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Analysis of Lightning Performance on 345 kV Transmission Lines Using Python Programming

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***Abstract*— One of main causes of interruption of electrical power supply is the lightning strike on overhead power transmission lines. The lightning performance of transmission line can be determined by value of shielding failure flashover rate (SFFOR) and back flashover rate (BFOR). The object of this study is to create a computer application to compute lightning performance on the transmission lines using Python programming. Pythons package tkinter used for program interface window. Application programming is done by using the concept of object-oriented programming (OOP) using Pythons keyword class. Validation shows that the application has applied the method correctly with a percentage error 0 % for SFFOR and 3.14 % for BFOR. The application can do analysis on the factors that affecting SFFOR and BFOR such as the effect of thunder day, tower foot resistance, and number of isolator disk. The results obtained in this study is computer application that can perform lightning performance analysis and analysis of factors that can affect it, such as thunder day, tower foot resistance and the number of isolator disk.**

***Keywords*— BFOR, lightning performance, OOP, overhead transmission line**

I. Introduction

At high voltage, power is distributed using overhead high voltage transmission line, that open to various factors that may causes abnormal conditions and cause interruption.

One of the main causes of interruption in electrical power distribution is the lightning stroke on the transmission lines. The overvolatage on transmission lines caused by lightning strike are a major problem that causes insulation failure in the electricity power system network.

The performance of high voltage (HV) overhead transmission lines, extra high voltage (EHV) transmission lines, can be determined by number of lightning strikes that hit lines component and cause flashover (FO) on insulators. According [1], if lightning hit conductor and cause FO on the insulators, then that was called shielding failure (SF), and it is necessary to compute the SFFOR, that indicates the number of lightning that hit the phase conductors, in 100 km of lines, in a year, that lead to FO. If lightning hit the shield wire or the tower, then there is overvolatage that may be high enough to cause back flashover (BFO) on the insulators. In this case it is necessary to compute BFOR, that indicates the number of lightning, in 100 km of lines, in a year, that cause BFO.

The purpose of this research is to create a computer application that can perform lightning performance analysis using Python programming. Methods for analyzing of the lightning performance continue to develop every time. The analytical method and the numerical method were carried out, even the software has been made based on the equations of lightning performance analysis. The following steps are several studies that discuss the method of performance analysis of lightning protection.

Valesco, et al., developed the methods to calculate lightning protection performance accurately, using software analysis transients' program – electromagnetic transients' program (ATP-EMTP) and Monte Carlo procedures. The software was developed at Matlab tools. Lightning parameters such as peak current, face time and tail time are determined randomly using the probability function. Power system modeling is done using ATP-EMTP, then a lightning strike simulation is performed on the model. If the voltage of the insulators exceeds the critical voltage of the insulator, then declared FO plus 1. Then the process is repeated using the Monte Carlo procedures. The Monte Carlo procedures are applied using parallel computing in Matlab tools. The Iteration were 100,000 times, and they were done in 12 minutes [2].

Mikropaulus et al, had developed a software called LPTL. LPTL is useful as a tool for evaluating lightning performance on air transmission lines, LPTL was developed in Matlab tools. LPTL generated a general relationship to the lightning strike density of shielded and phase wire, SFFOR, BFOR, maximum protective failure current and perfect protection angle on the transmission line [3]. Zoro and Murdiya, do analysis of lightning protection performance on the 275 kV Sigura Gura - Kualatanjung transmission lines in North Sumatra. The lightning data used in this study were obtained from the national weather office, showing that the total lightning strikes of clouds to the ground were very high compared to other areas around the study area. Shielding failure was analyzed using the concept of electro geometric and finite element method. The results show that lightning performance estimates calculated using the whitehead concept provide good grounding and good shielding [4].

Zoro and Pranomo, studied the lightning performance on the Paiton-Kediri 500 kV transmission lines. There had been many damages to insulators on the transmission line, especially during the rainy season. The results of this study found that some towers need to be improved for overvoltage due to direct strikes to the tower [5].

Abrantes et al., had made software for calculating SFFOR and BFOR, the software is based on equations adopted by the Institute of Electrical and Electronics Engineers (IEEE) and then developed by applying methods from the International Council on Large Electric Systems (CIGRE) and other researchers [6].

Lightning Strike Mechanism

Lightning is a natural phenomenon that occurs in the atmosphere when it rains. Lightning occurs because there are potential differences between clouds and earth. Lightning starts with a stepped leader approaching the earth, then divides into one or several paths (Figure 1A). After a stepped or downward leader approaches the earth, an upward leader from the earth meets the downward leader (Figure 1B). Then the upward leader moves up from the earth to the clouds (Figure 1C) in this process the current is released to the earth. From process A to C in Figure 1 is called the first stroke mechanism [7]. And a lightning can consist of many strikes.

Shortly after the first stroke, a second leader, named a dart leader, starts heading down from the clouds (Figure 1E). To start the dart leader, other loads on the cloud will be released. When the head of the dart leader approaches the earth, then the upward leader from the earth meets the dart leader, and once again the current is released to the earth. Another charge point on the cloud allows the emergence of another leader from the cloud to the earth, and starts another strike at lightning and so on [7].

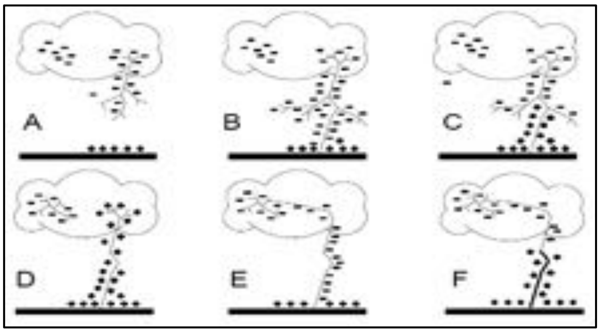

Fig. 1. The process of lightning which struck the transmission line

Isokeraunic Levels and Maps

Each region that passed by the transmission lines must have a certain isocyanic level. This level represents the average number of thunder days per year in a particular region, which is the average number of days per year where thunder is heard over a 24-hour period. The isocyanic level is usually determined based on an isocyanic map provided by a country's weather agency.

Isocyanic level is a statistic that depends on the hearing ability of the weather observer, the influence of the background lighting and geography of the area, and on the careful compilation of weather records. If two thunderstorms occur on a certain day, that day is still classified as a day of thunder. Isocyanic level and map shows in Figure 2.

Number of Flash To Ground

For simplicity, it is usually assumed that the number of strokes to the ground or to a transmission lines in a particular region is more or less the same as the isocyanic level in that region. Based on the isocyanic map then the number of strikes to the ground can be determined. to determine the density of the stroke to the ground Equation 1 is recommended [7].

$$N = 0.12 \text{ x Td} \quad (1)$$

Where N is the number of strikes to the ground, Td number of thunder days.

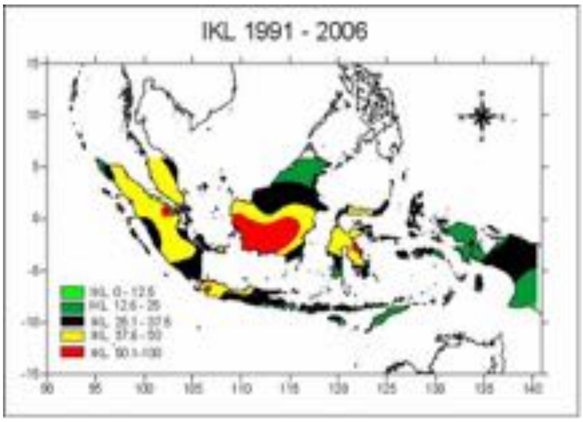

Fig. 2. Isocyanic levels map

Number of Flash to Buildings

The transmission lines that crosses the earth's surface can be said to cast an electric shadow to the ground below. Lightning strikes that end up on the ground in the shadow of the lines may be hit the lines. Figure 3 shows a simple approach to the wide shadow line that has two shield wires. The height (h_{avg}) in Figure 3 is the average height of the shield wires. The average height of a wire can be compute using the following equation [7].

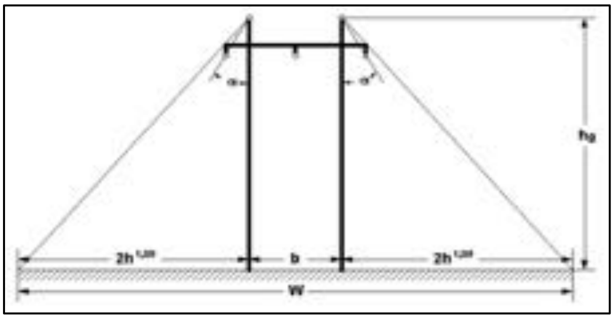

Fig. 3. Tower shadow width, with 3 horizontal conductor and 2 shielded wires

$$h_{avg} = h_g - \left(\frac{2}{3}\right) \text{x Sag} \quad (2)$$

Where h_g is the height of the wire in the tower. The width of the shadow can be determined using the following equation [7].

$$W = b + 4 \text{ x } h^{1.09} \quad (3)$$

Where W is the width of the line shadow, and h is the height of the tower. The number of possible strokes to buildings or lines in 100km in a year can be compute using the following equation [7].

$$N_L = \frac{0.12 \text{ x Td} \left(b + 4 \text{ x } h^{1.09}\right)}{10} \quad (4)$$

Where b is the distance between the shield wires, h is the height of the tower. If the shield wire is only 1, then b becomes 0.

Probability of Lightning Peak Distribution

The probability distribution of the lightning peak current value has been given by some researchers. In this study Equation 5 [8], which has also been used in the IEEE standard [9]. Where I is the peak lightning current.

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$$P(I) = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \quad (5)$$

Simplification Sub-Conductor

To further simplify the problem, it is recommended that each conductor which has a sub-conductor to be simplified to an equivalent conductor. Simplifying the conductive beam into an equivalent conductor can be calculated by the following equation [7].

$$R_{eq}= \sqrt[N]{r_{11}r_{12}r_{13}\ldots r_{1n}} \quad (6)$$

Where R_{eq} is the equivalent of the sub-conductor radius, r is the conductor wire radius, N is the number of sub-conductors, r_{1n} is the distance between sub-conductors.

Effective Radius of Wire with the Presence of Corona

At high voltage, the corona effect must be taken into account. In the case of shield wire, the corona diameter can exceed one meter and its impact on the induction of the voltage on the conducting wire can be very significant. The corona cover radius at one conduction can be determined by the following equation [7].

$$R \ln\frac{2h}{R}=\frac{V}{E_o} \quad (7)$$

Then by [6] the equation 7 solved to be equation 8, and can be solve by iteration. In this study simple fixed point method iteration was applied.

$$R_C^{n+1}= \frac{V}{E_o \ \ln\left(\frac{2h}{R_C^n}\right)} \quad (8)$$

The effective wire radius cause by corona can be computed using following equation 9 [7].

$$R_{C\ efektif} = R_C + R_{eq} \quad (9)$$

Where R_C is a corona radius in meter, E_o is the lower gradient corona (1500 kV/m) [7], h is wire height from the ground, in the case of SFFOR the height used is the average height of the wire, whereas in the case of BFOR it uses the height of the wire on the tower. V is the voltage applied to the wire (kV). RC is the wire radius due to the presence of corona.

Surge Impedance of Wire

The effective radius of a single conductor must be taken as a geometric mean of its effect with and without corona covers. Then, the impedance surges of one wire in a heavy corona are as follows in equation 10 [7].

$$Z_{s\_nn}=60 \text{ x } \sqrt{\ln\frac{2h}{r} \ . \ln\frac{2h}{R_{C\ effective}}} \quad (10)$$

Join Surge Imepedance of Shield Wires

If only one shield wire exists, then surge impedance of shield wire can be determined using equation 10. While the joint surge impedance between 2 shield wires can be computed using the following equation 11 [7].

$$Z_{s\_mn} =60 \ln\left(\frac{a_{mn}}{b_{mn}}\right) \quad (11)$$

Then, the equivalent surge impedance of 2 shield wires can be computed using the following equation 12 [7].

$$Z_S=\frac{Z_{s\_nn}+Z_{s\_mn}}{2} \quad (12)$$

Where mn is the distance from wire m to shadow wire n, b_{mn} is the actual distance between wire m and n.

Transmission Tower

In the book Transmission Line Reference Book 345 kV anf Above / Second Edition, Chapter 12 [7], transmission towers are classified into several shape that are often found. The shape and equations of tower impedance can be seen in the following figure.

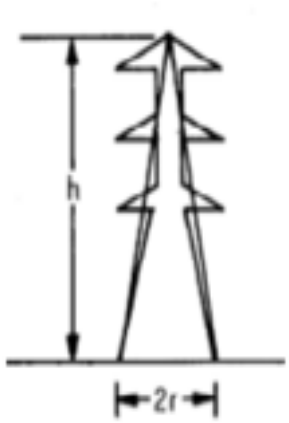

Fig. 4. Tower Class 1

The equation 13 for class 1 tower is:

$$Z_T=30 \ \ln\left[\frac{2 \text{ x } \left(h^2+r^2\right)}{r^2}\right] \quad (13)$$

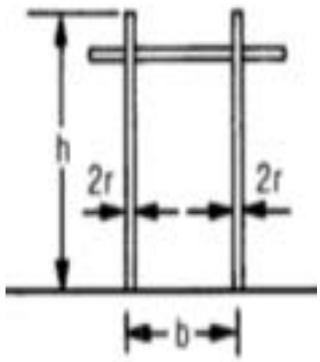

Fig. 5. Tower Class 2

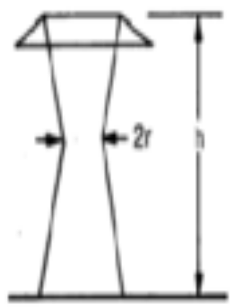

Figure 6. Tower Class 3

The equation 14,15,16 for class 2 tower is:

$$Z_t=\frac{(Z_s+Z_m)}{2} \quad (14)$$

$$Z_s=60 \ \ln\left(\frac{h_{tower}}{r}\right)+90\left(\frac{r}{h_{tower}}\right)-60 \quad (15)$$

$$Z_m=60\ \ln\left(\frac{h_{tower}}{b}\right)+90\left(\frac{b}{h_{tower}}\right)-60 \quad (16)$$

The equation 17 for class 3 tower is:

$$Z_T=60\left[\ln\left(\sqrt{2}\frac{2h}{r}\right)-1\right] \quad (17)$$

For each class, time travel time τT from the top of the tower to the foot of the tower can be calculated using the following equation 18 [7].

$$\tau_T = \frac{h}{300}\mu s \quad (18)$$

Determine the Coupling Factor

To determine the coupling factor of each conductor wire, the joint surge impedance is first determined between the conductor wire and the shield wire using equation 11, then the coupling factor for the 2 shield wire is as follows in equation 19 and 20 [7].

$$K_n=\frac{Z_{n1}+Z_{n2}}{Z_{11}+Z_{12}} \quad (19)$$

Whereas for 1 shield wire,

$$K_n=\frac{Z_{n1}}{Z_{11}} \quad (20)$$

Where Z_{n1} is the joint surge impedance between the shield wire 1 to conductor wire n, Z_{n2} is the joint surge impedance between the shield wire 2 to conductor n, Z_{11} is the surge impedance of one shield wire, Z_{12} is the joint surge impedance between the shield wire 1 and the shield wire 2.

Volt-Time Curve

The level of the surge voltage that causes the insulator or air gap flashover (FO) is not constant, but it is a function of time. The shorter the time that causes insulation failure, the higher the voltage [7]. The mathematical equation to get the FO voltage at a certain time is in equation 21 [7].

$$V_{cfo}=\left(K_1+ {K_2}/{t^{0,75}}\right) \text{ x } 1000 \quad (21)$$

Where K1 is 0.4 w, K2 is 0.71 w, t is the time to breakdown of isolator, and w is the total length of the insulator.

Compute Shielding Failure

To determine SFFOR several steps are needed which will be explained as follows.

1) Critical Current

The peak current that can cause FO in the insulator can be calculated using the following equation 22 [7].

$$I_{min} = \frac{2 \text{ x } V_C}{Z_{mm}} \quad (22)$$

Where V_C is the insulator's critical voltage and Z_{mm} is the conductor impedance. Then the minimum stroke distance can be calculated with the following equation 23 [7].

$$S = 10 \text{ x } I^{0.65} \quad (23)$$

2) Exposed Phase Conductor

To determine the exposed conductor wire, first determine the coordinates of the effective shield wire and the effective angle of protection using the following equation 24,25 [7].

$$X_G=\sqrt{S^2-(\beta S-Y_\Phi)^2}-\sqrt{S^2-(\beta S-Y_G)^2} \quad (24)$$

$$\alpha_E=\tan^{-1}\left(\frac{X_G}{Y_\Phi-Y_G}\right) \quad (25)$$

Then calculate the existing shield angle using the following equation 26 [7].

$$\alpha_s=\tan^{-1}\left(\frac{X_\Phi-X_G}{Y_G-Y_\Phi}\right) \quad (26)$$

If $\boldsymbol{\alpha}_S < \boldsymbol{\alpha}_E$, it can be said that the conductor wire is not exposed, so the SFFOR value for that conductor is 0. If $\boldsymbol{\alpha}_S > \boldsymbol{\alpha}_E$, the conductor wire can be said to be exposed and then an unshield area can be compute.

3) Compute Unshield Ares

For vertical lightning, the width of the unshield area X_S in figure 7 will establish an unshield area on the ground, where lightning will generally hit the ground but hit the conductor wire instead, because the distance of the strike to the conductor wire is closer.

If $\beta S>Y_\Phi$, then:

$$X_S = S[\cos\theta+\sin(\alpha_s-\omega)] \quad (27)$$

If, $\beta S < Y_\Phi$, then:

$$X_S = S[1+\sin(\alpha_s-\omega)] \quad (28)$$

where,

$$\theta = \sin^{-1}\frac{\beta S-Y_\Phi}{S} \quad (29)$$

$$\omega = \cos^{-1}\frac{F}{2S} \quad (30)$$

$$\alpha_s = \tan^{-1}\left(\frac{X_\Phi-X_G}{Y_G-Y_\Phi}\right) \quad (31)$$

Factor β, 0.8 for Extra High Voltage, 0.64 for Ultra High Voltage, and 1 for High Voltage and Medium Voltage. X_Φ and Y_Φ is the coodinate X and Y conductor wire. X_G and Y_G is the coordinate X and Y of shield wire. F is the distance from shield wire to conductor n.

4) Compute Maximum Stroke Distance

The maximum stroke distance can be determined using the following equation 32 [7].

$$S_{max}=Y_o\left(\frac{-B_s-\sqrt{B_s^2+A_sC_s}}{A_s}\right) \quad (32)$$

$$Y_o=\frac{Y_G+Y_\Phi}{2} \quad (33)$$

$$m=\left(\frac{X_\Phi-X_G}{Y_G-Y_\Phi}\right) \quad (34)$$

$$A_s=m^2-m^2\beta-\beta^2 \quad (35)$$

$$B_s=\beta\left(m^2+1\right) \quad (36)$$

$$C_s=\left(m^2+1\right) \quad (37)$$

5) Compute Maximum Stroke Current

Maximum stroke current is a stroke current which can cause shielding failure. The maximum stroke current can be calculated using the following equation 38 [7].

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$$I = 0.029 \cdot S^{1.54} \quad (38)$$

6) Compute the Peak Lightning Current Probability

Minimum and maximum current probabilities can be compute using the equation 5.

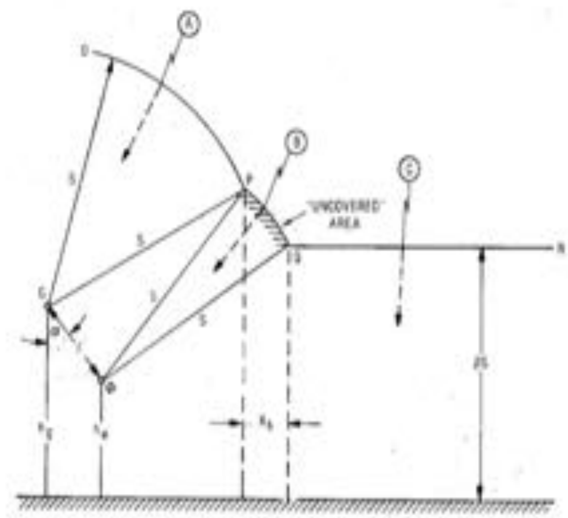

Figure 7. Simple concept of unshield area with electrogemetric theory

7) Compute SFFOR

If the conductor wire is exposed then the number of SFFOR can be compute using the following equation 39 [7].

$$N_{SF}=0.012 \cdot T_d \cdot \frac{X_s}{2} \cdot (P_{min}-P_{max}) \quad (39)$$

Where P_{min} is minimum stroke current probabilities and P_{max} maximum stroke current probabilities, T_d is thunder day.

Compute BFOR

For compute BFOR, only strikes to the shield wire on the tower are taken into account. Then a correction factor is needed which represents a reduction in the number of strikes to the copy. Based on [7] the factor is 0.6.

The peak voltage at the top of the tower must always be compute at around the time of the peak lightning strike, because at that time the peak voltage at the top of the tower is very high. In addition, when high tower foot resistance is involved in the computation, causing voltage at times of 3 to 6 μs needs to be considered, because the strength of the insulator based on the voltage-time curve, will weaken beetwen of 3 to 6 μs [7]. Then the two strike time points are chosen at 2 and 6 μs.

1) Tower Voltage

According [7], the equation of voltage at the top of the tower at 2 μs is in equation 40.

$$(V_T)_2=\left[Z_I-\frac{Z_W}{1-\psi} \times \left(1-\frac{\tau_T}{1-\psi}\right)\right] \times I \quad (40)$$

Where Z_I is the intrinsic impedance of the inner channel Ω.

$$Z_I=\frac{Z_S \times Z_T}{Z_S+2Z_T} \quad (41)$$

Z_W is the tower wave impedance in Ω.

$$Z_W=\left[\frac{2Z_s^2 Z_T}{(Z_S+2Z_T)^2}\right] \times \left[\frac{Z_T-R}{Z_T+R}\right] \quad (42)$$

R is the tower foot resistance in Ω, ψ is a tower dumping factor constant that reduces the contribution of reflection, the damping factor can be determined by the following equation 43.

$$\psi = \left(\frac{2Z_T-Z_S}{2Z_T+Z_S}\right)\left(\frac{Z_T-R}{Z_T+R}\right) \quad (43)$$

The peak voltage at the foot resistance of the tower at 2 μs, can be compute using the following equation 44 [7].

$$(V_R)_2=\left[\frac{\alpha_R \cdot Z_I}{1-\psi} \times \left(1-\frac{\psi \cdot \tau_T}{1-\psi}\right)\right] \times I \quad (44)$$

Where $\boldsymbol{\alpha}_R$ is,

$$\alpha_R=\frac{2R}{Z_T+R} \quad (45)$$

Meanwhile, to compute the reflection voltage generated by the nearest tower that appears across the tower struck at 2 μs, but first determine the travel time span using the following equation 46.

$$2\tau_S=\frac{2 \times \text{span (m)}}{300 \times 0{,}9}\ \mu s \quad (46)$$

If $2\tau_S < 2\ \mu s$ then [7],

$$(V'_T)_2=\frac{-4.K_s \times (V_T)_2^2}{Z_S} \times \left[\frac{1-2(V_T)_2}{Z_S}\right] \times (1-\tau_S) \quad (47)$$

If $2\tau_S > 2\ \mu s$ then [7],

$$(V'_T)_2=0 \quad (48)$$

Then the total voltage at the top of the tower is,

$$(\bar{V}_T)_2=(V_T)_2+(V'_T)_2 \quad (49)$$

The voltage on the tower arm at 2 μs can be compute using the following equation 50 [7].

$$(V_{pn})_2=(V_R)_2+\frac{\tau_T-\tau_{pn}}{\tau_T} \times [(V_T)_2-(V_R)_2] \quad (50)$$

Where τ_{pn} is travel time from the top of the tower to the tower arm,

$$\tau_{pn} =\frac{\text{distance top to the tower arm}}{300}\ \mu s \quad (51)$$

The peak voltage of isolator at 2 μs, is difference between tower arm and surge volatage of conductor wire [7].

$$(V_{sn})_2 = (V_{pn})_2-K_n(\bar{V}_T)_2 \quad (52)$$

The magnitude of the voltage at the top of the tower, the voltage across tower foot resistance and the tower arm voltage at 6 μs, can be computed with the following equation 53 [7].

$$(V_T)_6=(V_R)_6=(V_{pn})_6=\left[\frac{Z_S \cdot R}{Z_S+2 \cdot R}\right] I \quad (53)$$

The magnitude of the reflected voltage from the nearest tower when the opposite tower is struck at 6 µs, can be compute using the following equation 54 [7].

$$(V_{sn})_6=\left[(V_T)_6+(V'_T)_6\right] \cdot (1\text{-}K_n) \quad (54)$$

2) Critical Current

Critical currents that can cause BFO to insulators at 2 µs and 6 µs without the influence of voltage frequencies are in equation 55,56 [7].

$$(I_{cn})_2=\frac{(V_{cfo})_2}{(V_{sn})_2} \quad (55)$$

$$(I_{cn})_6=\frac{(V_{cfo})_6}{(V_{sn})_6} \quad (56)$$

The power frequency effect is calculated to get an accurate result of how the power frequency voltage affects the division between various possible failures that occur and because the power frequency voltage can cause an increase in total failure. Critical currents that are affected by the power frequency voltage can be calculated using the following equation 57 [7].

$$I'_{cn}=\left[\frac{V_{cn}\text{-}V_{on} \text{ x } \sin(\theta_n\text{-}\alpha_n)}{V_{cn}}\right] \text{x } I_{cn} \quad (57)$$

Where I_{cn} is the lowest critical isolator current between $(I_{cn})_2$ and $(I_{cn})_6$, V_{cn} is the critical voltage that causes I_{cn}, V_{on} is the conductor peak line to ground voltage of the transmission system, $\boldsymbol{\theta}_n$ is the instant degree of voltage from 0° to 360°, and $\boldsymbol{\alpha}_n$ is angle phase n. Equation 57 will produce dominance of each phase, dominance is where the phase has the lowest critical current compared to the other phases. Average critical current on domination time is computed to get the final result of the number of failures. Average critical current can be compute using the following equation 58 [7].

$$\bar{I}'_{cn}=I_{cn}\left\{1+\frac{V_{on}}{V_{cn}}\left[\frac{\cos(\theta_2\text{-}\alpha_n)\text{-}\cos(\theta_1\text{-}\alpha_n)}{\theta_2\text{-}\theta_1}\right]\right\} \quad (58)$$

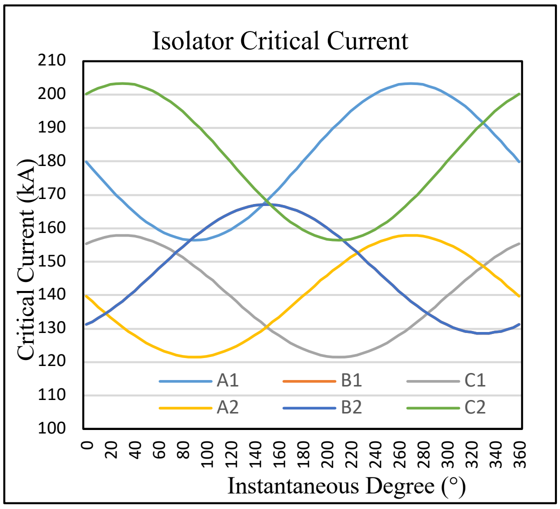

Figure 8. Critical current and phase domination

Where $\boldsymbol{\theta}_1$ dan $\boldsymbol{\theta}_2$ is instantaneous degrees domination in radiant. To determine critical current probability that exceeds $\bar{I}'_{cn}$ can be computed using Equation 5.

3) Compute BFOR

Number of effective stroke to the line can be determined using following equation 59 [7].

$$N_{L\ effective}=N_L \text{ x } 0.6 \quad (59)$$

Then multiply the number of effective strokes to the line, $NL_{effective}$ by the percentage of dominance of each conductor wire to get the number of strikes that are likely to cause BFO in each conductor.

$$\text{Phase n}=\frac{N_{L\ effective} \text{ x percentage of dominance phase n}}{100} \quad (60)$$

After the number of strikes that might cause BFO in each conductor, then multiply the number of strikes that are likely to cause BFO with the chance of the appearance of a peak lightning current that can cause BFO [7].

$$\text{FO Phase n} = \text{number flash to phase n x } P_I \quad (61)$$

Where PI is probability of average critical current. So that the total flash that are likely to cause BFOs at 100 km per year can be determined by adding up all of the FO phase n values.

II. Research Methodology

The steps that will be carried out are like, user interface and logic designing, that will get user input to do the lightning performance analysis, validation and application tests. Validation is done by comparing the application output with the theory outlined in the book [7]. Then do a test on the effect of the choices available on the application to SFFOR and BFOR.

Data

The data that will be used for verification and application tests are obtained from the book [7]. In Table 1, r wire is the radius of the wire, V_{LL} is the line to line voltage of the power system. In Figure 9, it can be seen that the conductor has 2 sub conductors, and the distance between sub conductors can be seen in Table 1. While other data such as the length of the insulator, span, thunder day and tower foot resistance can be seen in Table 2. For configuration of the wire coordinates on the tower can be seen in Figure 9.

Table 1. Data configuration of shield and conductor wire

No.	Function	r wire (m)	Distance Between bundle (m)	V_{LL} (kV)	Phase Angle (°)
1	SW	0.0045	-	0	-
2	SW	0.0045	-	0	-
3	A1	0.0148	0.457	345	0
4	B1	0.0148	0.457	345	-120
5	C1	0.0148	0.457	345	120
6	A2	0.0148	0.457	345	0
7	B2	0.0148	0.457	345	-120
8	C2	0.0148	0.457	345	120

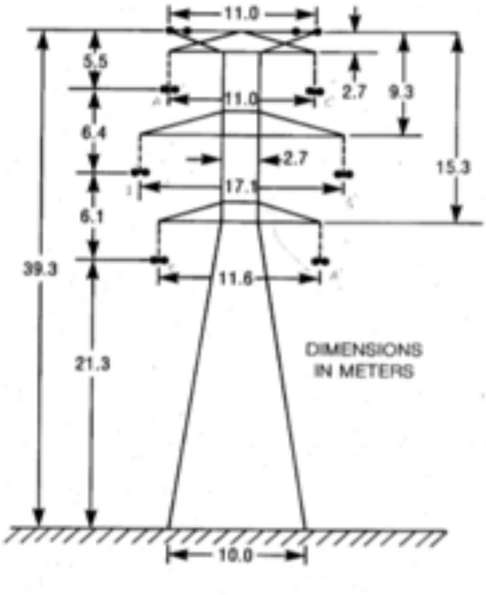

Figure 9. 345 kV transmission tower configuration

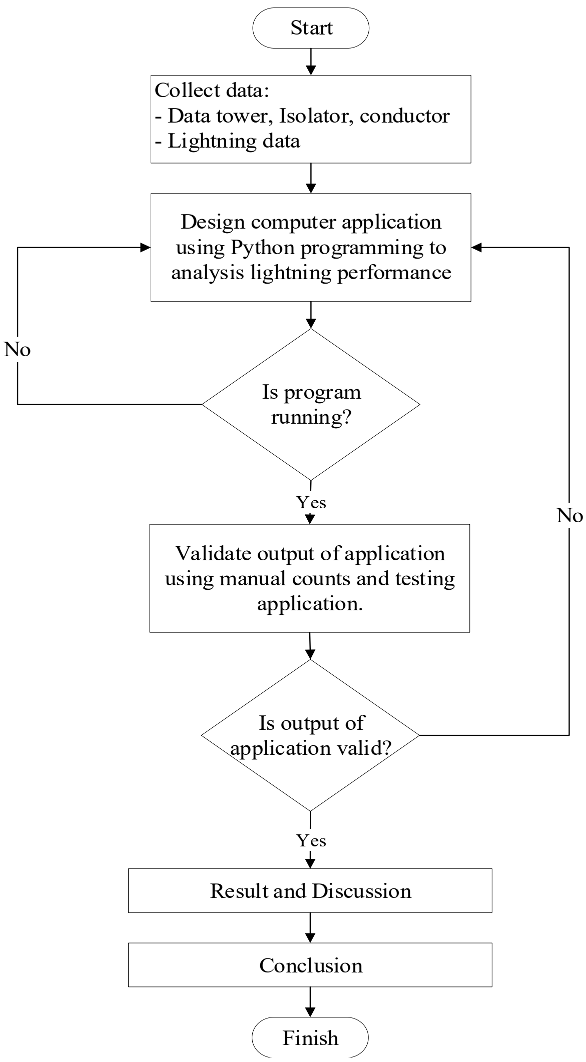

Figure 10. Research flow chart

Table 2. Other data needed

Parameter	Value
Isolator length (m)	2.63
Span (m)	335
Thunder day (days/year)	30
Tower foot resistance (Ω)	20
Length of isolator disk (m)	0.1753

Tools and Materials

The tools and materials used in this research are HP laptops with the following specifications:

Operating System : Windows 10 Pro 64-bit
RAM : 6 GB
Processor : Intel® Core™ i5-3230M CPU @2.60GHz (4 CPUs)

The version of Python used is Python 3.6.8 64 bit. The Integrated Development Environment (IDE) used is Pycharm 2019.3.1 (Community Edition) developed by JetBrains, while the virtual environment used is Pipenv.

Research Step

The research steps can be seen in the flow chart below.

Application Workflow

In general, the steps of the application work can be seen in figure 11. The dataset for tower foot resistance (R) and thunder day (T_d) has been established in application. For the dataset R can be seen in Table 3, and dataset for T_d can be seen in Table 4. If T_d is varied, SFFOR and BFOR calculations will use a dataset from T_d one by one. If not varied, then simply use the T_d data entered by the user. If the tower foot resistance is varied, the SFFOR and BFOR calculations will use a dataset of tower foot resistance one by one. If not varied, it will only use tower foot resistance data entered by the user. The program workflow can be seen in figure 11.

Table 3. Dataset tower foot resistance

Dataset name	Value
Tower foot resistance (Ω)	5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, 250, 300, 350, 400, dan input on Entry tower foot R.

Whereas for thunder day dataset can be seen in Table 4.

Table 4 Dataset thunder days

Dataset Name	Value
Thunder day (days/year)	5, 10, 20, 30, 40, 50, and input on Entry Td.

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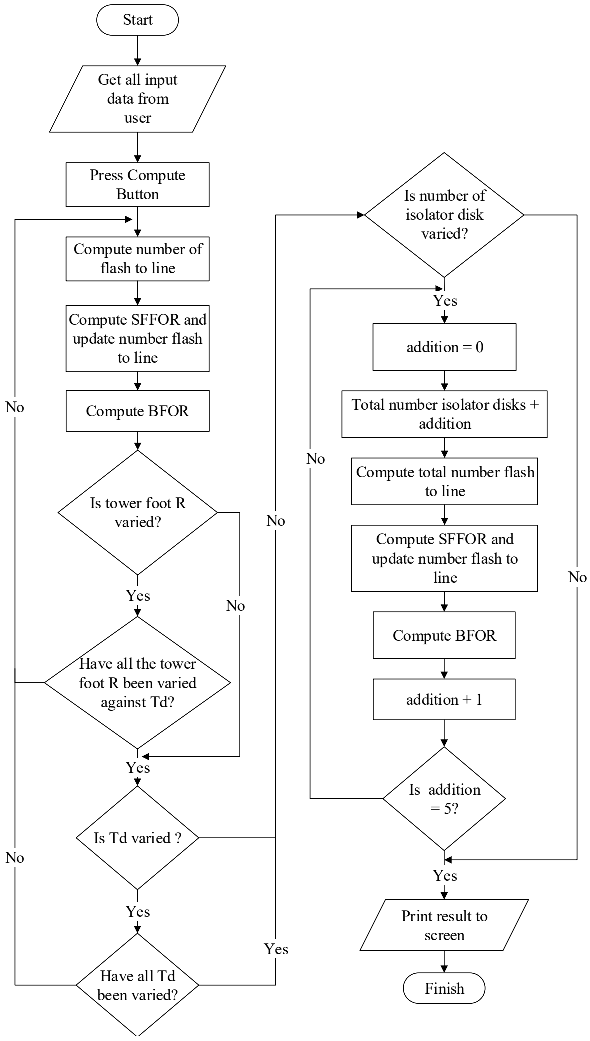

Figure 11. Program Workflow

III. Result and Discussions

The purpose of this research is to design an application to compute the lightning performance using Python programming language. The designed application can compute the lightning performance by using the method described in the reference book, Transmission Reference Book 345 kV and Above, Chapter 12 [7].

The first thing to do is to display the user interface window. Second, compare the results of the application output with the results of the manual calculation described in the book that is a reference with the aim of validating that the application is using the method correctly. Third, test the application by varying the choices in the application.

User Interface Window

In figure 12 shows the results of designed the application interface window. The interface has a default size is 730x640 pixels, for a minimum size is 730x640 pixels. The minimum size is to prevent the application from being less than the default size. If the application size is less than the default size, not all parts of the application can be displayed.

The application has a number of overlapping frames, namely the Conductor frame, the Shield Wire and Isolator frame, the Tower frame, the Result frame, the Graph frame. The frame can be accessed by pressing the button above the frame in figure 12.

The application also provides a choice of variations of thunder days, tower foot resistance, and the number of isolator disk. These choices can be selected by pressing Check button in the application interface window.

Figure 12 Application user interface window

Application Validation

Using the data that has been described in the previous section, validation is applied to the output of the application. Validation is done by comparing SFFOR and BFOR which are calculated using the application with the results of manual counts. The results show that the percentage of SFFOR and BFOR errors calculated using the application are 0% and 3.14%. It can be said that the application has implemented the SFFOR and BFOR analysis method correctly.

The Effect of Thunder Day Against SFFOR and BFOR

By pressing Check button variations of thunder days on the main Frame, the application will calculate SFFOR and BFOR with varying thunder days. The application displays output of calculation results with variations of thunder days as Appendix Table A. From the Appendix Table A, thunder day 5 days/year has lower SFFOR and BFOR compared to 50 days/year. This is due to the increasing thunder day, then the possibility of strikes to the line is increasing. The graph of the calculation results of SFFOR and BFOR with varying thunder days can be seen in figures 13 and 14.

The Effect of Tower Foot Resistance Against SFFOR and BFOR

By pressing Check button variations in tower foot resistance, the application will perform SFFOR and BFOR calculations with varying tower foot resistance (Table 4) while the other parameters remaining the same.

The data seen in Appendix Table B is generated by using the application. From the Appendix Table B, R is the tower foot resistance, while the total is the sum of SFFOR and BFOR values. SFFOR in Appendix Table B did not change due to variation tower foot resistance. Even the tower foot resistance is varied to 400 Ω, the SFFOR value is still the same at 0.0293 flash/100km/year. While the BFOR in Appendix Table B continues to increase with the increasing value of the tower foot resistance. The graph of the influence of tower foot resistance can be seen in figure 15.

Increased tower foot resistance, causing the BFOR value also increases. This is because as tower foot resistance increases, the voltage at the foot of

the tower will also increase. High tower foot resistance causes the insulator's critical current fall down, thus making it easier for isolators to be FO when lightning striking directly on a line that is hit the shield wire or tower. This is related to the chance of lightning

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with a certain peak current that can exceeds the isolator critical current.

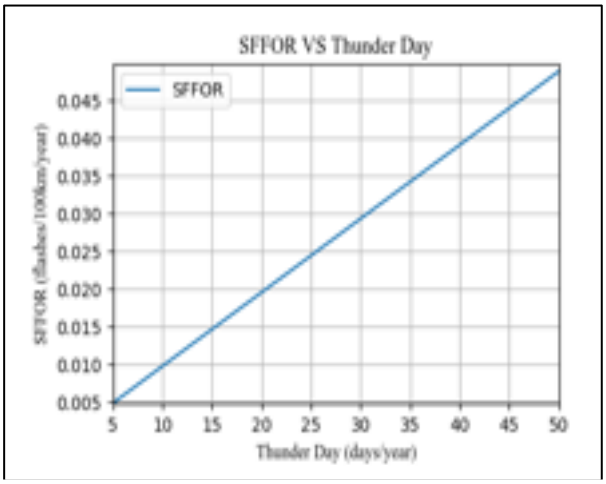

Figure 13. Effect of thunder day variations on SFFOR, with feet tower resistance 20 Ω

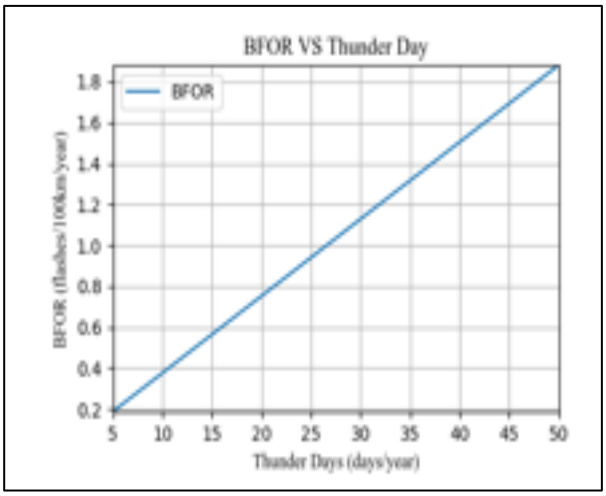

Figure 14. Effect of thunder day variations on BFOR, with feet tower resistance 20 Ω

Figure 16 is showing the effect of tower foot resistance against the critical current of the isolator. Figure 16 was generated by the application. From Figure 16 only 3 curves can be seen because some of the insulators have the same critical current, isolator phase A1 with C2, isolator phase B1 with B2, isolator phase C1 with A2.

The phases C1 and A2 are taken as examples because they have lower insulator critical currents than the other phases. The effect of tower foot resistance on the insulator's critical current can be seen in Appendix Table C.

To cause FO in isolators phase C1 and A2 with foot tower resistance 20 Ω, a lightning peak current of 139.64 kA is required, while to cause FO in isolators with foot tower resistors 80 Ω, lightning with a peak current of 56.37 kA is required.

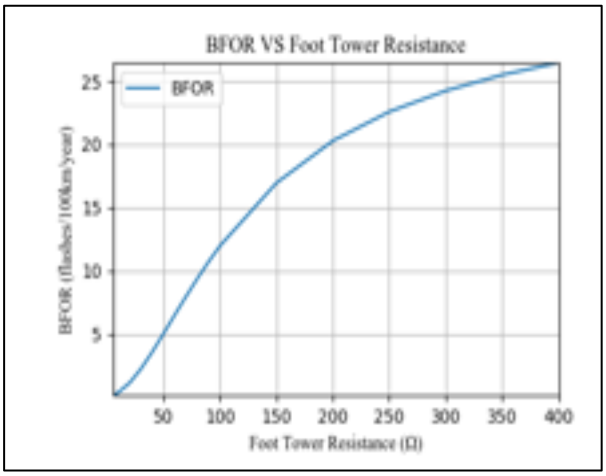

Figure15. The effect of tower foot resistance on BFOR, with thunder days 30 day/year

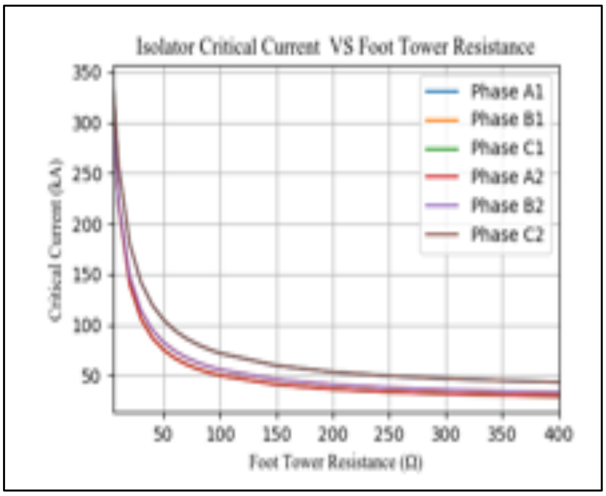

Figure 16. The effect of tower foot resistance against the critical current of the insulator, with thunder days 30 days / year

Using Equation 5, the probability that the lightning peak current can exceed the insulator critical current is, 0.01958 or 1.958% for 139.64 kA and 0.17475 or 17.475% for 56.37 kA. Because the probability of lightning with a current of 56.37 kA appears more frequently, it causes the tower to be struck and FO to occur in phase C1 and A2 isolators also greater. Therefore BFOR with a tower foot resistance 80 Ω higher.

The Effect of Number of Isolator Disks on SFFOR and BFOR

If Checkbutton variations in the number of isolator plates are checked, the application will perform SFFOR and BFOR computation with varying numbers of isolators. Variation of the number of isolators is done by adding 1 disk isolator to the number of insulators entered by the user 5 times. Appendix Table D is the application output. In Appendix Table D, 15 disks was the number entered by the user, while 16 and so on are variations made by the application. L is the total length of the insulator. the overall length of the isolator is obtained by multiplying the number of isolator plates by the length per isolator disk.

Figure 17 and Figure 18 show the effect of insulator length on the values of SFFOR and BFOR.

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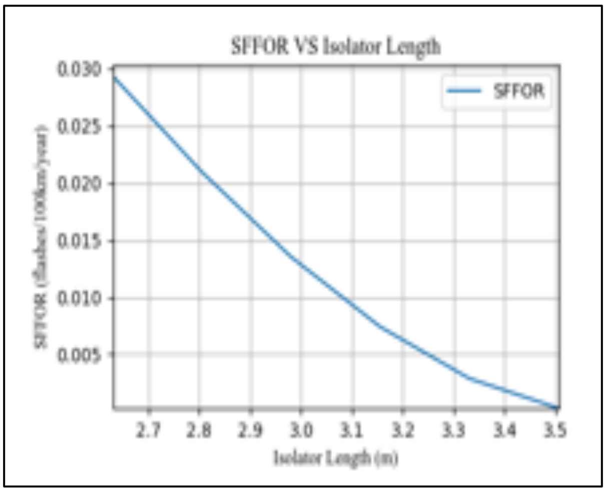

Figure 17. Effect of length of isolator against SFFOR

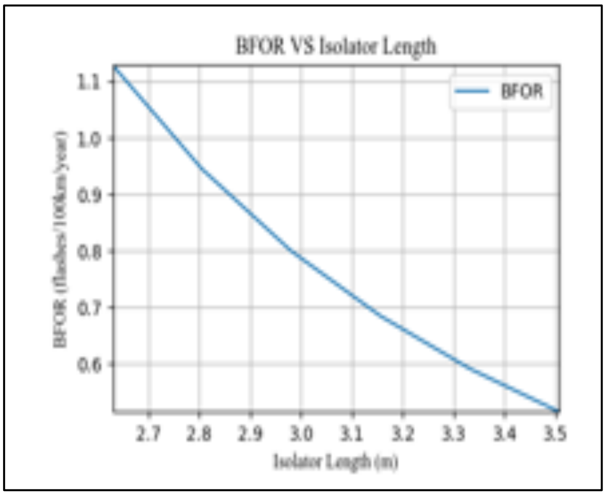

Figure 18. Effect of length of the insulator on the BFOR value

In Appendix Table D, the isolator with a length of 2.63 m, has the lowest critical current which is 139.65 kA on the isolator phase C1 and A2, compared to the insulator along 3.51 m, has the lowest critical isolator current which is 184.31 kA in the isolator phase C1 and A2. This means that the longer the isolator, the higher the critical current of the insulator so that FO is not easy to occur. This also relates to the probability of a lightning peak current that appears, the higher the lightning peak current the less frequently it will appear. This certainly increases the performance of lightning protection on the transmission line, this is evidenced by the longer the isolator, the lower SFFOR and BFOR. The effect of isolator length on SFFOR and BFOR values can be seen in Appendix.

IV. Conlusions

Python is a programming language that is easy to understand because its syntax is close to human language. Detecting errors in Application development is made easy by using Python, because Python executes programs directly from source code without having to compile manually. So that in testing the application code lines, it can be done more easily to find errors and quickly correct them. SFFOR and BFOR analysis using the application has been validated with a percentage of errors for SFFOR and BFOR are 0% and 3.14% respectively. By using the application of lightning performance analysis can be done. Applications can also be used to analyze variables that affect the lightning performance analysis. Variables that can be analyzed are the effect of thunder day, tower foot resistance and number of isolator disk.

Acknowledgment

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Table A

Effect of thunder days against SFFOR and BFOR, with R tower feet 20 Ω

Thunder Day (day/year)	Lightning Performance (flashes/100km/year)		
	SFFOR	BFOR	Total
5	0.0049	0.1879	0.1928
10	0.0098	0.3759	0.3856
20	0.0195	0.7517	0.7713
30	0.0293	1.1276	1.1569
40	0.0391	1.5035	1.5426
50	0.0488	1.8793	1.9282

Table B

Effect of tower foot resistance against SFFOR and BFOR, with thunder days 30 days/year

R (Ω)	Lightning Performance (flashes/100km/year)		
	SFFOR	BFOR	Total
5	0.0293	0.1436	0.1729
10	0.0293	0.3658	0.3951
20	0.0293	1.1276	1.1569
30	0.0293	2.235	2.2643
40	0.0293	3.5673	3.5966
50	0.0293	5.0212	5.0505
60	0.0293	6.5104	6.5397
70	0.0293	7.9711	8.0004
80	0.0293	9.3826	9.4119
90	0.0293	10.7172	10.7465
100	0.0293	11.9658	11.9951
150	0.0293	16.944	16.9733
200	0.0293	20.281	20.3103
250	0.0293	22.5847	22.614
300	0.0293	24.2427	24.272
350	0.0293	25.4998	25.5291
400	0.0293	26.4568	26.4861

Table C

The effect of tower foot resistance against insulator's critical current, thunder day is 30 days / year

R (Ω)	Critical Current of Isolator (kA)					
	A1	B1	C1	A2	B2	C2
5	340.94	308.88	321.68	321.68	308.88	340.94
10	258.52	222.56	219.72	219.72	222.56	258.52
20	179.89	147.85	139.68	139.68	147.85	179.89

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R (Ω)	Critical Current of Isolator (kA)					
	A1	B1	C1	A2	B2	C2
30	141.92	114.15	105.78	105.78	114.15	141.92
40	119.55	94.96	87.05	87.05	94.96	119.55
50	104.81	82.57	75.18	75.18	82.57	104.81
60	94.35	73.91	66.97	66.97	73.91	94.35
70	86.56	67.52	60.96	60.96	67.52	86.56
80	80.52	62.6	56.37	56.37	62.6	80.52
90	75.71	58.71	52.75	52.75	58.71	75.71
100	71.78	55.54	49.82	49.82	55.54	71.78
150	59.57	45.79	40.86	40.86	45.79	59.57
200	53.21	40.76	36.27	36.27	40.76	53.21
250	49.31	37.7	33.49	33.49	37.7	49.31
300	46.67	35.63	31.62	31.62	35.63	46.67
350	44.77	34.14	30.27	30.27	34.14	44.77
400	43.33	33.02	29.26	29.26	33.02	43.33

Table D

Effect of insulator length against insulator critical currents, tower foot resistance is 20 Ω, thunder day is 30 days/year

Isolator		Critical Current of Isolator (kA)					
N	L (m)	A1	B1	C1	A2	B2	C2
15	2.63	179.86	147.83	139.65	139.65	147.83	179.86
16	2.805	191.34	157.34	148.66	148.66	157.34	191.34
17	2.98	202.77	166.81	157.62	157.62	166.81	202.77
18	3.155	214.13	176.24	166.55	166.55	176.24	214.13
19	3.331	225.43	185.63	175.45	175.45	185.63	225.43
20	3.506	236.68	194.98	184.31	184.31	194.98	236.68

Table E

Effect of length of insulator against SFFOR and BFOR, tower foot resistance is 20 Ω, thunder day is 30 days / year

Isolator		Lightning Performance (flashes/100km/year)		
N	L (m)	SFFOR	BFOR	Total
15	2.6295	0.0293	1.1282	1.1576
16	2.8048	0.0209	0.9446	0.9655
17	2.9801	0.0135	0.7995	0.8130
18	3.1554	0.0074	0.6844	0.6918
19	3.3307	0.0029	0.5913	0.5942
20	3.5060	0.0003	0.5150	0.5153

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