electric stress at the bottom unit of the string, which enabled us to determine its string efficiency. Based on the results of simulations, the string efficiency was found to be 64% without capacitance grading and 76% with capacitance grading. The simulation confirmed that capacitance grading method improves the string efficiency and therefore the performance capability of the string insulators. Inaccuracy in estimating the shunt capacitance, the presence of the cross arm, and the numerical errors introduced during the rounding-off of numbers are factors that affect the accuracy of the result.

5. ACKNOWLEDGMENT

The first author, Dr. Federico Roy, Jr., a senior lecturer at the INTI International University and who supervised this project, would like to express gratitude for the precious contribution of his guide by providing the much-needed help for this project. The successful completion of this project was made possible due to his sincere cooperation, guidance, inspiration, moral support and timely advice. Moreover, the authors give special thanks to Dr. Hazlee Azil illias and Dr. Mohsin Ali Tunio, both from the Department of Electrical Engineering, Faculty of Engineering, University of Malaya, more especially to Dr. Hazlee Azil illias, who is also affiliated with the UM Power Energy Dedicated Advanced Centre, for providing the specifications for the LXWP4-70 glass suspension insulator. The authors are also grateful to the people who supported and encouraged them to complete this paper successfully.

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