โปรแกรมประเมินอัตราการเกิดไฟฟ้าดับของสายส่งเหนือศีรษะเนื่องจากฟ้าผ่า

นายสมหวัง ทิบพะวงไช

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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A PROGRAM FOR ESTIMATING LIGHTNING OUTAGE RATES OF OVERHEAD TRANSMISSION LINES

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A Thesis Submitted in Partial Fulfillment of the Requirements
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สมหวัง ทิบพะวงไช: โปรแกรมประเมินอัตราการเกิดไฟฟ้าดับของสายส่งเหนือศรีษะเนื่องจากฟ้าผ่า (A PROGRAM FOR ESTIMATING LIGHTNING OUTAGE RATES OF OVERHEAD TRANSMISSION LINES) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ดร.ชาญณรงค์ บาลมงคล, 86 หน้า.

วิทยานิพนธ์นี้ นำเสนอการพัฒนาโปรแกรมสำหรับการประเมินอัตราการเกิดไฟฟ้าดับของสายส่งเหนือศรีษะเนื่องจากฟ้าผ่า จำนวน 2 โปรแกรม คือโปรแกรม STPM และ I-EMTP ซึ่งทั้งสองโปรแกรมจะมีความแตกต่างกันในวิธีการหาค่ากระแสฟ้าผ่าวิกฤติที่สามารถก่อให้เกิดไฟฟ้าดับ โดยที่โปรแกรม STPM ใช้วิธีการสองจุดอย่างง่าย (simplified two-point method) ส่วนโปรแกรม I-EMTP อาศัยโปรแกรม EMTP ในการจำลองระบบไฟฟ้าเพื่อหาค่ากระแสฟ้าผ่าวิกฤต แต่ทั้งสองโปรแกรมจะใช้กระบวนการที่เหมือนกัน ในการประเมินหาอัตราการเกิดไฟฟ้าดับของสายส่งจากค่ากระแสฟ้าผ่าวิกตที่ได้มา จากการทดสอบเปรียบเทียบโปรแกรมทั้งสองพบว่าให้ผลการประเมินอัตราการเกิดไฟฟ้าดับของสายส่งที่ใกล้เคียงกัน แต่โปรแกรม STPM สามารถใช้งานได้ง่าย และประหยัดเวลา ในขณะที่ผู้ใช้โปรแกรม I-EMTP จำเป็นจะต้องสร้างโมเดลเพื่อจำลองระบบไฟฟ้าซึ่งสิ้นเปลืองเวลา แต่สามารถพัฒนาปรับปรุงแบบจำลองของระบบไฟฟ้า ให้มีความถูกต้องใกล้เคียงกับความเป็นจริงได้ง่ายกว่า

นอกจากนี้ มีการนำโปรแกรม STPM ไปใช้ในการศึกษาปัจจัยที่มีผลต่ออัตราการเกิดไฟฟ้าดับเนื่องจากฟ้าผ่า ได้แก่ รูปแบบของเสาไฟฟ้า ความต้านทานรากสายดิน มุมป้องกัน ระดับการฉนวน อัตราการเกิดฟ้าผ่าลงดิน และการกระจายของขนาดกระแสฟ้าผ่า

ภาควิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่ออ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

ปีการศึกษา 2551

4970810421 : MAJOR ELECTRICAL ENGINEERING

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SOMVANG TIPPHAVONGXAY: A PROGRAM FOR ESTIMATING LIGHTNING OUTAGE RATES OF OVERHEAD TRANSMISSION LINES. THESIS PRINCIPAL ADVISOR: CHANNARONG BANMONGKOL, Dr. Eng, 86 pp.

This thesis presents the development of two software programs, STPM and I-EMTP, for estimating the lightning outage rates of overhead transmission lines. Both programs apply the different methods for determining the critical lightning current required to cause a flashover. The STPM program uses a simplified two-point method, while the I-EMTP program gets the critical lightning current from the simulation with Electromagnetic Transients Program (EMTP). However, both software programs have the same procedure for calculating the outage rate with the obtained critical lightning current. The STPM program is easier to use and saves time, while the user of I-EMTP program must model the power system to simulate the critical lightning current which wastes time. However, it is easier to develop models in EMTP program for more accurate result.

The STPM program is implemented to study the parameters that have effects on the lightning outage rates of overhead transmission lines, i.e. tower configuration, tower footing resistance, shielding angle, insulation level, ground flash density and probability distribution of lightning current.

Department: Electrical Engineering Student's signature..........................

Field of study: Electrical Engineering Principal advisor's signature..........................

Academic year: 2008.

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CHAPTER I

INTRODUCTION

1.1 General

Technical and economic factors play important roles in route selection of overhead transmission lines installation. Transmission lines often pass a mountain or risk area that can be affected by lightning. Therefore, lighting is the primary cause of unscheduled interruption of most overhead power transmission lines. There was a report that lightning occupied 26% and 65% of the outage cause for 230 kV and 345 kV circuits, respectively [1]. Lightning tripout can occur in two aspects, i.e. shielding failure flashover and backflashover as following description:

1) *Shielding failure flashover* : It occurs when a flash misses the overhead ground wire or tower and terminates directly on the phase conductor. Extremely high voltages will quickly develop at the contact point. They will travel in both directions along the phase conductor and eventually reach one or more insulators, resulting in a flashover. Shielding failure flashover may occur from phase conductor to crossarm or leg of tower.

2) *Backflashover* : In case of lightning strikes on the overhead ground wire or tower top, it forces current to flow down the tower and along the overhead ground wire. Thus, voltages are built up across the line insulation. If these voltages equal or exceed the insulator critical flashover (CFO), flashover occurs from crossarm to phase conductor.

1.2 Problem Statement

In tropical countries with intensive lightning activity, the incidence of lightning stroke on overhead transmission lines is a very important problem. Even if overhead transmission lines are normally shielded by overhead ground wires (OHGW), the lightning is still one of the largest causes of service interruption and equipment damage occurring on power systems due to backflashover and shielding failure. Many researchers have studied on the reduction in lightning outage rate and improvement of overhead transmission line design. The lightning tripout rate is an index to indicate lightning performance of overhead transmission lines. It depends on several complicated factors such as tower configuration, tower footing resistance, thunderstorm day level, lightning parameters, etc. Therefore, it is difficult to determine the lightning tripout rate by hand calculation. A software program can help calculating such complicated tasks. Many commercial programs are available, but some database in the programs do not match with those of our power systems. Moreover, program editing and addition of new models are difficult or impossible. This motivates us to develop a software program by ourselves. It can be used to design a new transmission lines or improve the lightning performance of existing transmission lines.

1.3 Objective

This research objective aims to develop a software program to predict the lightning tripout rate of overhead transmission lines. It contributes to the improvement of transmission system reliability and the reduction in costs due to lightning-caused damage and service interruptions.

1.4 Survey of Commercial Software Programs

Many researchers have been published the methods and guidelines for improving lightning performance of overhead lines. Several software programs for estimating lightning tripout rates of power lines are also available. At present, the widely used software programs for calculating the backflashover rate and shielding failure rate are Tflash, Flash 1.7 and CIGRE programs. Among them, Tflash is the most advanced program. It uses traveling wave analysis as the means of calculating voltages on phase insulation. For Flash 1.7 and CIGRE methods, the voltages are calculated at one or two predetermined times after the initiation of the flash and compared against various insulation breakdown models.

The differences in algorithms of those programs are summarized as follows:

Table 1.1 Summary the difference in algorithm of TFlash, Flash 1.7 and CIGRE programs

Algorithm	**TFlash**	**Flash 1.7**	**CIGRE**
Which wire the stroke hits	EPRI improved Electro-Geometric Model including stroke attraction to the line and user defined terrain	IEEE [4] natural shielding limited to flat open terrain	Brown-Whitehead natural shielding limited to flat open terrain.
Corona Coupling	Considered	Considered	Ignored
Soil Ionization	EPRI improved dynamic ionization model or Weck	None	Weck
Insulation Breakdown	Disruptive Effect or Volt-Time curve	Volt-Time	Leader Progression
Wave Front	2 usec front double exponential or user selected	2 usec front ramp	Log-Normal Distribution on front steepness and minimum equivalent linear front
Stroke Probability distribution	IEEE, CIGRE, NLDN historical data, or user defined table	IEEE	CIGRE
Power frequency Voltage	Constant voltage or 6 steps 3 phase rotation	Multiple phase angles for backflash, ignored for shielding failure	Constant voltage for backflash only, ignored for shielding failure
Insulator voltage calculation	Traveling wave analysis with 20 nsec steps	Direct calculation at 2 usec and 6 usec	Direct calculation of peak voltage

1.5 Scope of Thesis

This research will develop a software program for estimating lightning outage rates of overhead transmission lines. The critical stroke currents, used for estimating lightning outage rates, will be determined based on:

- Simplified two-point method proposed by [2]
- Electromagnetic Transient Program (EMTP)

The software program will be tested by doing case studies. Many parameters which influence the service interruption of overhead transmission lines due to lightning will be also studied.

1.6 Research Benefit

The benefits of this research are:

1) A software program for predicting lightning outage rates of overhead lines.
2) Better understanding in the methods for determining lightning outage rate.
3) Better understanding in the parameters which have effects on the flashover of overhead transmission lines due to lightning.

1.7 Research Procedure

1) Do literature reviews of background knowledge relevant to the research topic.
2) Study the models of equipment and lightning parameters.
3) Study the method to compute the shielding failure flashover and backflashover rates of overhead transmission lines as well as the ways to improve lightning performance.
4) Design and write the software program for estimating lightning outage rates for overhead transmission lines.
5) Test the software program.
6) Write the instruction of the software program.
7) Do case studies using the software program.

CHAPTER II

THEORIES

This chapter describes the lightning parameters, the number of lightning strikes on power line, circuit elements involved in computation of flashover performance, shielding failure computation, backflashover computation. The Electromagnetic Transient Program (EMTP) is also described.

2.1 Lightning Parameters

In the estimation of lightning outage rate of overhead transmission lines, the lightning parameters important in consideration are:

1) Number of stroke
2) Stroke waveshape
3) Front time of crest stroke current
4) Magnitude of stroke current

2.1.1 Number of Stroke

Each lightning flash may contain several strokes. These strokes are the short duration peaks of high current that travel in rapid succession down the flash channel. The entire flash may persist for a second or more, but the high current peaks that can cause flashover will only exist for tens or hundreds of microseconds of first stroke. Therefore, this research will only study the severity of first stroke.

2.1.2 Stroke Waveshape

There are two types of waveshape, i.e. negative and positive waveshapes. Almost strokes are negative, but they are less severity than positive ones [2]. This research is interested in the negative strokes as shown in Fig. 2.1.

2.1.3 Front Time of Crest Stroke Current

Assumed t_f is a front time of crest current as shown in Fig. 2.1. This value is important to specify the slop of lightning current and use in the consideration of surge voltage. The relationships between lightning crest current (I), front time (t_f) and slop of lightning current are shown in Fig. 2.2.

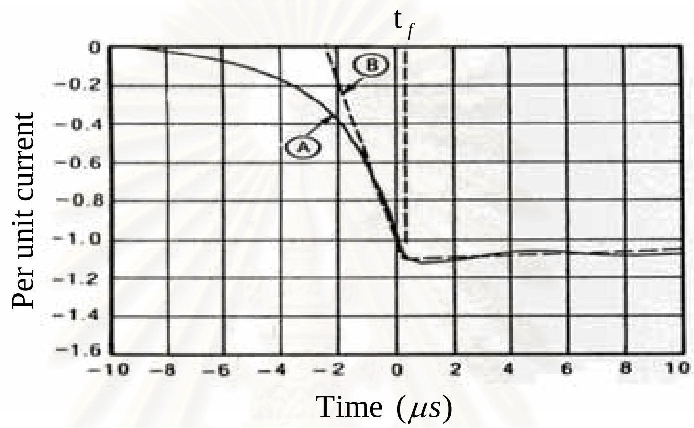


Figure 2.1 Anderson and Eriksson computer synthesis of median current wavefront for negative first stroke (A) and a ramp current approximation to it (B)

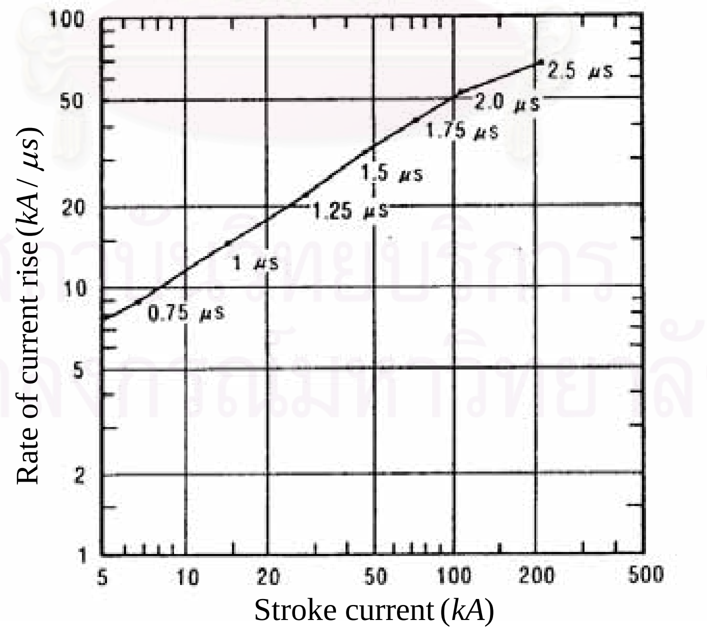


Figure 2.2 Relationships between stroke current, frontal rate of current rise and time to crest of a ramp function, stroke current wave to meet probability requirements

2.1.4 Magnitude of Stroke Current

Many probability distribution of stroke current magnitude have been proposed. For example, the cumulative probability distribution of stroke current magnitude in negative lightning flashes proposed by R. Anderson and A. Eriksson is shown in Fig. 2.3 [2]. The approximate equation is given by equation (2.1).

$$P_i = \frac{1}{1+(\frac{I}{31})^{2.6}} \tag{2.1}$$

Where P_i is the probability of exceeding stroke current I

I is the stroke current (kA)

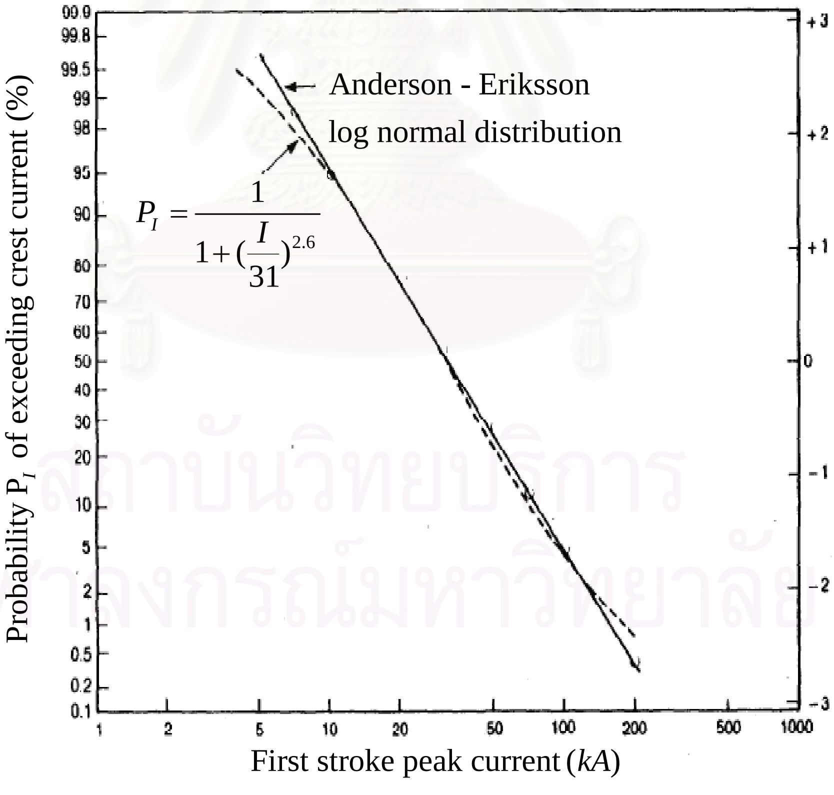


Figure 2.3 Cumulative probability distribution of stroke current magnitude in negative lightning flashes

2.2 Incidence of Lightning Strikes on Power Line

In general, excluding local topographic effects, two main factors influence the incidence of direct lightning strikes to practical transmission lines:

1) The regional incidence of lightning in the area. This is normally defined by the annual average ground flash density, N_g $(flash/km^2/year)$ in the vicinity of the line. If the data of N_g are not available, the regional keraunic level T_d $(days/year)$ can be used to determine N_g [5].

$$N_g = 0.04T_d^{1.25} \tag{2.2}$$

Where N_g is annual average ground flash density $(flash/km^2/year)$

T_d is regional keraunic level $(days/year)$

2) A transmission line, passing above the earth, throws an electrical shadow on the land beneath. Lightning flashes that would generally terminate on the land inside the shadow will strike the line instead, whereas flashes outside this shadow will miss the line entirely. Fig. 2.4 shows a simple approximation for the width W of this shadow for a line with two OHGWs. For a line with only one OHGW, b becomes zero.

Eriksson has suggested an equation to calculate the width W.

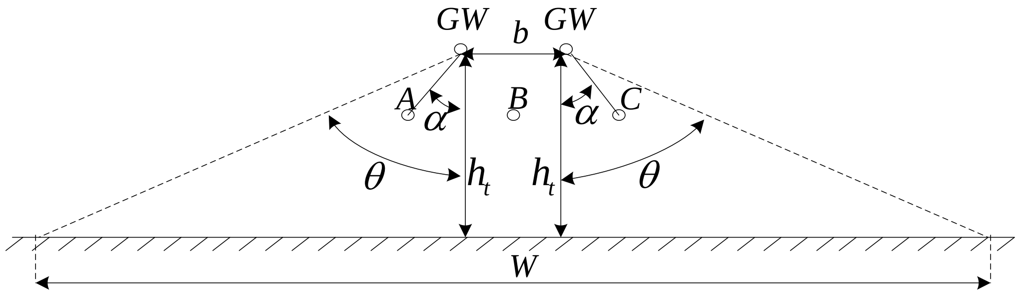
$$W = b + 28h_t^{0.6} \tag{2.3}$$

Where W is the shadow width on earth's surface (m)

b is the horizontal spacing between the OHGWs (m)

h_t is the tower height (m)

From equations (2.2) and (2.3), the number of flash on the lines (N_L) at 100 km length and width W is therefore given by the equations (2.4)-(2.5) [5].



θ	shadow angle
α	shield angle between OHGW and phase conductor
W	shadow width on earth's surface
GW	OHGW location
A, B, C	phase conductors

Figure 2.4 Electrical shadow created on the earth's surface by a transmission line

$$N_L = N_g \times \frac{W}{10} \tag{2.4}$$

$$N_L = \frac{N_g}{10}(b + 28h_t^{0.6}) \tag{2.5}$$

Where N_L is the number of lightning strikes on line $(flash/100km/year)$

2.3 Circuit Elements Involved in Computation of Flashover Performance

Fig. 2.5 shows the basic elements used for calculating the voltages across the insulator strings. Some of these elements are influential in establishing the backflashover, and others influence the shielding failure performance.

2.3.1 Reducing Bundle Conductor to Equivalent Single Conductor

To make the problem more tractable, each bundle conductor should be reduced to an equivalent single conductor. This is done by assuming that the single conductor will carry the same charge and voltage to ground as the bundle and will be located at the center of the bundle. The general formula is derived for symmetrical bundles as follows [2]:

$$R_{eq} = \sqrt[N]{r_{11} r_{12} r_{13} \ldots r_{1n}} \tag{2.6}$$

Where R_{eq} is the equivalent radius (Cm)

r_{11} is the conductor radius (Cm)

$r_{12}, r_{13}, \ldots r_{1n}$ is the spacing from conductor 1 to conductor n (Cm)

N is the number of subconductors

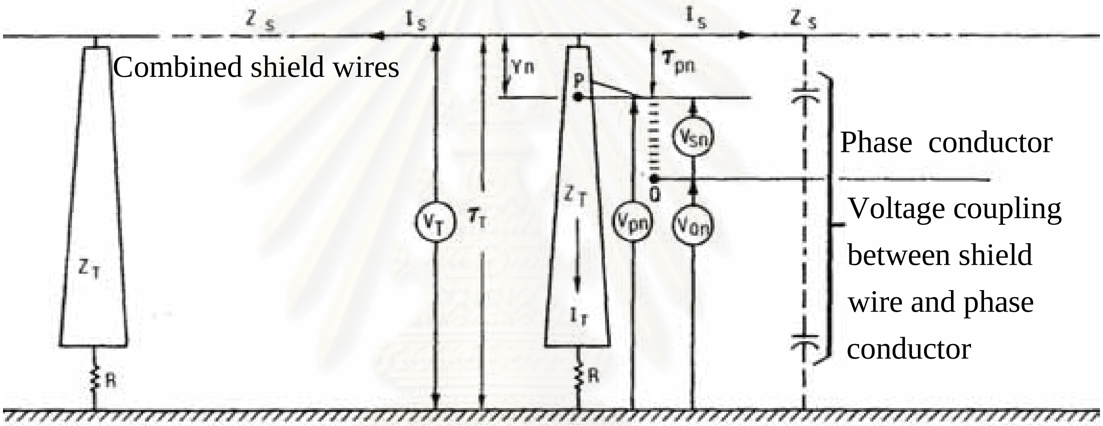


Figure 2.5 Basic elements in computation of insulator voltage

2.3.2 Finding Effective Radii of Shield Wires and Phase Conductors with Corona Present

After each bundle conductor is reduced to an equivalent single conductor, a further adjustment should be made to account for the effects of the corona envelope that forms when high voltage appears. In the case of the OHGWs, the corona envelope may be over a meter in diameter, and its effect on the voltages induced on the phase conductors may be very significant. Similarly, for a phase conductors, the corona envelope that forms when a stroke strikes the phase conductor directly may be sufficiently large to help limiting the overvoltage and improve the shielding failure performance. The single conductor radius of this envelope can be derived from Gauss's law. The resulting equation is [2]:

$$R\ln\frac{2h}{R}=\frac{V_C}{E_0} \tag{2.7}$$

Where R is the radius of the corona envelope (m)

h is the height of the conductor above ground (m)

V_C is the critical voltage applied to the conductor (kV)

E_0 is the limiting corona gradient below which the envelope can no longer grow (normally use $E_0 = 1500kV/m$)

The corona envelope modifies only the capacitance of the conductor. It has little effect on the inductance. The effective radius of a single conductor should be taken as the geometric mean of its effects with and without the corona envelope. Therefore, the self-surge impedance of a single conductor in heavy corona is given by

$$Z_{nn}=60\sqrt{\ln\frac{2h}{r}\ln\frac{2h}{R}} \tag{2.8}$$

Where Z_{nn} is the self-surge impedance of conductor (Ω)

h is the height of conductor above ground (m)

r is the radius of the metallic conductor (m)

R is the radius of the corona sheath around the conductor (m)

2.3.3 Reduction of Shield Wire Surge Impedances to Equivalent Single Shield Wire Impedance

From Fig. 2.6, the mutual impedance between the two OHGWs is derived as [2]

$$Z_{mn}=60\ln\left(\frac{a_{mn}}{b_{mn}}\right) \tag{2.9}$$

Where Z_{mn} is the mutual impedance between the two shield wires (Ω)

a_{mn} is the distance from conductor m to the image of n in the earth (m)

b_{mn} is the direct distance between conductor m and n (m)

An equivalent surge impedance or combined surge impedance of two or more conductors is desired for calculation of the tower top voltage. The combined surge impedance of the two OHGWs is given by equation (2.10).

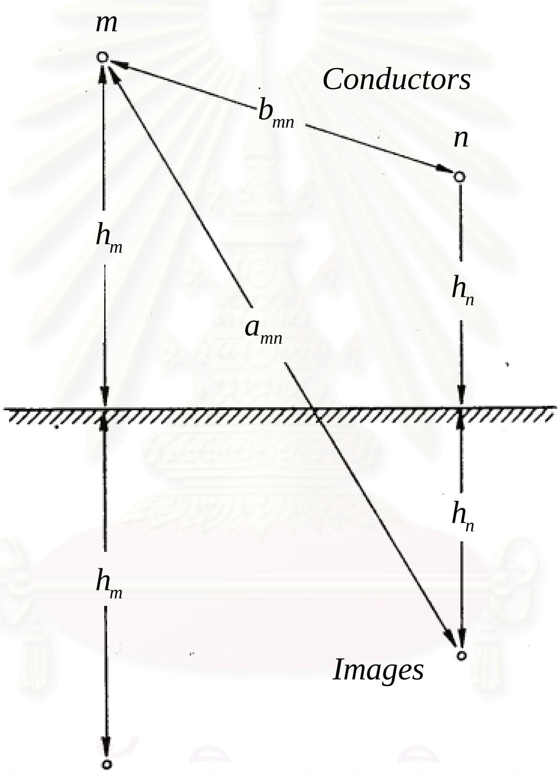


Figure 2.6 Distance evolved in computing mutual impedance between two conductors

$$Z_S = \frac{Z_{11} + Z_{12}}{2} \tag{2.10}$$

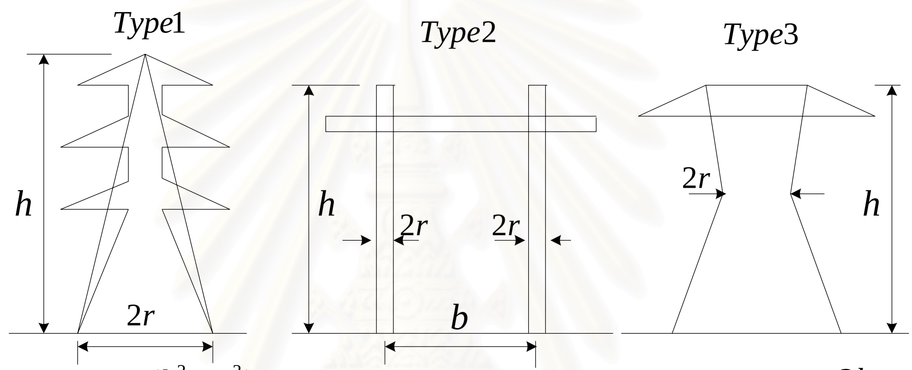
Where Z_S is the self-surge impedance of one of the OHGWs (Ω)

Z_{12} is the mutual surge impedance between conductor 1 and conductor 2 (Ω)

Z_{11} is the self-surge impedance of conductor 1 (Ω)

2.3.4 Tower Surge Impedances

A transmission tower can be represented by a vertical transmission line of constant surge impedance protruding upward from the earth's surface. This transmission line has the same length as the tower height. The velocity of propagation of current waves up and down is assumed to be about 70-90% of the velocity of light [2]. The presence of braces and tower crossarms tends to retard wave propagation. Fig. 2.7 provides some relationships which can be used to approximate the tower surge impedance Z_T for various tower shapes.



$$Z_t = 30\ln[\frac{2(h^2+r^2)}{r^2}]$$

$$Z_t = 0.5(Z_s + Z_m)$$
$$Z_s = 60\ln(h/r) + 90(r/h) - 60$$
$$Z_m = 60\ln(h/b) + 90(b/h) - 60$$

$$Z_t = 60[\ln(\sqrt{2}\frac{2h}{r}) - 1]$$

Figure 2.7 Approximations for surge impedance for various tower shapes

2.3.5 Coupling Factors for Phase Conductors

The portion of the stroke current flowing outward over the OHGWs induces a voltage called the coupled voltage in each phase conductor. The ratio of the total coupled voltage on phase conductor n to the tower top voltage is known as the coefficient of coupling (K_n). For the case of two OHGWs at equal height above ground is:

$$K_n = \frac{Z_{1n} + Z_{2n}}{Z_{11} + Z_{12}} \tag{2.11}$$

If only a single OHGW exists

$$K_n = \frac{Z_{1n}}{Z_{11}} \tag{2.12}$$

Where K_n is the coefficient of coupling

Z_{1n} is the mutual impedance between OHGW 1 and conductor n

Z_{2n} is the mutual impedance between OHGW 2 and conductor n

Z_{11} is the self-surge impedance of each OHGW

Z_{12} is the mutual impedance between OHGW 1 and 2

2.3.6 Tower Footing Resistance

The tower footing resistance is an extremely important parameter in the determination of lightning flashover. Unfortunately, it is a fluctuating statistical variable. The magnitude of resistance is governed not only by geography, but also by nonlinear conduction physics in the earth. High magnitudes of lightning current, flowing through the soil, decrease the soil resistance significantly below the measured low current values, because of soil iornization. Fig. 2.8 is a correction curve of footing resistance due to stroke currents [2].

In IEEE guideline, the footing resistance is assumed to be a constant while in CIGRE guideline, the effect of soil ionization is taken in to account. The decrease in the tower footing resistance when the lightning current amplitude exceeds a critical value I_g is taken by

$$R_i = \frac{R_0}{\sqrt{1 + (I / I_g)}} \tag{2.13}$$

Where R_0 is the low current footing resistance (non-ionized soil) and the critical value of the lightning current is given by the soil ionization threshold field E_g $(E_g = 400kV/m)$ using equation (2.14).

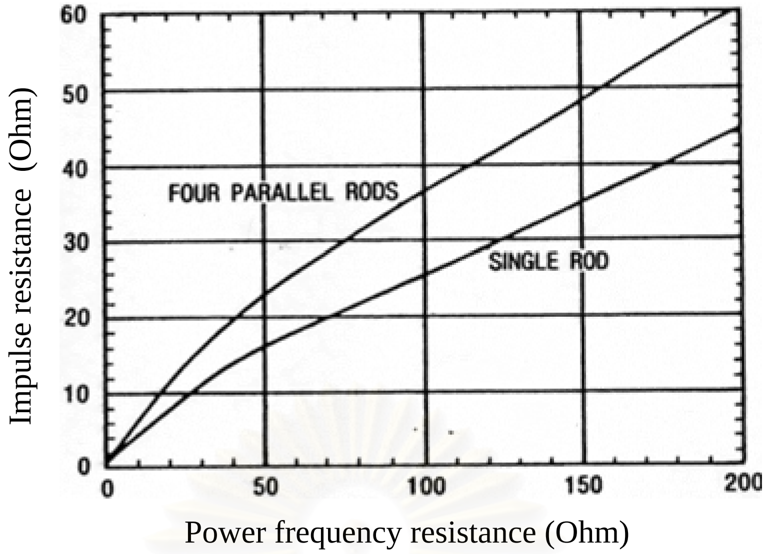


Figure 2.8 Suggested reduction of resistance due to lightning currents

$$I_g = \frac{E_g \rho}{2\pi R_0^2} \tag{2.14}$$

The low current, low frequency resistance R_0 of a single ground rod of length L and radius r_0 driven in soil having a resistivity of ρ is:

$$R_0 = \frac{\rho}{2\pi L}[\ln(\frac{4L}{r_0}) - 1] \tag{2.15}$$

If n ground rods are parallel with the same distance s, the R_0 can be expressed by

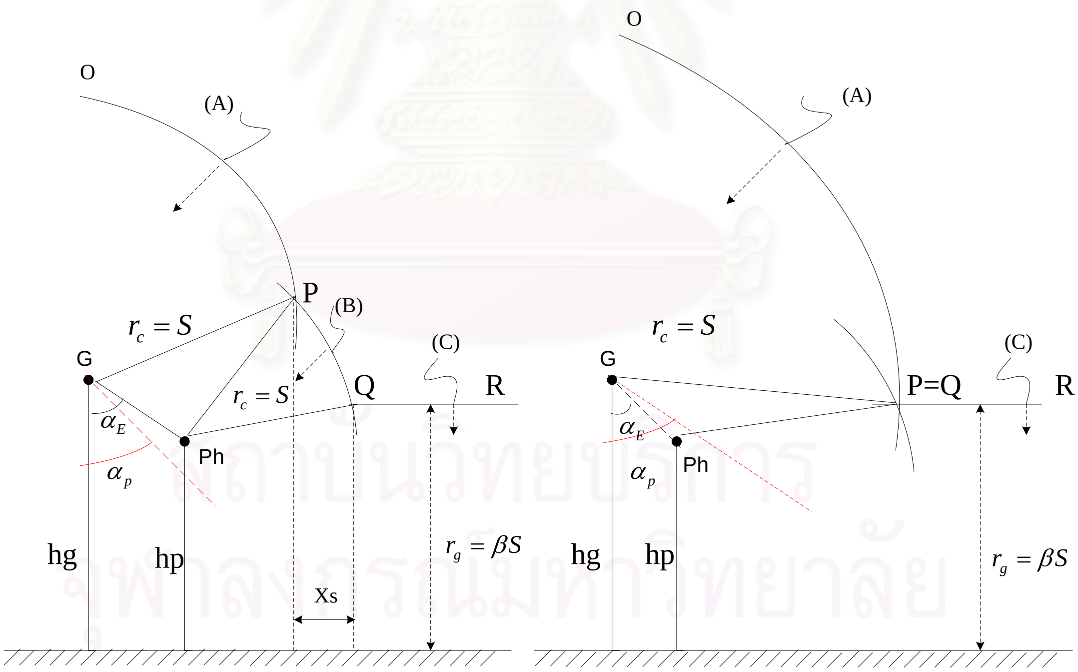
$$R_{0n} = \frac{1}{n}(R_0 + \frac{\rho}{\pi s}(\frac{1}{2} + \frac{1}{3} + ... + \frac{1}{n})) \tag{2.16}$$

2.4 Shielding Failure of Overhead Transmission Line

In consideration the shielding failure of overhead transmission lines, many researchers [2-10] were used the simplified model of the last step or striking distance of the lightning stroke. The electrogeometric model is the primary method to use in the study of the last step or striking distance. Therefore, this model will be presented as following:

2.4.1 Electrogeometric Model

Fig. 2.9 shows a simplified model of the postulated shielding failure mechanism for one OHGW and one phase conductor above a horizontal earth. In Fig. 2.9(A), three flashes of equal current magnitude are shown nearing the line. As a flash approaches within a certain distance S of the earth and the line, it is influenced by what is below it and jumps the distance S to make contact. This distance S is called the striking distance. It is a key concept in the electrogeometric theory. The striking distance is a function of the charge (and consequently the current) in the channel of the approaching flash. There are many researchers proposed the equations to find this striking distance [3].



(A) Incomplete shielding (B) Effective shielding

Figure 2.9 An electrogeometric model for shielding failures

Based on IEEE std 1243, the following striking distance equation are recommended.

$$r_c = 10I^{0.65} \tag{2.17}$$

$$\begin{aligned} r_g &= [3.6 + 1.7\ln(43 - y_c)]I^{0.65} \quad , \; y_c < 40m \\ r_g &= 5.5I^{0.65} \qquad\qquad\qquad\qquad , \; y_c \geq 40m \end{aligned} \tag{2.18}$$

$$y_c = y - \frac{2}{3}s_c \tag{2.19}$$

Where y_c is the average conductor height (m)

s_c is the sag of conductor (m)

2.4.2 Uncovered Distance

For vertical flashes, the width X_s then establishes the uncovered area of the earth in which flashes that generally would reach the earth contact the phase conductor instead. If S is known and if $\beta S > Y_\phi$ (β is the coefficient factor, $\beta = 1$ for HV, $\beta = 0.8$ for EHV and $\beta = 0.64$ for UHV [2]) a trigonometric solution for the uncovered width X_s is:

$$X_s = S[\cos\theta + \sin(\alpha_s - \omega)] \tag{2.20}$$

Where

$$\theta = \arcsin(\frac{\beta S - Y_\phi}{S}) \tag{2.21}$$

$$\omega = \arccos(\frac{F}{2S}) \tag{2.22}$$

$$\alpha_s = \arctan(\frac{X_\phi - X_G}{Y_\phi - Y_G}) \tag{2.23}$$

If $\beta S < Y_\phi$, $\cos\theta$ is set equal to unity. Thus

$$X_s = S[1 + \sin(\alpha_s - \omega)] \tag{2.24}$$

2.4.3 Maximum Shielding Failure Current

As the distance S in Fig 2.9(A) increases, the arc PQ decreases. If S is sufficiently large, arc PQ becomes zero, and it becomes equivalent to Fig 2.9(B). This distance, designated $S_{\max}$, is the striking distance corresponding to the maximum value of stroke current $I_{\max}$ that can cause a shielding failure flashover.

The solution for $S_{\max}$ is equivalent to solving for maximum striking distance as follows:

$$S_{\max} = Y_0\left(\frac{-B_s - \sqrt{B_s^2 + A_s C_s}}{A_s}\right) \tag{2.25}$$

Where

$$Y_0 = \frac{Y_G + Y_\phi}{2} \tag{2.26}$$

$$A_s = m^2 - m^2\beta - \beta^2 \tag{2.27}$$

$$B_s = \beta(m^2 + 1) \tag{2.28}$$

$$C_s = m^2 + 1 \tag{2.29}$$

m is slope of line OP in Fig. 2.10.

$$m = \frac{X_\phi - X_G}{Y_G - Y_\phi} \tag{2.30}$$

$S_{\max}$ and $I_{\max}$ are related by

$$I_{\max} = \left(\frac{S_{\max}}{A}\right)^{1/b} \tag{2.31}$$

Where A and b are the constant value $(A = 10 \;\; and \;\; b = 0.65)$

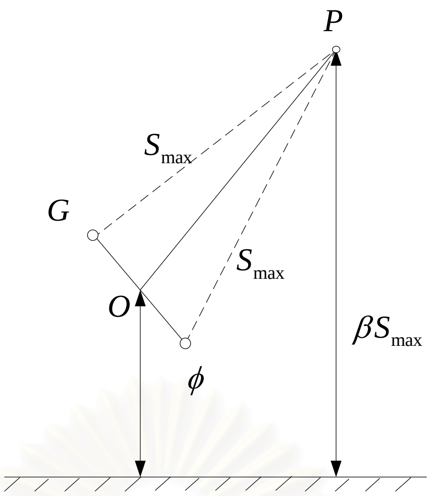


Figure 2.10 The maximum striking distance

2.4.4 Shielding Failure Flashover Rates

If the line is not effectively shielded, shielding failures may occur. To solve for the shielding failure flashover rate, first compute the magnitude of stroke current, $I_{\min}$ to phase ϕ (the most exposed phase) just sufficient to flashover its insulator as

$$I_{\min} = \frac{2V_C}{Z_\phi} \tag{2.32}$$

Where $I_{\min}$ is the minimum shielding failure flashover stroke current (kA)

V_C is the insulator critical flashover voltage (kV)

Z_ϕ is the surge impedance of the phase conductor, including corona effects (Ω)

Next, insert $I_{\min}$ into the equation (2.17) and solve for the minimum striking distance $S_{\min}$ of that phase. After $S_{\min}$ is determined, the unshielded width X_s can be calculated using equation (2.20) or equation (2.24).

For the stroke currents between $I_{\max}$ and $I_{\min}$ can cause a shielding failure flashover according to the electrogeometric theory. These currents must terminate within the unprotected area X_s.

At this point, the minimum and maximum stroke currents that can cause a shielding failure flashover have been determined as has the unshielded width X_s associated with the minimum stroke current. As defined, for the maximum stroke current $I_{\max}$, X_s shrinks to zero. The average unshielded width is $X_s/2$. This width is used for the shielding failure flashover computation. The number of flashes causing shielding failure flashover is then determined by computing the most probable number of flashes per 100km per year falling within X_s and multiplying this number by the difference of the probabilities of the $I_{\min}$ and $I_{\max}$.

$$SFFOR = \frac{N_g}{10}(\frac{X_s}{2})(P_{\min} - P_{\max}) \tag{2.33}$$

Where $SFFOR$ is the shielding failure flashover rate $(flash/100km/year)$

N_g is the ground flash density $(flash/km^2/year)$

X_s is the unprotected width (m)

$P_{\min}$ is the probability that a stroke will exceed $I_{\min}$

$P_{\max}$ is the probability that a stroke will exceed $I_{\max}$

It should be noted that the equation (2.33) is the case of one OHGW and one phase conductor. There may be other phase conductors that are also exposed or there may be one phase conductor that is exposed on both sides. In these cases, each shielding failure flashover rate is summed to find the total shielding failure flashover rate.

2.4.5 Effective Shielding Angle

If the OHGW is moved close to the phase conductor (Fig. 2.9.B) so that the uncovered arc PQ disappears, any incoming stroke cannot reach the phase conductor. For good shielding, if the X coordinate of the phase conductor is taken as zero and the X_G coordinate of the shield wire is taken as nonzero. X_G can be calculated as follows:

$$X_G = \sqrt{S^2 - (\beta S - Y_\phi)^2} - \sqrt{S^2 - (\beta S - Y_G)^2} \qquad (2.33)$$

In this case the effective shielding angle α_p becomes

$$\alpha_p = \arctan\left(\frac{X_G}{Y_\phi - Y_G}\right) \qquad (2.34)$$

2.5 Backflashover of Overhead Transmission Line

Referring to Fig. 2.5 will show that the insulator voltage for any phase is difference between the crossarm voltage V_{pn} and the voltage induced on the phase conductor V_{Qn}. In addition, the tower top voltage V_T must be computed for most severe stroke in a flash, so that V_{Qn} may be determined by using appropriate coefficient coupling. Therefore, the tower top voltage is computed first.

2.5.1 Tower Top Voltage

The tower top voltage V_T is derived in appendix A.1 as follows [2]:

$$V_T(t) = Z_I I(t) - Z_w \sum_{n=1}^{N} [I(t - 2n\tau_T)\varphi^{n-1}] \qquad (2.35)$$

Where $V_T(t)$ is the tower top voltage (kV) at any selected time $t(\mu s)$

$I(t)$ is the stroke current into the equivalent circuit (kA) at the same time

Z_I is the intrinsic circuit impedance (Ω) encountered by the stroke current at the instant it enters the equivalent circuit:

$$Z_I = \frac{Z_s Z_T}{Z_s + 2Z_T} \qquad (2.36)$$

Z_w is the constant wave impedance on which all traveling wave current component operate to provide components of tower top voltage:

$$Z_w = [\frac{2Z_s^2 Z_T}{(Z_s + 2Z_T)^2}][\frac{Z_T - R}{Z_T + R}] \tag{2.37}$$

τ_T is the Travel time (μs) from tower top to base:

$$\tau_T = \frac{Lenght}{velocity} \tag{2.38}$$

$I(t - 2n\tau_T)$ is the stroke current that entered the equivalent circuit at a previous time, $(t - 2n\tau_T)$ where n is a whole number, called the wave number, that defines the component

φ is the damping constant that successively reduces the contribution of reflections:

$$\varphi = (\frac{2Z_T - Z_s}{2Z_T + Z_s})(\frac{Z_T - R}{Z_T + R}) \tag{2.39}$$

N is the largest value that the wave number n can reach

2.5.2 Crossarm Voltage

When insulator voltages must be determined, it will usually be necessary to compute all the crossarm voltages. Hence, a numerical routine requiring the least computation is highly desirable. Because the tower top voltage must be computed to find the coupled voltages on the phase conductors, the simplest procedure for calculating crossarm voltage is to compute the voltage at the base of the tower (across the footing resistance) and then interpolate between these two end voltages for each crossarm. The voltage at the tower base is derived in reference [2] as follows:

$$V_R(t+\tau_T) = \bar{\alpha}_R Z_I \sum_{n=0}^{N} I(t-2n\tau_T)\varphi^n \tag{2.40}$$

Where $V_R(t+\tau_T)$ is the voltage across footing resistance R at time $(t+\tau_T)$ and

$$\bar{\alpha}_R = \frac{2R}{Z_T + R} \tag{2.41}$$

After the base voltage is determined, the interpolated voltage for any crossarm n is

$$V_{pn}(t+\tau_{pn}) = V_R(t+\tau_T) + \frac{h-Y_n}{h}[V_T(t) - V_R(t+\tau_T)] \tag{2.42}$$

Where h is the tower height (m)

Y_n is the distance from the tower top down to the crossarm (m)

2.5.3 Insulator String Voltage

The insulator string voltage is the difference between the crossarm voltage (V_{pn}) and the voltage coupled to the phase conductor from the tower top.

$$V_{sn}(t+\tau_{pn}) = V_{pn}(t+\tau_{pn}) - K_n V_T(t+\tau_{pn}) \tag{2.43}$$

Where K_n is the coupling factor

τ_{pn} is the time from tower top to crossarm

Combining the equations yields

$$V_{sn}(t+\tau_{pn}) = V_R(t+\tau_{pn}) + \frac{\tau_T - \tau_{pn}}{\tau_T}[V_T(t) - V_R(t+\tau_T)] - K_n V_T(t) \tag{2.44}$$

2.5.4 Critical Stroke Current

Till this point, all lightning voltages have been calculated in per unit (i.e. kV of voltage per $1kA$ crest stroke current entering the tower). All insulator voltages have been derived for the ramp function of stroke current. To fit probability requirements, it has been shown that this ramp function should crest somewhere between 1.25 and 2.5 μs (See Fig. 2.2). Next, the stroke current required to cause flashover must be determined from the per unit voltage and from the insulator's volt-time curve or the air gap's volt-time curve. Fig. 2.11 presents a mathematically convenient set of insulator volt-time curves proposed by Darvenaza [2].

The stroke current required for the insulator overvoltage in any phase n to reach the insulator's volt-time curve is defined as the critical stroke current I_{cn} for that phase. It is computed by a ratio between insulator's volt-time curve and insulator overvoltage at the crest time of the stroke current as depicts in Fig. 2.12. This critical stroke current is used to compute the tripout rate for that phase.

2.5.5 Backflashover Rates

After the critical stroke current (I_{cn}) was calculated, the probability of I_{cn} being equal or exceeded the critical stroke current can be determined. For general formula, the backflashover rate is computed by

$$BFOR = N_{L1} \times P_i \tag{2.45}$$

Where N_{L1} is the number of strokes that terminate on the OHGW

P_i is the probability of the lightning current exceeding a backflashover critical value

The number of strokes that terminate on the OHGW is computed by

$$N_{L1} = N_L - SFFOR \tag{2.46}$$

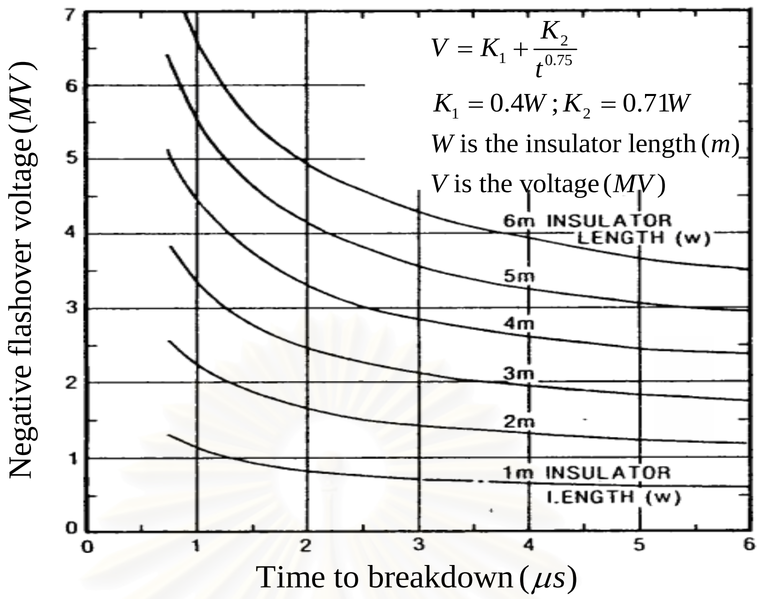


Figure 2.11 CIGRE volt-time curve for flashover of line insulators

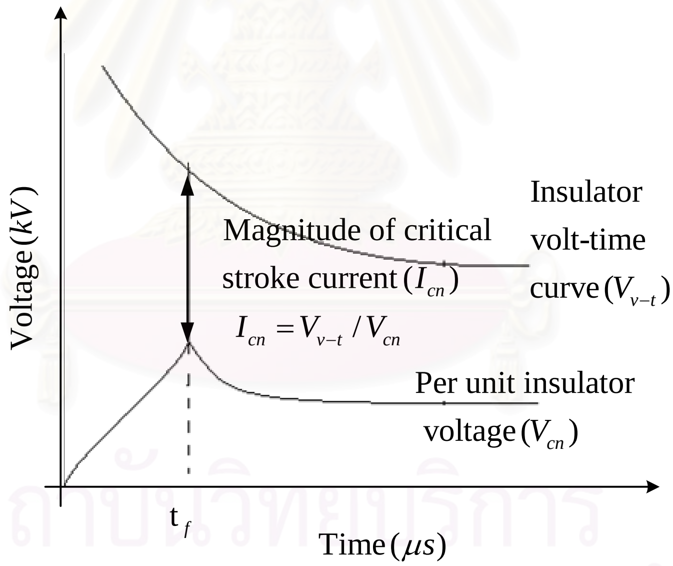


Figure 2.12 Per unit insulator overvoltage under the volt-time curve

2.5.5.1 Effect of Adjacent Tower

Reflections from adjacent towers can drive down the insulator voltages at the stricken tower by reflected current waves as shown in Fig. 2.13. Depending on the span length, these reflections may arrive before or after the crest voltage that would otherwise occur at the stricken tower. The magnitude of the reflections is not easily determined by simple analytical means because the reflected waves are badly distorted by corona and resistance losses which are functions of voltage, rise time and distance. Many multiple reflections and refractions may be involved. However, consideration of these reflections is required because they can reduce the tripout rate if they arrive soon enough.

The reflected voltage arriving at the tower top at crest time t_0 is given by the following equation [2]:

$$V_T^{'}(t_0) = \frac{-4K_s[V_T(t_0)]^2}{Z_s}[1 - \frac{2V_T(t_0)}{Z_s}][\frac{t_0 - 2\tau_s}{t_0}] \tag{2.47}$$

Where $V_T^{'}(t_0)$ is the sum of the reflected voltage waves from adjacent towers appearing at the tower top at crest time (t_0)

$V_T(t_0)$ is the crest tower top voltage at time t_0 without reflections from adjacent towers

$2\tau_s$ is the travel time for a wave to travel to the adjacent tower and return

$$\tau_s = \frac{span}{velocity} = \frac{span}{0.9 \times 300} \tag{2.48}$$

Z_s is the shield wire surge impedance (Ω)

The attenuation constant (K_s) may be assumed to be about 0.85 if no specific data are available. The total tower top voltage at stroke crest time (t_0) is then

$$\bar{V}_T(t_0) = V_T(t_0) - V_T^{'}(t_0) \tag{2.49}$$

If $t_0 < 2\tau_s$; $\quad V_T^{'}(t_0) = 0$

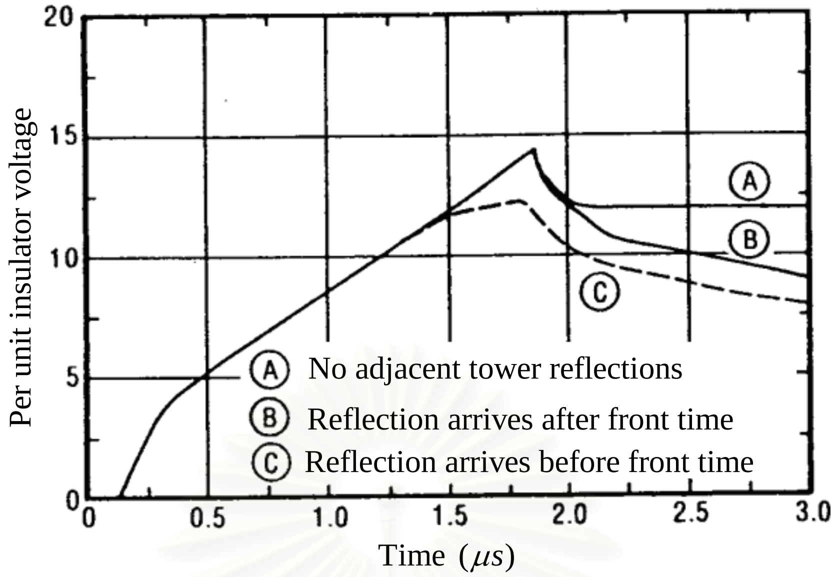


Figure 2.13 Reflections from adjacent tower reduce the crest insulator voltage

2.5.5.2 Effect of Power Frequency Voltage

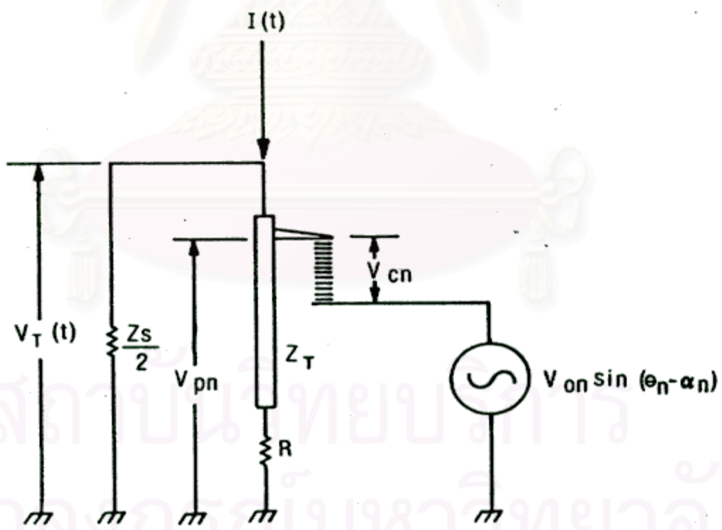


Figure 2.14 Circuit for studying the effects of power frequency voltage

As the power frequency voltage on phase n varies with the instantaneous voltage angle θ_n it adds to or subtracts from the flashover voltage V_{cn} for that insulator string. At any instant, the critical stroke current $I_{cn}^{'}$ required to create a flashover on phase n with power frequency voltage superimposed is

$$I_{cn}^{'} = [\frac{V_{cn} - V_{on}\sin(\theta_n - \alpha_n)}{V_{cn}}]I_{cn} \tag{2.50}$$

Where V_{on} is the crest phase-to-ground voltage for phase n

θ_n is the instantaneous voltage angle for phase A (the reference phase)

α_n is the phase angle of phase n (either $0^\circ, -120^\circ, or +120^\circ$)

I_{cn} is the critical stroke current without power frequency voltage

V_{cn} is the insulator flashover voltage at the time of I_{cn}

One must know not only the percentage of time that each phase n is dominant, but also the average $\bar{I}_{cn}$ for that phase during that time because this is used to compute the ultimate tripout rate. If wave n dominates between instantaneous phase angle θ_2 and θ_1, where θ_2 is the greater, then the average value of $I_{cn}^{'}$ for phase n during the dominant interval is symbolized by $\bar{I}_{cn}$ and may be computed from

$$\bar{I}_{cn} = I_{cn}\{1 + \frac{V_{on}}{V_{cn}}[\frac{\cos(\theta_2 - \alpha_n) - \cos(\theta_1 - \alpha_n)}{\theta_2 - \theta_1}]\} \tag{2.51}$$

Where $(\theta_2 - \theta_1)$ must be in radians.

2.5.5.3 Effect of Strokes within the Span

A stroke terminating on the OHGW within the span produces voltage across the air insulation between the OHGW and the phase conductor and also the air porcelain insulation at the tower. Although the voltage across the span insulation exceeds that across the tower insulation, the span insulation strength exceeds that of the tower. Thus dependent on the relative voltage and insulation strength, flashover can occur either across the span or across tower insulations. The voltage produced at the tower by a stroke within the span is equal to or less than that produced by a stroke to a tower [3]. Thus, in conclusion,

1) For strokes within the span, although flashovers can occur within the span, they are insignificant to flashovers that occur at the tower and therefore can be neglected.
2) Strokes within the span cause flashovers at the tower.
3) Strokes within the span produce voltage at the tower that are usually less than those produced by strokes to the tower.
4) The BFOR considering all stroke terminating points is equal to about 60 % of the BFOR if only strokes to the tower are considered.

Therefore, the BFOR that considered the effect of power frequency voltage and strokes within the span is given by.

$$BFOR = 0.6 N_{L1} \sum_{i=1}^{N_c} (t_i P_i) \tag{2.52}$$

Where N_c is the number of phase conductors

t_i is the period of time in which each phase is dominant

2.6 Lightning Outage Rates of Overhead Transmission Line

The lightning outage rate is summation between the shielding failure flashover rate and the backflashover rate.

2.7 Electromagnetic Transient Program (EMTP)

Analysis of transient state in the power system can be done by electromagnetic transient program (EMTP). The accurate model is necessary for each parameter. Therefore, the following topic will present each parameter models such as tower, footing resistance, insulator string, conductors (OHGWs and phase conductors) which are the main factors that have effects on lightning overvoltage calculation.

2.7.1 Transmission Line Model

The transmission line parameter is an important parameter in the transient analysis for electrical power system. Therefore, the accurate modeling is required, the transmission line model of EMTP for transient analysis, there are two types which give highly accuracy such as

1) Constant - parameter model

2) Frequency - dependent model

2.7.1.1 Constant – Parameter Model

This model consist of the resistance $R = R(f_t)$, surge impedance $Z_0 = Z_0(f_t)$ and velocity $v = v(f_t)$ where f_t is the dominant transient frequency which can compute as following:

$$f_t = 1/4\,\tau \quad \text{: Open circuit at the end line} \tag{2.53}$$

$$f_t = 1/3\,\tau \quad \text{: Connected resistance at the end line} \tag{2.54}$$

$$f_t = 1/2\,\tau \quad \text{: Short circuit at the end line} \tag{2.55}$$

Where $\tau = x / v(f_t)$, x is the length of transmission line

The equivalent of this model is depicted in Fig. 2.15. In this model, if $R = 0$ it will be come lossless model.

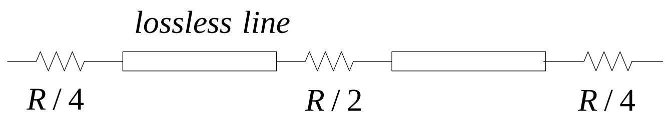


Figure 2.15 Constant - parameter model

2.7.1.2 Frequency – Dependent Model

These model, the surge impedance Z_0 depends upon the frequency and propagation constant Γ. Recently there are two models such as Semlyen model and JMarti model that are mostly used in EMTP, because of these model are given highly the accuracy in transient state analysis.

2.7.2 Tower Model

Several models with a different level of complexity have been proposed for representing towers [2, 13-16]. In this work, some model is described such as lossless homogenous line model and multistory model.

2.7.2.1 Lossless Homogenous Line Model

This model is represented as a single conductor distributed parameter line, its surge impedance is computed at section 2.3.4.

2.7.2.2 Multistory Model

This model separates into many parts, each part is represented with parallel of R and L and then series with lossless line as depicts in Fig. 2.16, this model is necessary when analyzing extra-high voltage (EHV) and ultra-high voltage (UHV) lines [15-16].

In the Fig. 2.16 each parameter can be found as follows:

1) Surge impedance was divided into two parts, i.e. the upper part (Z_T) and lower part (Z_B). Where (Z_T) and (Z_B) obtained from experiment [13] is shown in Table 2.1

Upper part $Z_{t1} = Z_{t2} = Z_{t3} = Z_T$

Lower part $Z_{t4} = Z_B$

Table 2.1 The parameters of multistory model

Source	$Z_T(\Omega)/Z_B(\Omega)$	γ
Experiment	220/150	0.8

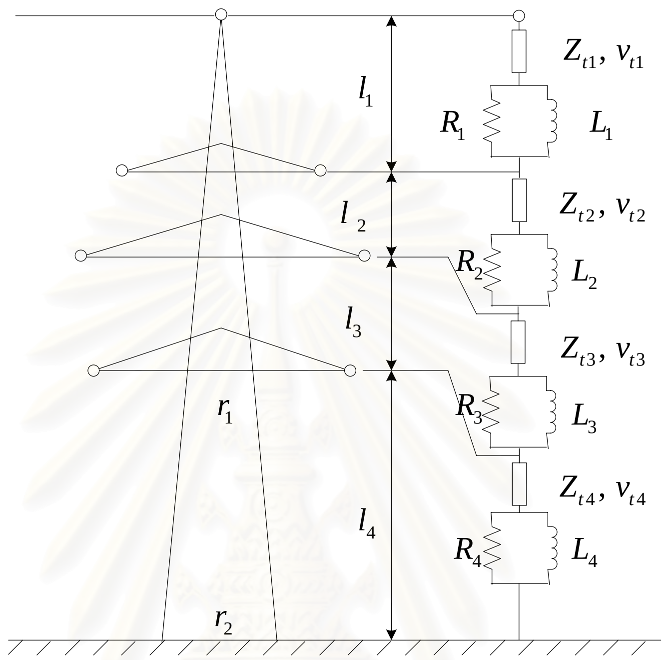


Figure 2.16 Multistory model

2) Surge propagation velocity

$$v_{t1} = v_{t2} = v_{t3} = v_{t4} = 300m/\mu s$$

3) Surge traveling time

$$\tau = \frac{2H}{v_t} = \frac{L}{R} \tag{2.56}$$

4) Attenuation coefficient (γ)

$$\gamma = \gamma_T \times \gamma_B \tag{2.57}$$

$$\gamma_T = \gamma_B = \sqrt{\gamma}$$

Where γ_T is the attenuation coefficient of upper part

γ_B is the attenuation coefficient of lower part

5) Resistance (R) and Inductance (L)

- Upper part

$$r_1 = \frac{-2Z_T \ln \gamma_T}{l_1 + l_2 + l_3} \tag{2.58}$$

$$R_1 = r_1 l_1;\ R_2 = r_1 l_2;\ R_3 = r_1 l_3 \tag{2.59}$$

- Lower part

$$r_2 = \frac{-2Z_B \ln \gamma_B}{l_4} \tag{2.60}$$

$$R_4 = r_2 l_4 \tag{2.61}$$

$$L_n = R_n \times \tau \qquad (n = 1, 2, 3, 4) \tag{2.62}$$

2.7.3 Tower Footing Resistance Model

Footing resistance modeling is one of the most critical aspects. A frequency-dependent nonlinear resistance and/or a current-dependent nonlinear resistance are required to obtain an accurate simulation. The second is provided by CIGRE guideline as define in equation (2.13) and (2.14).

2.7.4 Insulator String Breakdown Model

Several approaches have been developed for representation of insulators flashover voltage model such as [11]

1) Volt-time model

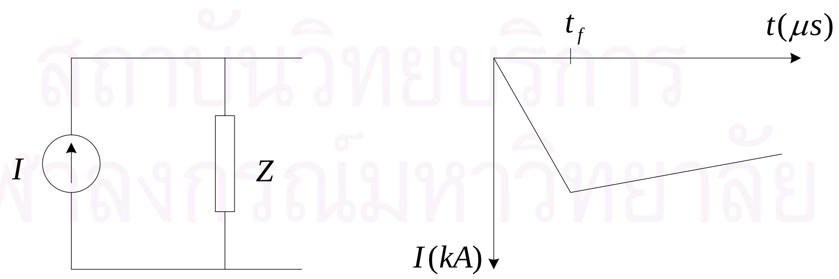
2) Integration model

3) Leader model

In this work, some model is described. The voltage-controlled switch of EMTP is represented the volt-time model. The voltage of the insulator chain is compared with the critical flashover voltage (CFO) of volt-time curve. If the voltage across terminals of the insulator exceeds the CFO, the switch closes its contacts simulating the arc flash. This value of current that originates flashover is the critical current (I_C).

2.7.5 Lightning Stroke Model

The lightning stroke model is represented by a parallel connection of a current source and a channel lightning impedance or only source current. If the channel lightning impedance is used, its value is a few thousand ohm $(2000-3000\Omega)$ [1]. The current source is defined by its shape and characteristic parameter such as a triangular shape and the characteristic time of stroke current is considered constant (the front time and the time to half-value). The stroke waveshape is only considered negative waveshape with the front time $2\mu s$ and the time to half-value $50\mu s$. The lightning waveshape and lightning stroke model show in the Fig. 2.17.



a) Lightning source model b) Lightning waveshape

Figure 2.17 Lightning stroke model

CHAPTER III

A STRUCTURE OF SOFTWARE PROGRAMS

In the chapter 2 provided the foundations for computing lightning tripouts with all the rigor that is justified considering the sparsity of data and the uncertainties of the statistics of lightning, climate, and geology. The computation is clearly too complex for convenient solution. Therefore, a simplified method or the simulation is required. Hence, in this chapter, a simplified two–point method and the simulation of EMTP are presented for application in development of software program.

3.1 A Simplified Two-Point Method (STPM)

This method, its algorithm is directly applied to develop the software program.

3.1.1 The Concept of Simplified Two-Point Method

The method is based on the following concepts:

1) Only one waveshape is utilized. Although stroke crest currents and rise times have different probability distributions, they are not independent once, one selects the time to crest of a ramp function used to simulate the stroke waveshape. Therefore, for this simplified method, the standard wave will be a ramp function cresting at $2\mu s$ with a flat top.

2) Reflections from adjacent towers are included. Reflections from adjacent towers can reduce tower top potentials and significantly reduce the line flashover rate. These reflections are distorted by corona currents and their velocity of propagation is slowed appreciably by resistance and corona effects. (The velocity is equal to $0.9C$ for waves from adjacent towers, where C is $300m/\mu s$).

3) Penetrations into the volt-time curve are computed at only two points. Fig. 4.1 shows the per unit stroke current wave adopted as the standard and the two points A and B at which the critical stroke current required to make the insulator voltage

penetrates into the volt-time curve is computed. The lower of the two stroke currents is then used as the true critical stroke current for flashover calculations. The two voltages A and B are computed for each insulator on the tower unless it is determined by inspection that the insulators have identical stresses.

4) Subsequent strokes are ignored. The analysis suggests that as far as the severity of voltage across the insulators is concerned, subsequent strokes in the same flash are no worse than the first stroke. Subsequent strokes create more insulator voltage but at shorter times where the insulator strength is higher.

5) By selecting the two penetration points at times of $2\mu s$ and $6\mu s$, all the voltage equations are greatly simplified. With t_0 equal to $2\mu s$ (at point A in Fig. 3.1) and no reflections from adjacent towers, therefore the equation for tower top voltage is reduced to the following good approximation:

$$(V_T)_2 = [Z_I - \frac{Z_w}{1-\varphi}(1-\frac{\tau_T}{1-\varphi})]I \tag{4.1}$$

Where $(V_T)_2$ is the magnitude of tower top voltage at $2\mu s$ for one per unit stroke current cresting at $2\mu s$

Z_w, τ_T, φ are defined in chapter 2

The magnitude of the footing resistance voltage $V_R(t+\tau_T)$ is closely approximated as follows:

$$(V_R)_2 = [\frac{\alpha_R \bar{Z}_I}{1-\varphi}(1-\frac{\varphi\tau_T}{1-\varphi})]I \tag{4.2}$$

Where $(V_R)_2$ is the magnitude of voltage across the footing resistance at $(2+\tau_T)\mu s$ for a one per unit stroke current cresting at $2\mu s$

The voltage reflection from adjacent towers, which appears across the stricken tower at $2\mu s$ (provided $2\tau_s < 2\mu s$) is

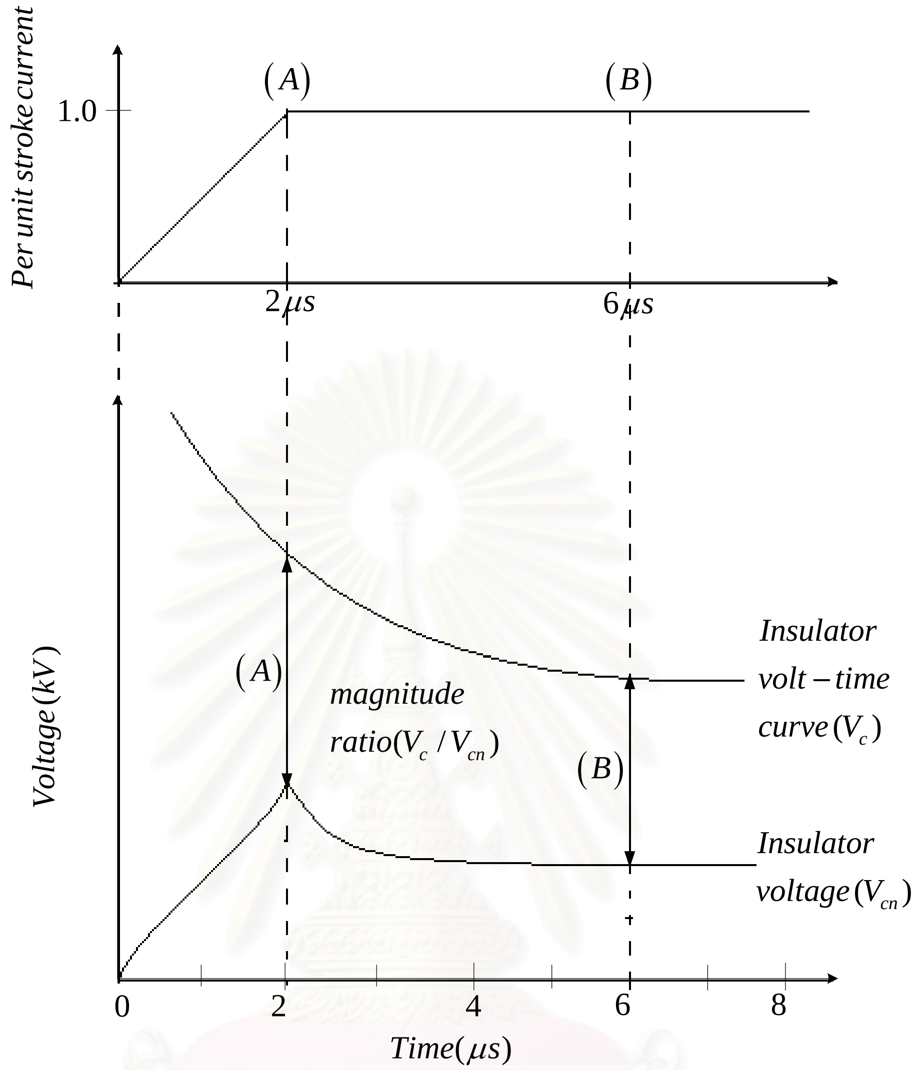


Figure 3.1 A simple ramp function stroke current is used and insulator voltages computed at only two point in time

$$(V_T')_2 = \frac{-4K_S(V_T)_2^2}{Z_s}\left[\frac{1-2(V_T)_2}{Z_s}\right](1-\tau_s) \tag{4.3}$$

Where K_S is the span attenuation factor

Therefore, the total tower top voltage magnitude is

$$(\bar{V}_T)_2 = (V_T)_2 + (V_T')_2 \tag{4.4}$$

The voltage $(V_{pn})_2$ at crossarm n at $2\mu s$ is still determined by interpolation as follows

$$(V_{pn})_2 = (V_R) + \frac{\tau_T - \tau_{pn}}{\tau_T}[(V_T)_2 - (V_R)_2] \tag{4.5}$$

The insulator surge voltage for phase n at $2\mu s$ is the difference between the crossarm surge and the phase conductor surge voltage as follows

$$(V_{sn})_2 = (V_{pn})_2 - K_n(\bar{V}_T)_2 \tag{4.6}$$

After the current wave has crested and the towers have rung down and after the effect of tower surge impedance disappears. Therefore, the surge voltage developed at $6\mu s$ is

$$(V_T)_6 = (V_R)_6 = (V_{pn})_6 = [\frac{Z_s R}{Z_s + 2R}]I \tag{4.7}$$

The reflections from the adjacent towers have not rung down completely. For simplification, only the first set of reflections is used. Then the voltage reflection is computed by

$$(V_T^{'})_6 = -4K_s Z_s(\frac{R}{Z_s + 2R})^2[1 - \frac{2R}{Z_s + 2R}]I \tag{4.8}$$

The total per unit insulator voltage at $6\mu s$ is

$$(V_{sn})_6 = [(V_T)_6 + (V_T^{'})_6](1 - K_n) \tag{4.9}$$

The dielectric strengths of insulator string at $2\mu s$ and $6\mu s$ are

$$(V_I)_2 = 820W \tag{4.10}$$

and

$$(V_I)_6 = 585W \tag{4.11}$$

Where $(V_I)_2$ is the insulator flashover strength at $2\mu s$ (kV)

$(V_I)_6$ is the insulator flashover strength at $6\mu s$ (kV)

W is the insulator length (m)

The critical stroke currents required to flashover insulator n at $2\mu s$ and $6\mu s$ respectively (in the absence of power frequency voltage) are

$$(I_{cn})_2 = \frac{820W}{(V_{sn})_2} = \frac{(V_I)_2}{(V_{sn})_2} \tag{4.12}$$

and

$$(I_{cn})_6 = \frac{585W}{(V_{sn})_6} = \frac{(V_I)_6}{(V_{sn})_6} \tag{4.13}$$

6) A general analysis of power frequency voltage effects is included to obtain a good simulation of the way power frequency voltages influence the sharing among the various phases of the tripouts that occur and because the presence of power frequency voltages can make a noticeable increase in total tripouts observed. Therefore, the critical stroke currents required to flashover insulator n at $2\mu s$ and $6\mu s$ with power frequency voltage present are

$$(I'_{cn})_2 = [\frac{820W - V_{on}\sin(\theta_n - \alpha_n)}{(V_{sn})_2}](I_{cn})_2 \tag{4.14}$$

and

$$(I'_{cn})_6 = [\frac{585W - V_{on}\sin(\theta_n - \alpha_n)}{(V_{sn})_6}](I_{cn})_6 \tag{4.15}$$

Where V_{on} is the crest phase to ground for phase n

θ_n is the instantaneous voltage angle

α_n is the phase angle of phase n (either $0^\circ, -120^\circ, +120^\circ$)

7) Probabilities of flashover are determined directly from the stroke probability curves. After the critical stroke currents (with power frequency voltage effects included) are determined, the probability of a stroke equaling or exceeding this value is found directly from the stroke probability distribution curve (P_i). The Anderson-Eriksson curve is used. Knowing this probability and the number of strokes to the line (with shielding failure strokes deleted), the expected number of flashovers per 100 km per year immediately follows.

8) Shielding failures are included. The electrogeometric theories are applied to establish the shielding failure rate for the phase conductors on each side of the center line. The shielding failure rates are then summed to find the total shielding failure rate.

3.1.2 The Procedure of Calculation

The following flowcharts summarize the method and procedure used for estimating tripout rates of power lines in this software program by using simplified two point method.

3.1.2.1 Estimation the Lightning Incidence on Power Lines

The procedure to compute lightning incidence on overhead line is shown in the following flowchart:

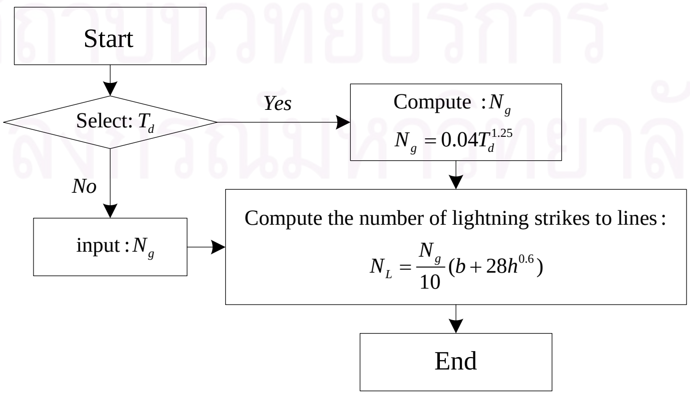


Figure 3.2 Flowchart of calculation of lightning incidence on overhead lines

3.1.2.2. Shielding Failure Flashover Rate Calculation (SFFOR)

The procedure to compute shielding failure flashover rate of overhead line is shown in the following flowchart:

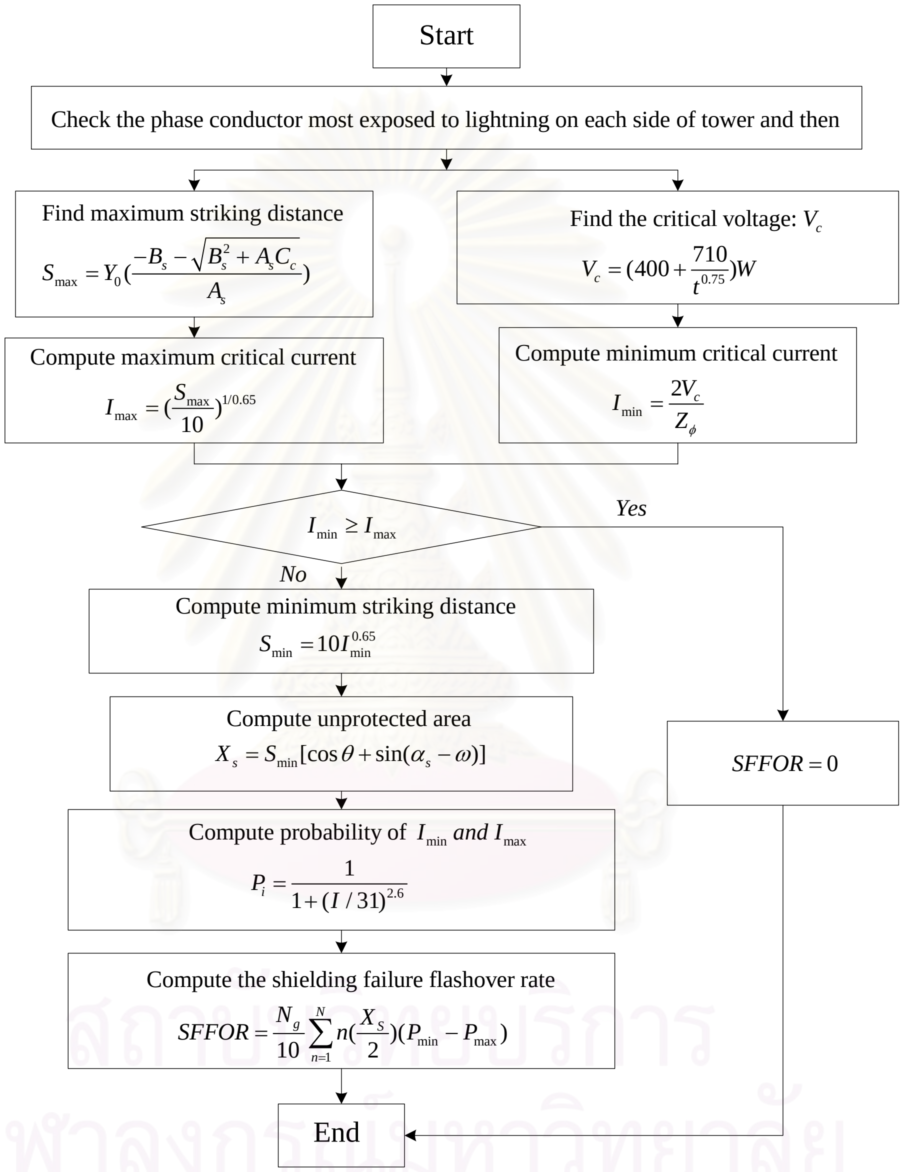


Figure 3.3 Flowchart of shielding failure flashover rate calculation

3.1.2.3 Backflashover Rate Calculation (BFOR)

The procedure to compute backflashover rate of overhead line is shown in the following flowchart:

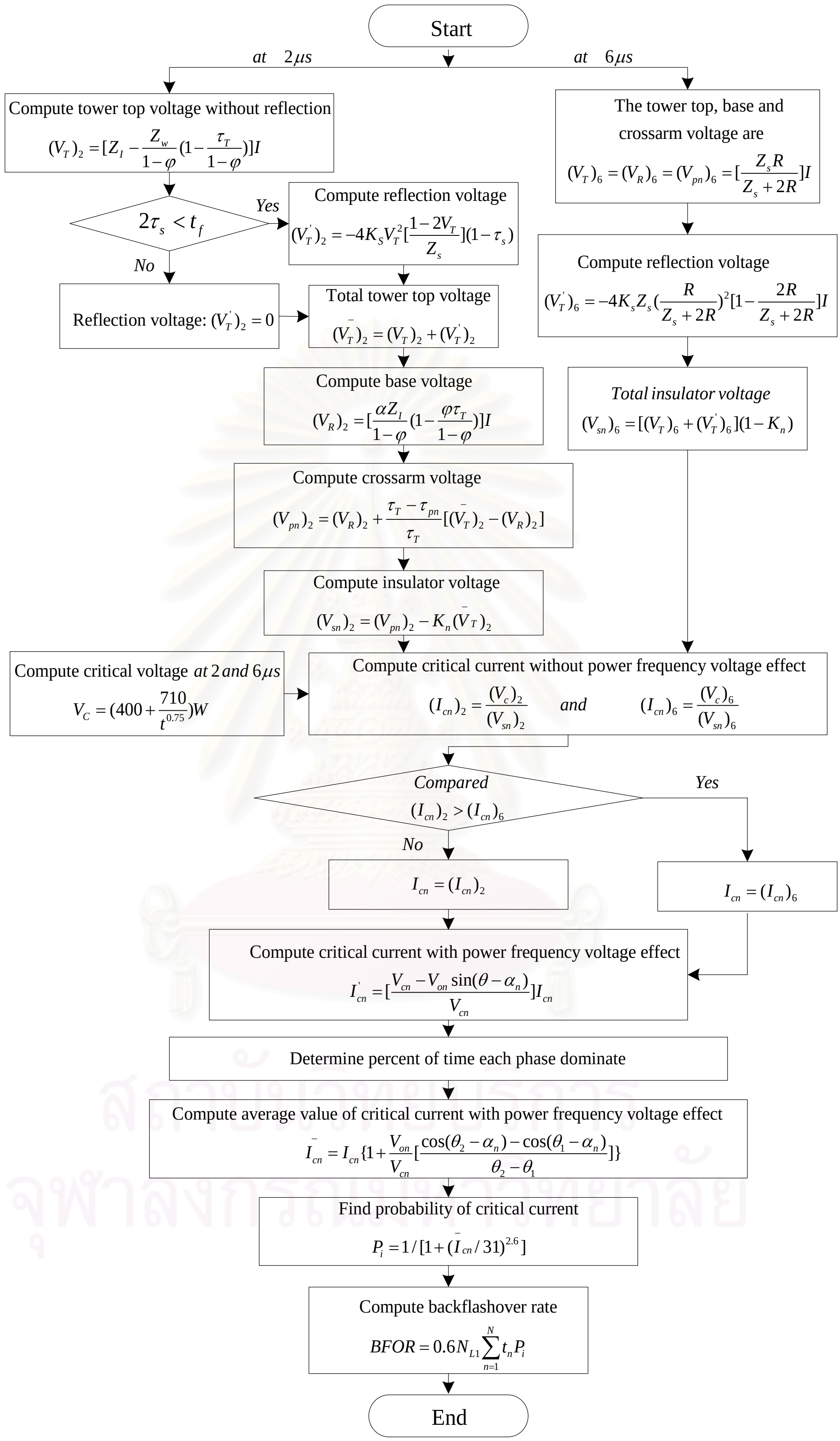


Figure 3.4 Flowchart of backflashover rate calculation

3.1.2.4 Lightning Outage Rate Calculation (LOR)

The lightning outage rate of the overhead lines is the result of summation of shielding failure flashover rate and backflashover rate.

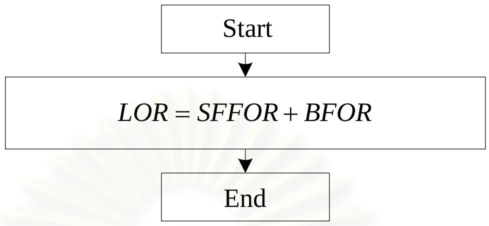


Figure 3.5 Flowchart of lightning outage rate calculation

3.2 Electromagnetic Transient Program (EMTP)

EMTP is used to simulates the power system for determination the critical stroke currents (minimum critical stroke current requires to cause shielding failure flashover and critical stroke current requires to cause backflashover). These values are inputted into software program. Therefore, the modeling guideline is described.

3.2.1 Modeling Guideline

The power system simulation is based on the following models and guidelines to be applied in ATPDraw program of EMTP.

1) The transmission line is modeled by two or three spans at each side of the point of impact. Each span is represented by a multiphase untransposed distributed parameter line section. This representation is made by using a frequency-dependent model such Jmarti model.

2) The representation of a line termination is needed at each side of the above model to avoid reflections that could affect the simulated overvoltages around the point of impact. This can be achieved by adding a long enough section at each side of the line, or by inserting a resistance matrix at each termination whose values equal the line surge impedances.

3) The tower is modeled by the lossless homogenous line model and/or multistory model. All the details are described in chapter 2.

4) The tower footing impedance is modeled by a constant value model and/or a current-dependent nonlinear resistance model. A lumped resistance is usually chosen for representing the tower footing impedance.

5) The insulator string breakdown is modeled by the volt-time model. This model is represented by the voltage-controlled switch model.

6) The lightning stroke is modeled by a parallel connection of a current source and a channel lightning impedance or only a current source.

7) Phase voltages at the instant at which the lightning stroke impacts the line must be included. For a deterministic calculation, worst case conditions should be determined and used.

3.2.2 Power System Simulation with ATPDraw Program

Based on the modeling guideline above, we can be modeled the power system as following:

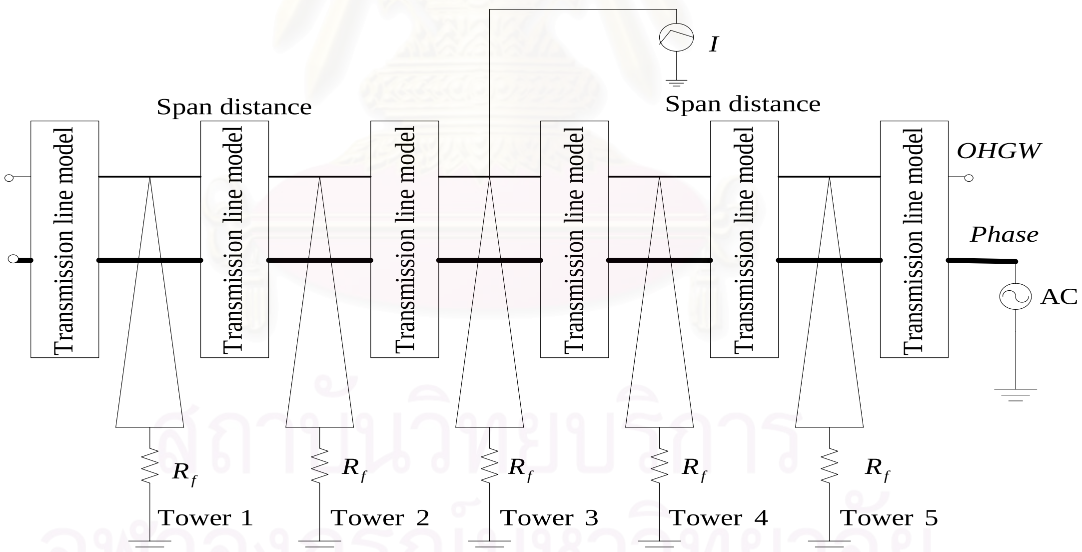


Figure 3.6 Transmission line model

3.2.3 The Procedure of Calculation

The following flowcharts summarize the method and procedure used for estimating tripout rates of power lines in this software program by using critical stroke current from simulation of EMTP.

3.2.3.1 Estimation Lightning Incidence on Power Lines

The numbers of lightning flashes on the overhead lines used in this method are similar to the numbers that uses in the simplified two-point method.

3.2.3.2 Shielding Failure Flashover Rate Calculation (SFFOR)

The procedure to compute shielding failure flashover rate of overhead line is shown in the following flowchart:

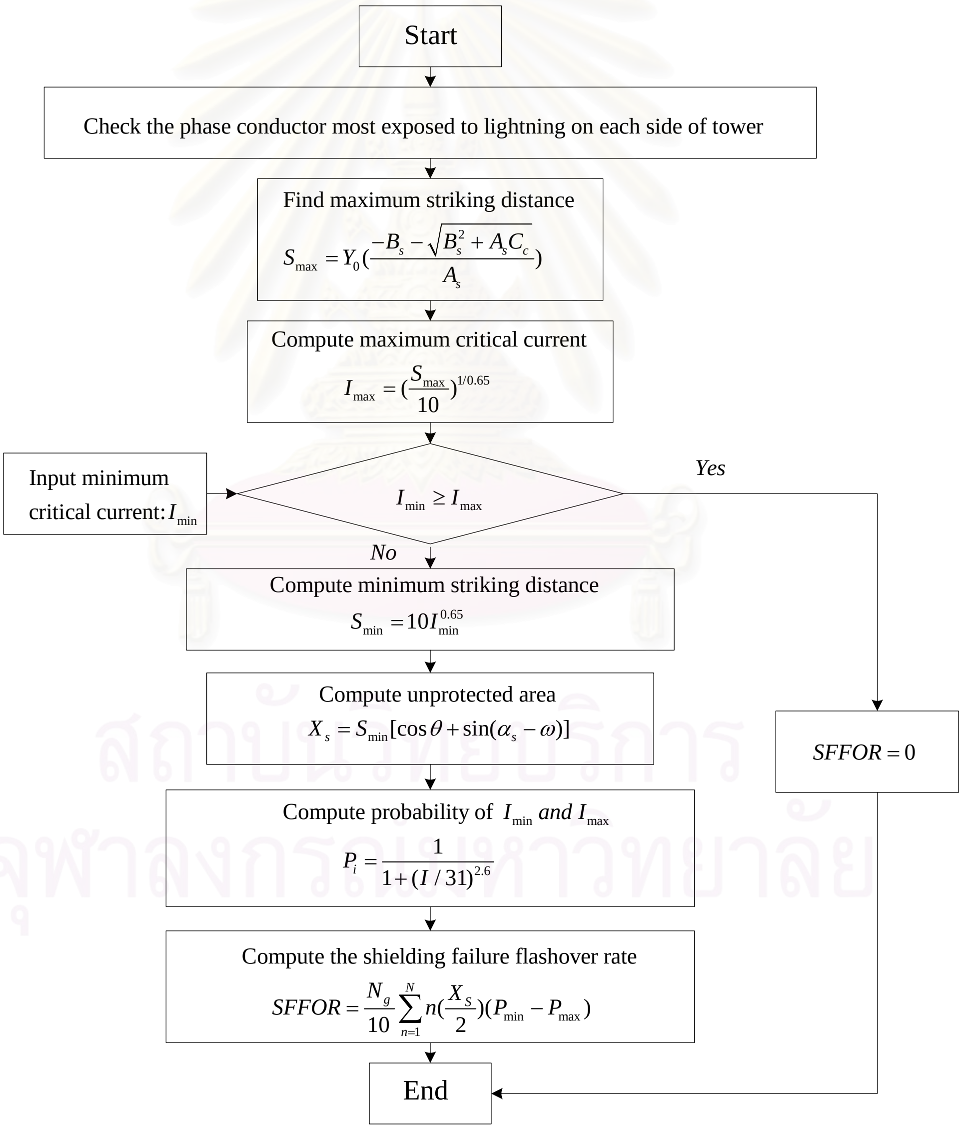


Figure 3.7 Flowchart of shielding failure flashover rate calculation

3.2.3.3 Backflashover Rate Calculation (BFOR)

The procedure to compute backflashover rate of overhead line is shown in the following flowchart:

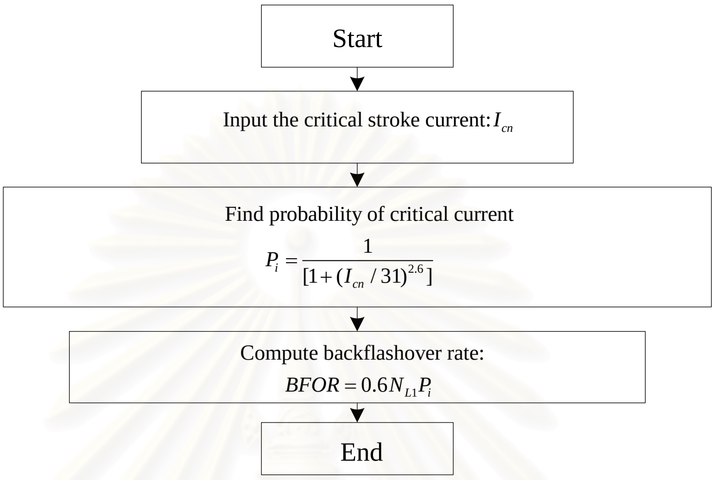


Figure 3.8 Flowchart of backflashover rate calculation

3.2.3.4 Lightning Outage Rate Calculation (LOR)

The lightning outage rate of the overhead lines is the result of summation of shielding failure flashover rate and backflashover rate.

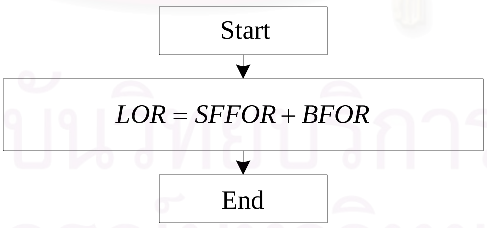


Figure 3.9 Flowchart of lightning outage rate calculation

CHAPTER IV

PROGRAM INSTRUCTION AND VERIFICATION

In this chapter, the instruction of software program is described. The validation of the software program is verified by comparison against the calculated lightning performance of a double-circuit 345 kV transmission line presented in reference [2]. Moreover, the software program is also compared against a commercial program, named TFlash, to calculate lightning performance of a 500 kV transmission line of Thailand.

4.1 Software Program with Simplified Two-Point Method (STPM)

This software program applies a simplified two point method to determine the critical stroke current for flashover rate calculation. Therefore, it is named as STPM program. The source code of STPM program is written by the Matlab programming language. This is because Matlab has highly computational capabilities and it can also create the graphical user interface that enables a user to perform interactive tasks. The main screen of STPM Program is shown in Fig 4.1. It consists of input and output data tabs. The input tabs are conductor position, conductor parameter, system parameter and grounding system. Their screens are shown in Fig 4.2 to Fig 4.7. The output tab presents the calculation results. Its screen is shown in Fig 4.8.

To estimate the lightning performance of a transmission line by using STPM program, the following input data must be available:

1) Ground flash density or thunderstorm days
2) Tower configuration and its dimensions
3) Phase conductor positions and parameters
4) Overhead ground wire positions and parameters
5) System voltage
6) Insulator length or critical impulse flashover voltage of insulator

The usage of this software program is described as following:

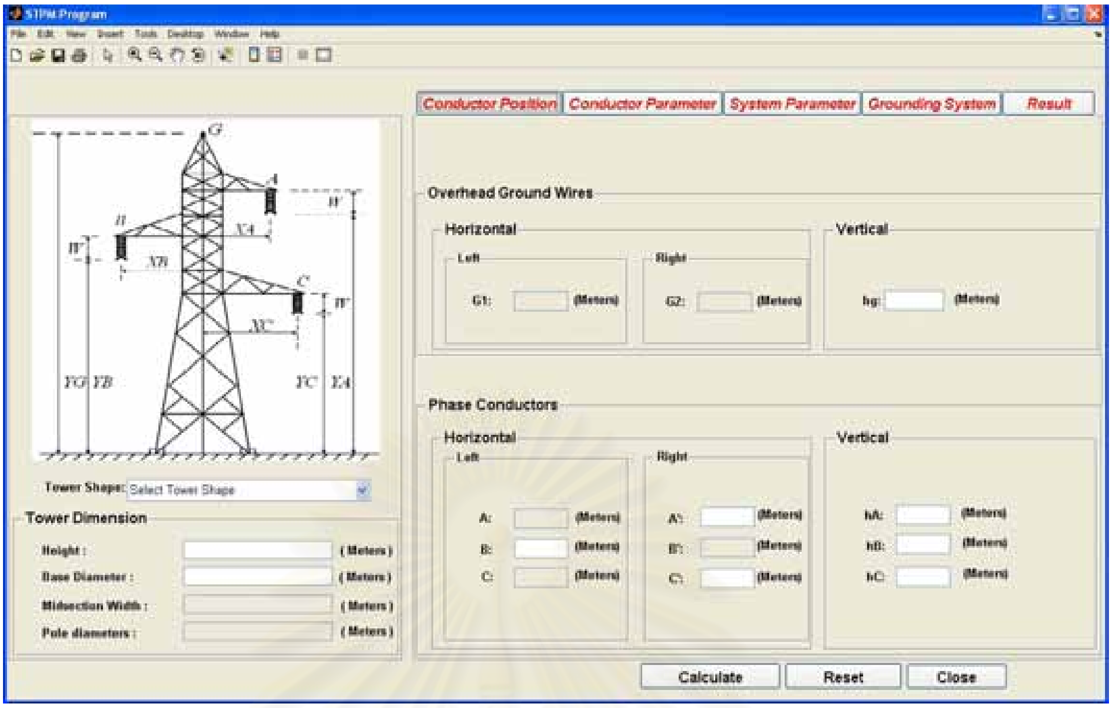


Figure 4.1 Main screen

1. Start up the STPM program. On the left side of main screen as shown in Fig 4.2, select the Tower Shape from the list in library (At present, the library consists of five tower configurations as shown in Fig. 4.3).
2. Input the data of Tower Dimension (See Fig. 4.4).

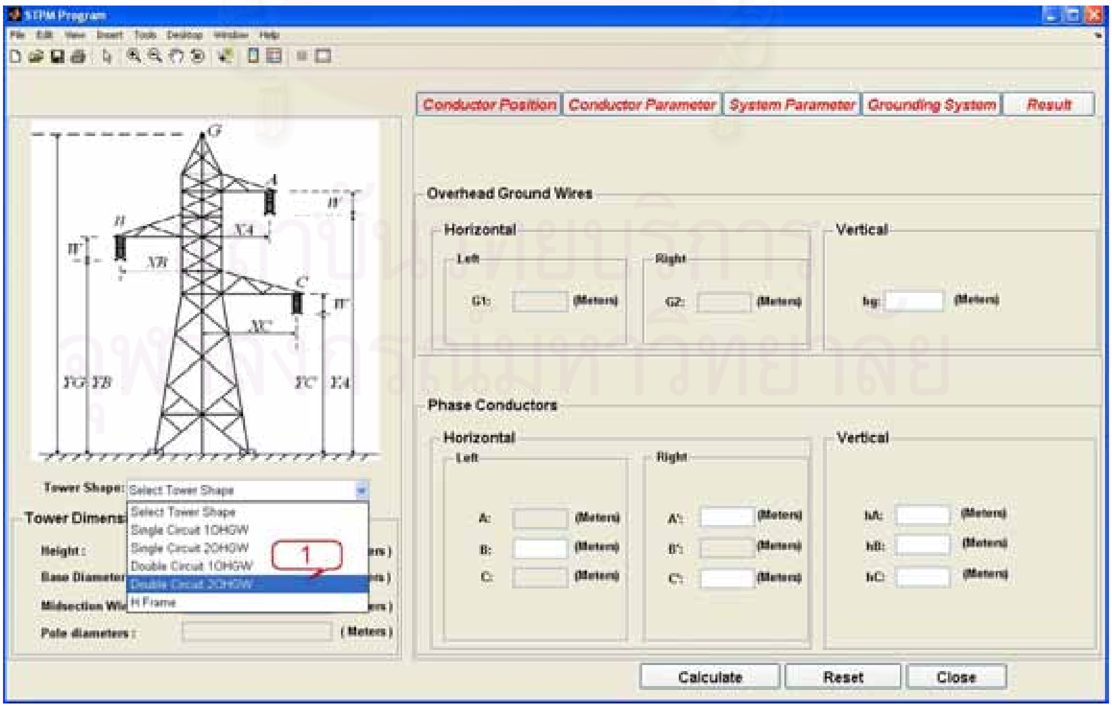
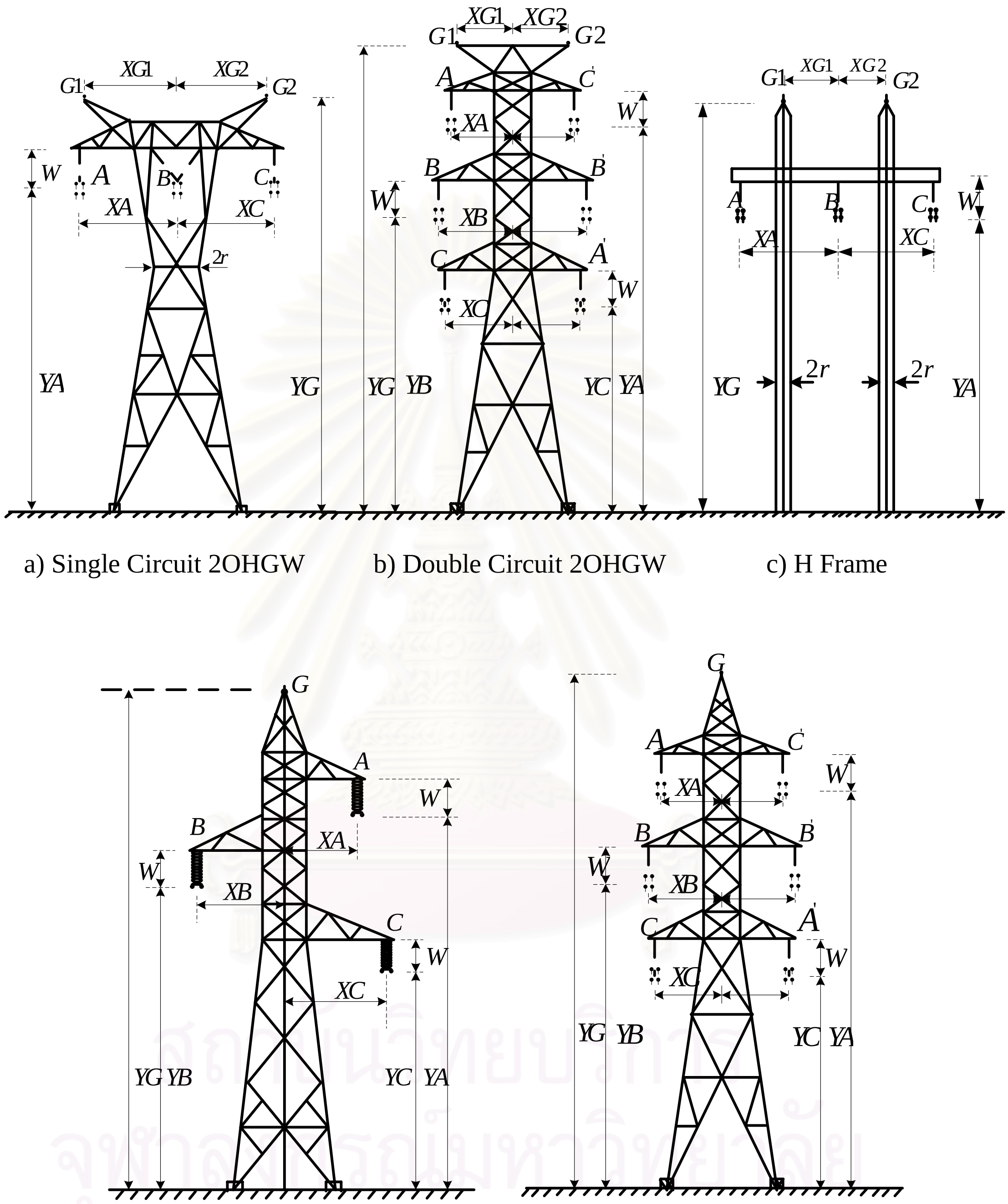


Figure 4.2 Setting of the tower configuration



a) Single Circuit 2OHGW b) Double Circuit 2OHGW c) H Frame

d) Single Circuit 1OHGW e) Double Circuit 1OHGW

Figure 4.3 Tower configurations

3. Fill the positions of overhead ground wire(s) and phase conductors in according to the tower configuration (See Fig. 4.4).

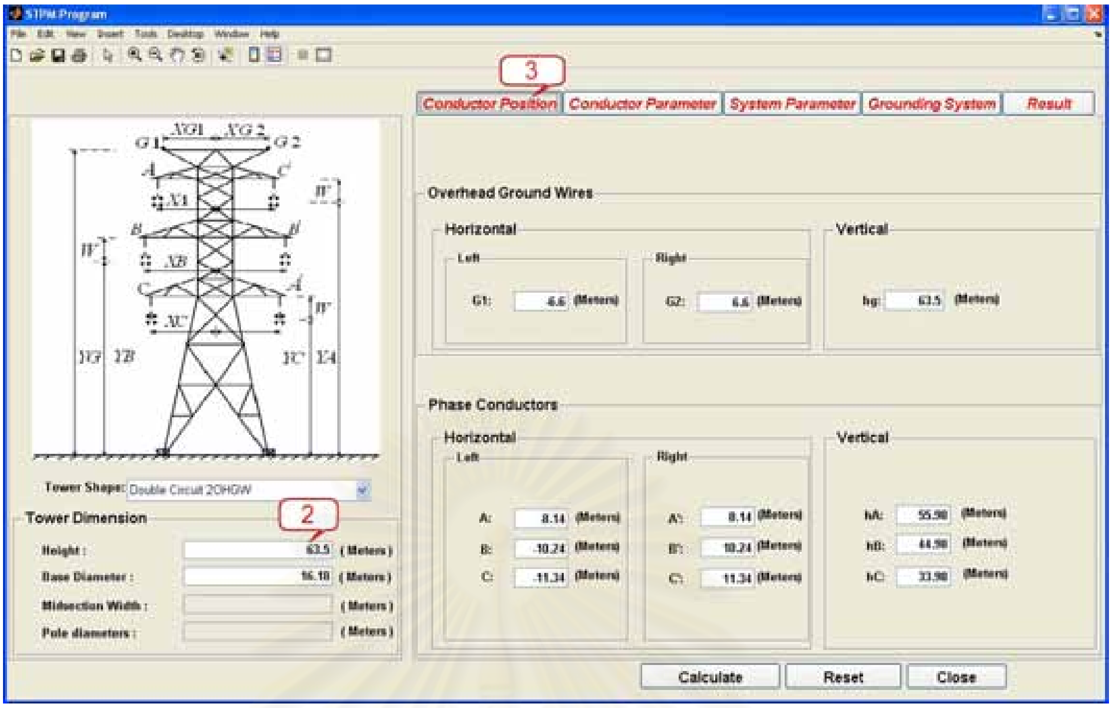


Figure 4.4 Conductor position tab

4. Select the Conductor Parameter tab for inputting the information of overhead ground wire and phase conductor parameters such as diameter and sag (See Fig. 4.5).

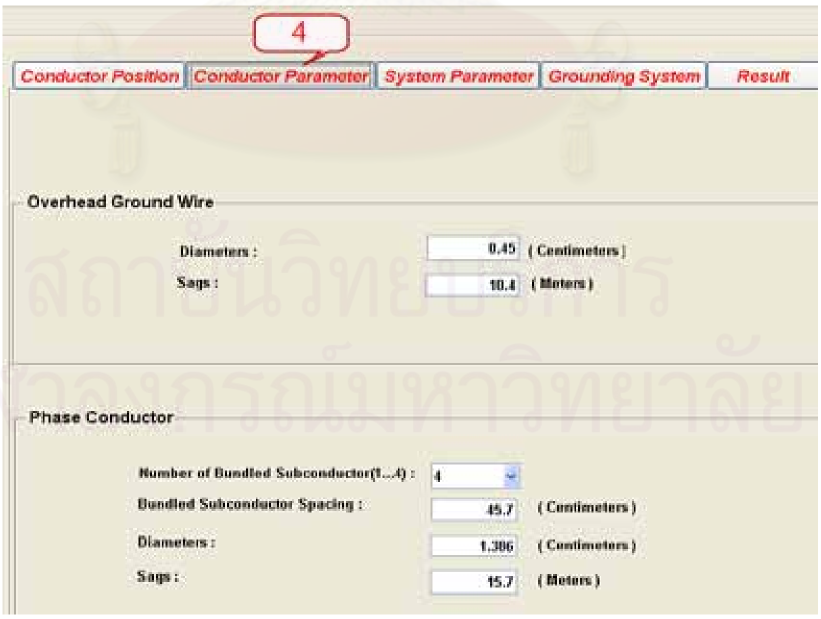


Figure 4.5 Conductor parameter tab

5. Select the System Parameter tab for inputting the data of power system such as system voltage, insulator string length and thunderstorm day or ground flash density (See Fig. 4.6).

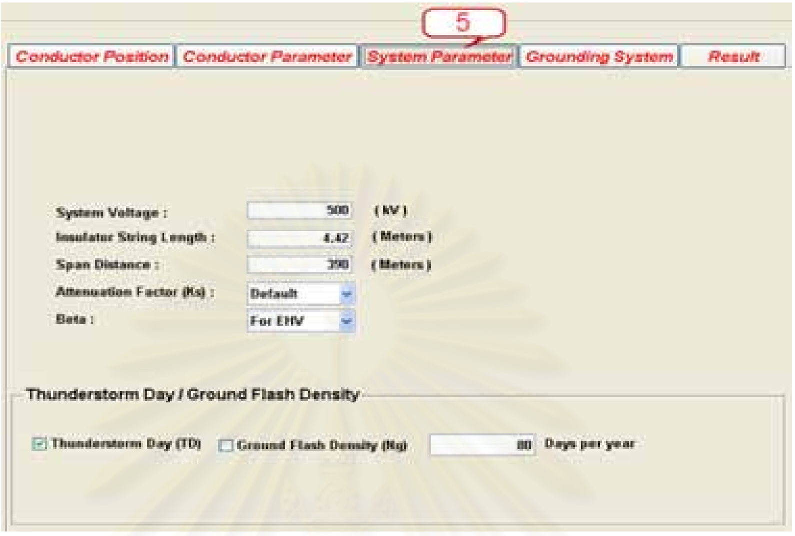


Figure 4.6 System parameter tab

6. Select the Grounding System tab for inputting the parameters related to grounding system such as tower footing resistance (See Fig. 4.7).

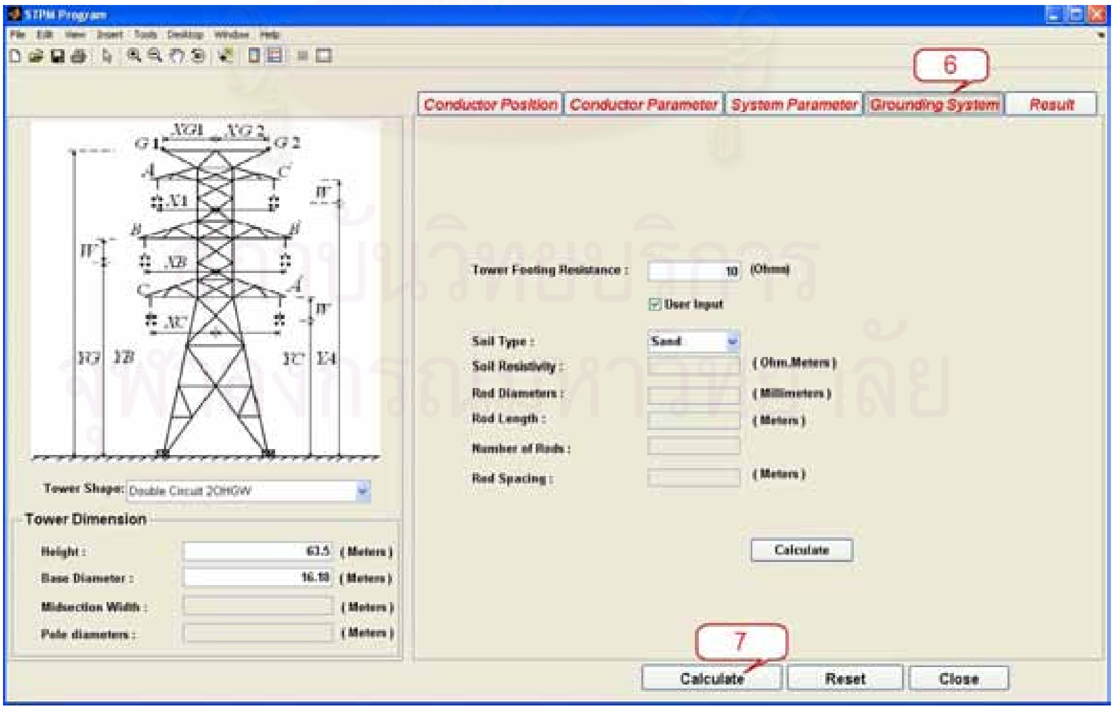


Figure 4.7 Grounding system tab

7. After input all data, press the $\boxed{\text{Calculate}}$ button at the main screen. The result screen will be displayed automatically (See Fig.4.8). The lightning performance report consists of the following data:

a) Minimum and maximum critical stroke current that can cause shielding failure flashover.

b) Critical stroke current required to cause backflashover.

c) Number of lightning strikes to power line.

d) Shielding failure flashover rate (SFFOR).

e) Backflashover rate (BFOR).

f) Lightning outage rate (LOR).

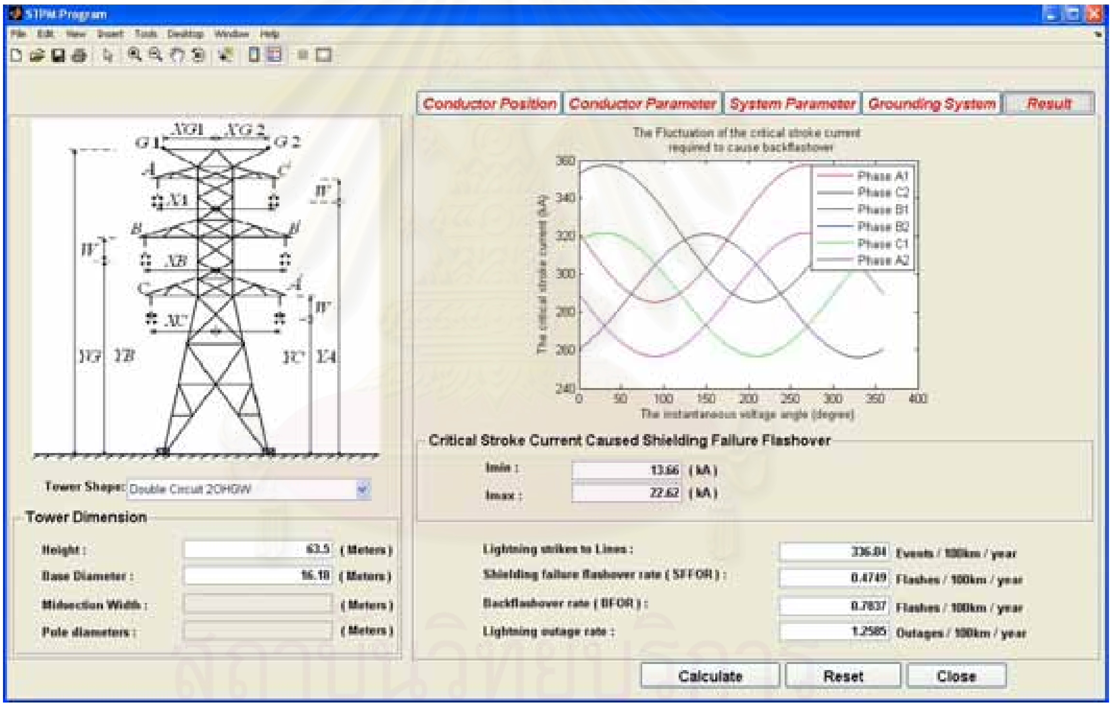


Figure 4.8 Result tab or output data screen

The critical stroke current required to cause backflashover is illustrated in the sinusoidal wave for indicating the effect of power frequency voltage of each phase conductor at the instant of lightning strike. The detail of calculation is described in section 2.5.5.2 of chapter 2.

4.2 Software Program with the Critical Stroke Current Calculated by EMTP (I-EMTP)

Unlike the STPM program, this software program needs the critical stroke current as an input data to estimate lightning performance. The critical stroke current is determined by the simulation with EMTP. The method applied to calculate flashover rate is the same as that of STPM program. This software program is named as I-EMTP program.

The main screen of I-EMTP program is shown in Fig 4.9. It consists of input and output data tabs. The input data tabs lead the user to conductor position and parameter screens as shows in Fig 4.10 and Fig 4.11. The output tab leads the user to result screen as shown in Fig 4.13.

To estimate the lightning performance of a transmission line by using I-EMTP program, the following input data must be available:

a) Ground flash density or thunderstorm day

b) Phase conductor positions and phase conductor sag

c) Overhead ground wire positions and overhead ground wire sag

d) Minimum critical stroke current required to cause shielding failure

e) Critical stroke current required to cause backflashover

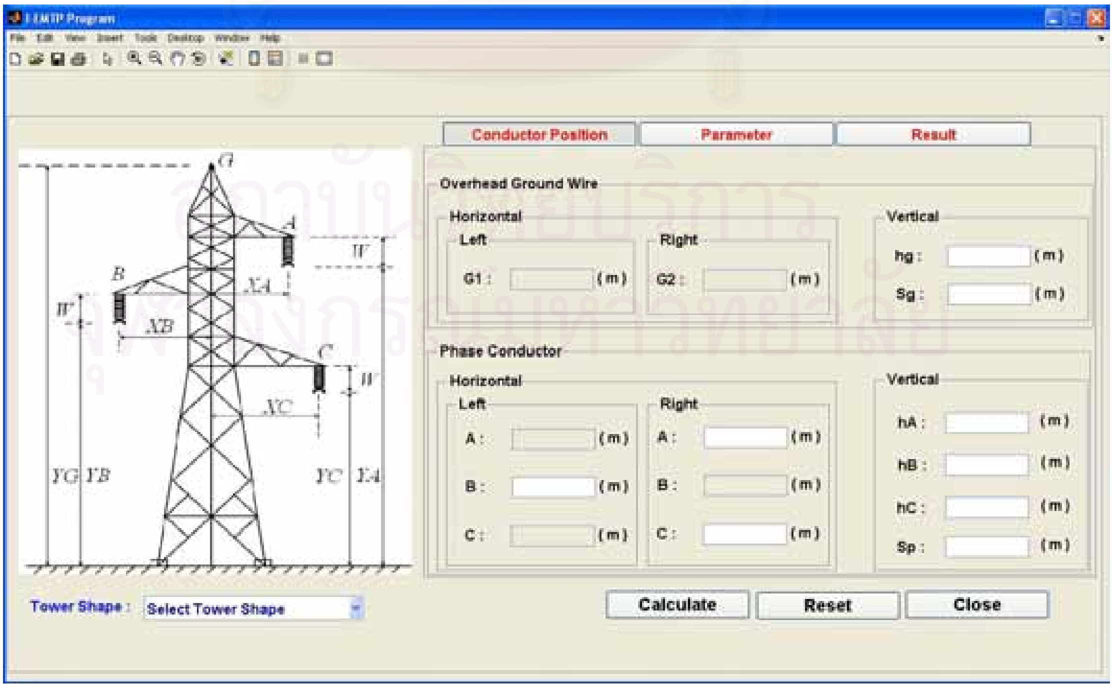


Figure 4.9 General screen (I-EMTP)

The usage of this software program is described as following:

1. Start up the I-EMTP program. On the left side of main screen as shown in Fig 4.10, select the Tower Shape from the list in library (At present, the library consists of five tower configurations as shown in Fig. 4.3).

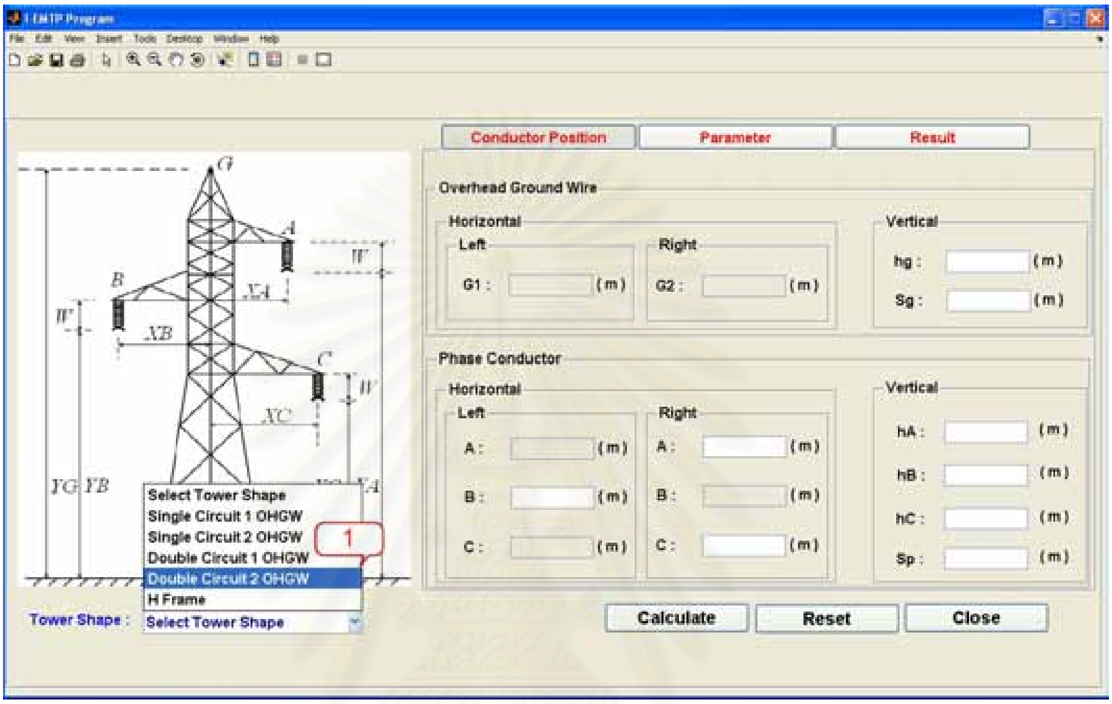


Figure 4.10 Setting up the tower configuration

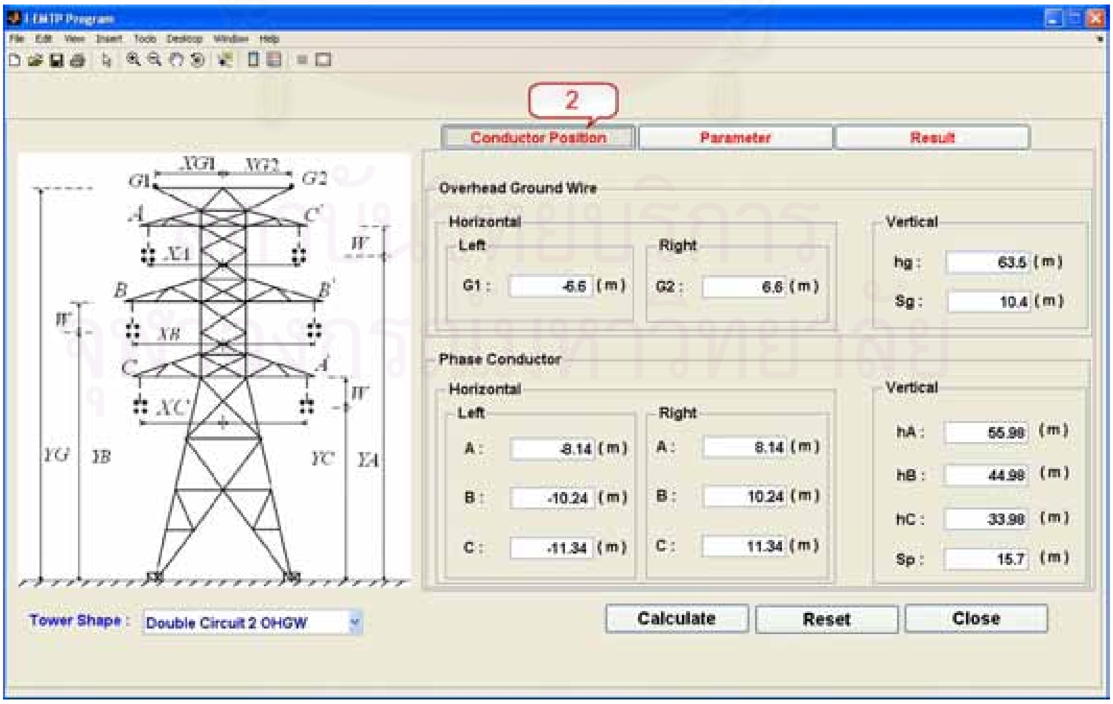


Figure 4.11 Conductor position tab

2. Fill the positions of overhead ground wire(s) and phase conductors according to the tower configuration (See Fig. 4.11).

3. Select the Parameter tab for inputting the ground flash density (N_g) or thunderstorm day per year (T_d), and critical stroke currents required to cause shielding failure flashover and backflashover).

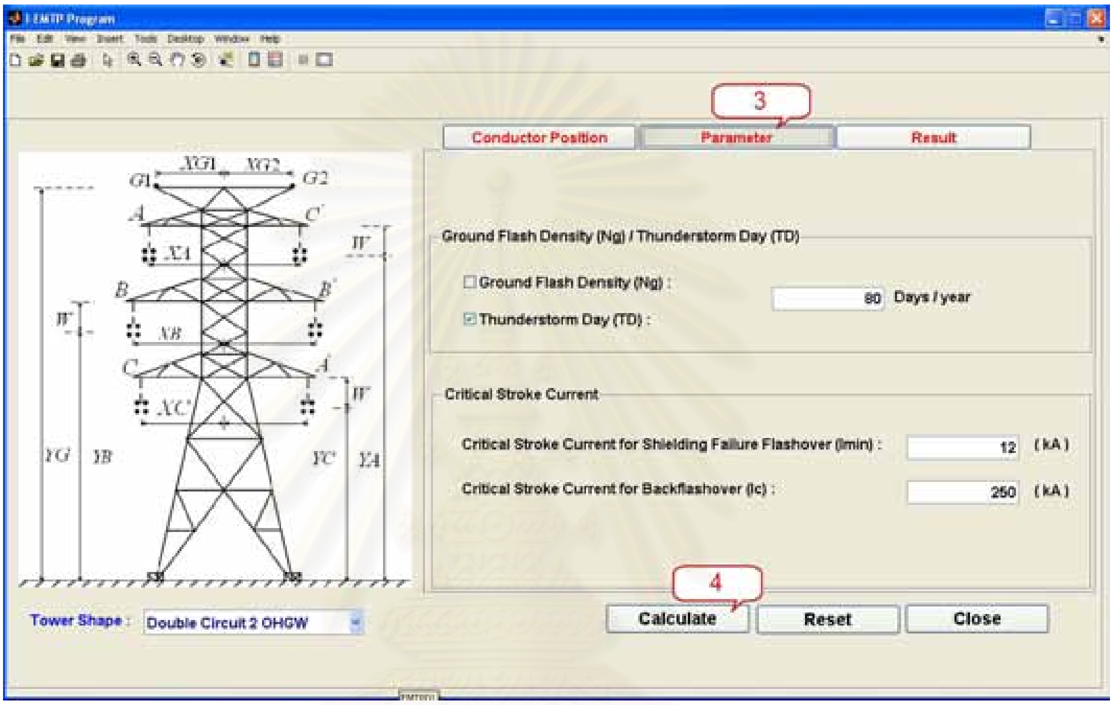


Figure 4.12 Parameter tab

4. After input all data, press the Calculate button. The result screen will be displayed automatically (See Fig.4.13). The lightning performance report consists of the following data:

a) Number of lightning strikes to power line.

b) Shielding failure flashover rate (SFFOR).

c) Backflashover rate (BFOR).

d) Lightning outage rate (LOR).

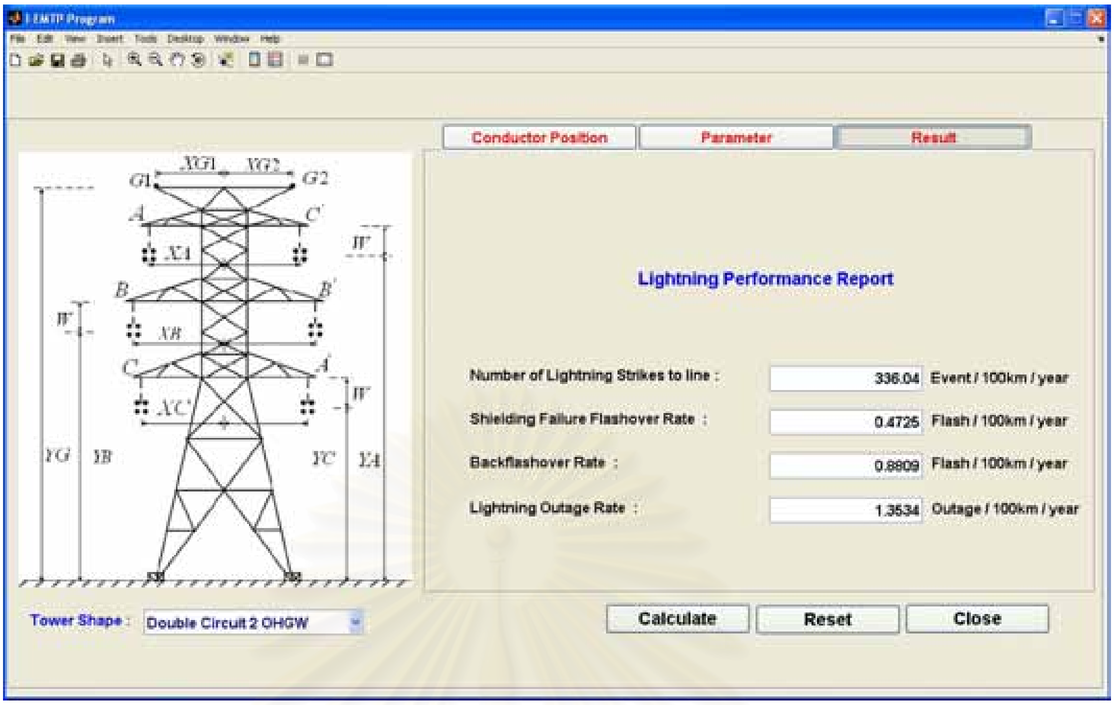


Figure 4.13 Output data tab

4.3 Verification of STPM Program

In this section, the validation of STPM program is verified. The SPTM program is implemented to compute the lightning performance of a double-circuit 345 kV transmission line. The calculation result is compared against the step-by-step solution presented in the reference [2] that applied almost the same procedure to compute the lightning performance. The parameters of tower configuration, system voltage, phase conductors, overhead ground wires and insulator are shown in appendix C. In this case study, it is assumed that the thunderstorm day is 30 days/year and the tower-footing resistance is 20Ω. The lightning outage rates of the double-circuit 345 kV transmission line calculated by the STPM program and the reference [2] are shown in Table 4.1.

From Table 4.1, we can see that the STPM program gives a little bit higher output. This is because the STPM program uses the top tower height for computing the number of lightning strikes to power line, while the reference [2] uses the average tower height. If the equivalent tower height is inputted to both methods, the closer results are obtained. The STPM program uses the top tower height to compute the number of lightning strikes to power line because it has been proposed that using tower height rather than average span height, would yield a more realistic estimation [5].

Table 4.1 Lightning performance of a double-circuit transmission line

Output	Method	
	Reference [2]	STPM program
Lightning incidence to a line $(flash/100km/year)$	72	74.25
Shielding failure flashover rate $(flash/100km/year)$	0.026	0.0233
Backflashover rate $(flash/100km/year)$	1.1	1.1825
Lightning outage rate $(outage/100km/year)$	1.126	1.2048

4.4 Comparison with Other Software Programs

In this section, the STPM program is compared with I-EMTP and TFlash programs that apply different methods to determine lightning performance. A 500 kV transmission line in Thailand shown in Fig. 4.14 is used for this comparison. The parameters of tower configuration, system voltage, phase conductors, overhead ground wires and insulator are based on the specification of EGAT as shown in Table B.1 and B.2 of appendix B. It is assumed that the thunderstorm day is 80 days/year and the tower-footing resistance is 10Ω. The lightning performance of the 500 kV transmission line is shown in Table 4.2 and Fig. 4.15.

Table 4.2 Lightning performance of a 500 kV transmission line

Output	Program		
	STPM	I-EMTP	TFlash
Lightning incidence to a line $(flash/100km/year)$	336	336	415
Shielding failure flashover rate $(flash/100km/year)$	0.475	0.473	0.439
Backflashover rate $(flash/100km/year)$	0.784	0.796	2.613
Lightning outage rate $(outage/100km/year)$	1.259	1.268	3.052

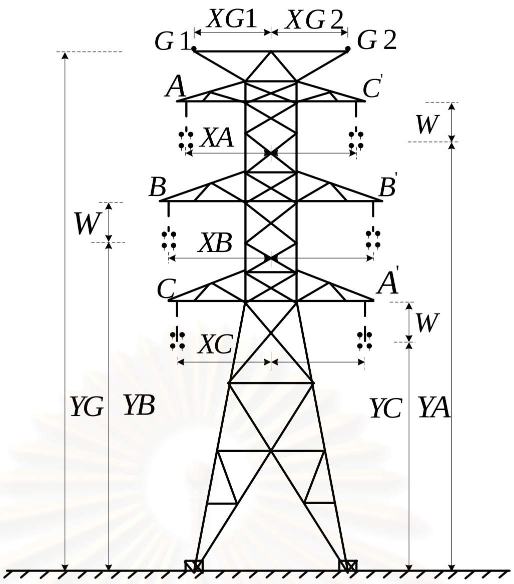


Figure 4.14 A tower configuration of 500 kV lines, type $DM\ (0^\circ - 3^\circ)$

The number of lightning incidence is the same for both STPM and I-EMTP programs because they use the same equation to calculate. The critical stroke current obtained from EMTP simulation also agrees with that obtained form simplified two-point method. This is because the components and parameters of power system are modeled closely with those used in SPTM program. As a result, the predicted values of shielding failure flashover and backflashover rates from I-EMTP program show matching trend with those from SPTM program. This suggests that SPTM program is a convenient way of estimating outage rate for lightning performance study of transmission lines because the users can do simply without the knowledge of power system modeling. However, it is expected that the detailed models and parameters of power system and lightning in EMTP simulation will give more accurate results.

In comparison with TFlash program, STPM program estimate a lower number of lightning incidence, nearly the same shielding failure flashover rate but a considerable lower backflashover rate. The considerable difference in backflashover rate can be attributed to the difference in CFO value. STPM and Tflash programs estimate the CFO values using different model, giving the CFO values as 3,634 kV and 2,473 kV, respectively. Therefore, TFlash program gives a lower critical stroke current.

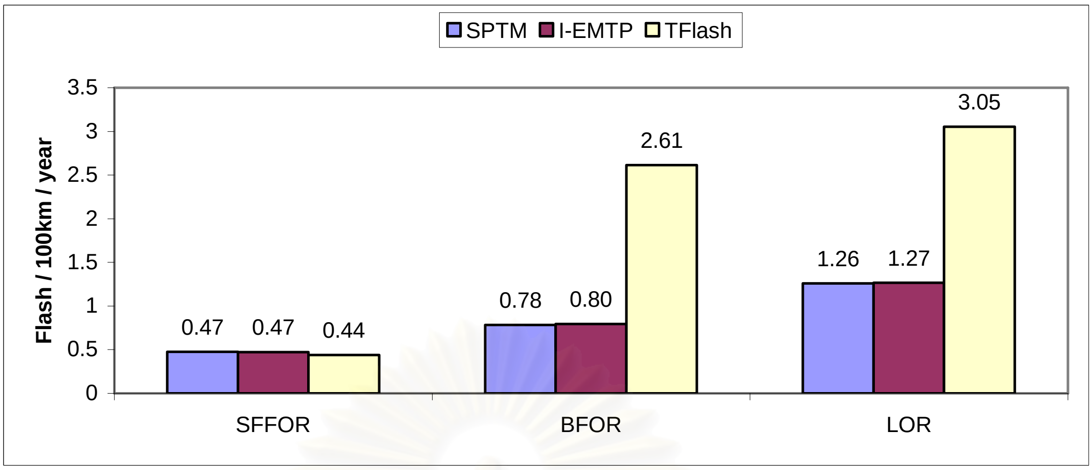


Figure 4.15 Comparison of lightning performance of a 500 kV transmission line obtained from different programs

If the STPM program and the TFash program use the same CFO (2,473 kV), they give quite similar results as shown in Fig. 4.16.

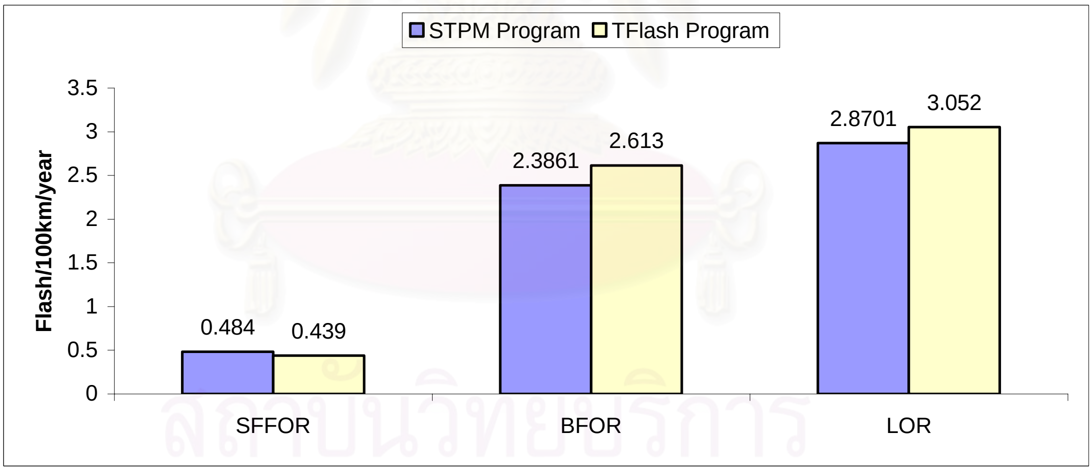


Figure 4.16 Comparison of lightning performance of a 500 kV transmission line obtained from STPM program and TFash program (CFO = 2473 kV)

CHAPTER V

PARAMETIC ANALYSIS

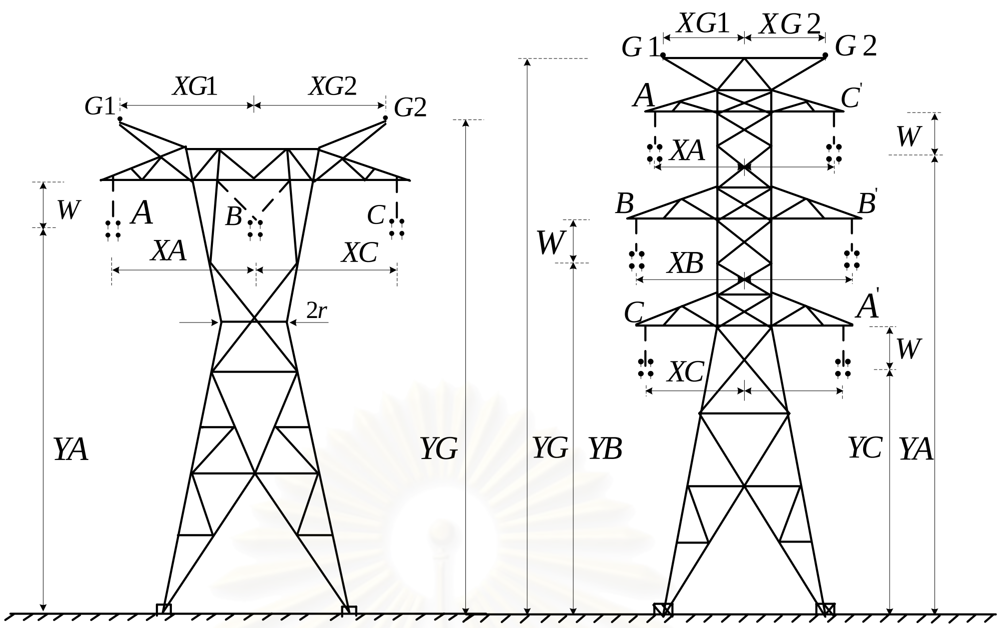
In this chapter, the STPM programs is implemented to study the effects of many parameters which influence the lightning outage rate of overhead transmission lines, i.e. tower configuration, tower footing resistance, shielding angle, insulation level, ground flash density and stroke current distribution. Table 5.1 shows the data used as the base case for parametic analysis.

Table 5.1 Data of base case for parametic analysis

Tower configuration	Type $SLV\,(0^\circ - 3^\circ)$
Tower footing resistance	$10\,\Omega$
Shielding angle	19.88°
Insulation level	$4.42\ m$
Ground flash density	$9.6\ Flash/km^2/year$ (or $80\,Days/year$)
Stroke current distribution	$P_I = \dfrac{1}{1+\left(\dfrac{I}{31}\right)^{2.6}}$

5.1 Effect of Tower Configuration

Fig. 5.1 shows two typical tower configurations of 500 kV transmission lines used in Thailand used in this study. Parameters of tower configuration, system voltage, phase conductors, overhead ground wires and insulator are based on the specification of EGAT as shown in Table B.1 and B.2 of appendix B. The calculated lightning performance of both typical tower configurations is shown in Table 5.2.



(a) Type $SLV\,(0^\circ - 3^\circ)$ (b) Type $DM\,(0^\circ - 3^\circ)$

Figure 5.1 A typical tower configuration of 500 kV lines

Table 5.2 Lightning performance report of tower types $SLV\,(0^\circ - 3^\circ)$ and $DM\,(0^\circ - 3^\circ)$

Output	Tower configuration	
	$SLV\,(0^\circ - 3^\circ)$	$DM\,(0^\circ - 3^\circ)$
Lightning incidence to a line ($flash/100km/year$)	284.82	336.04
Shielding failure flashover rate ($flash/100km/year$)	0.0000	0.4749
Backflashover rate ($flash/100km/year$)	0.4779	0.7837
Lightning outage rate ($outage/100km/year$)	0.4779	1.2586

It is found that the lightning outage rate of tower type $DM\,(0^\circ - 3^\circ)$ is higher than that of tower type $SLV\,(0^\circ - 3^\circ)$. This is because some characteristics of tower type $DM\,(0^\circ - 3^\circ)$ is inferior such as

1) The tower is higher, resulting in higher incidence of lightning strokes.

2) Effective shielding angle is smaller (Unprotected area is larger), resulting in higher shielding failure.

3) The coupling factor is smaller, resulting in the lower induced voltage on the phase conductor. As a result, the voltage across the insulator string, which is the potential difference between tower voltage and phase conductor voltage, become higher.

5.2 Effect of Tower Footing Resistance

When the lightning strikes on tower top, a portion of the stroke current travels down the tower. The remainder passes out along the overhead ground wires. The initial fractions along these two paths are determined by their relative surge impedances. The tower current flows to earth at the base of the tower through the tower footing resistance as shown in Fig 5.2. The resultant voltage drop and the magnitude of the voltage wave reflected back up the tower, depending directly on the value of the footing resistance encountered by the current. The voltage stress across the insulator strings is the difference between the tower voltage and the instantaneous value of the voltage of the phase conductors. A sufficiently high voltage stress may result in backflashover. Since the tower voltage is highly dependent on the footing resistance, the footing resistance is an extremely important factor in determining lightning performance.

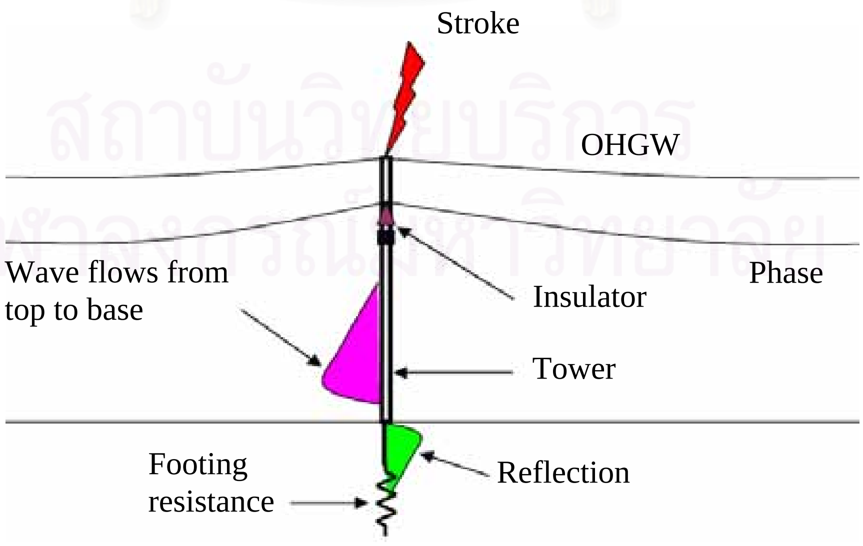


Figure 5.2 Reflection of tower footing resistance

In this study, the tower footing resistance is varied from 5Ω to 50Ω with a step of 5Ω. The calculation result is shown in Fig. 5.3. It seems that the backflashover rate increases proportionally to the increase in tower footing resistance. Therefore, the reduction in tower footing resistance is a way to control lightning outage rate of transmission lines.

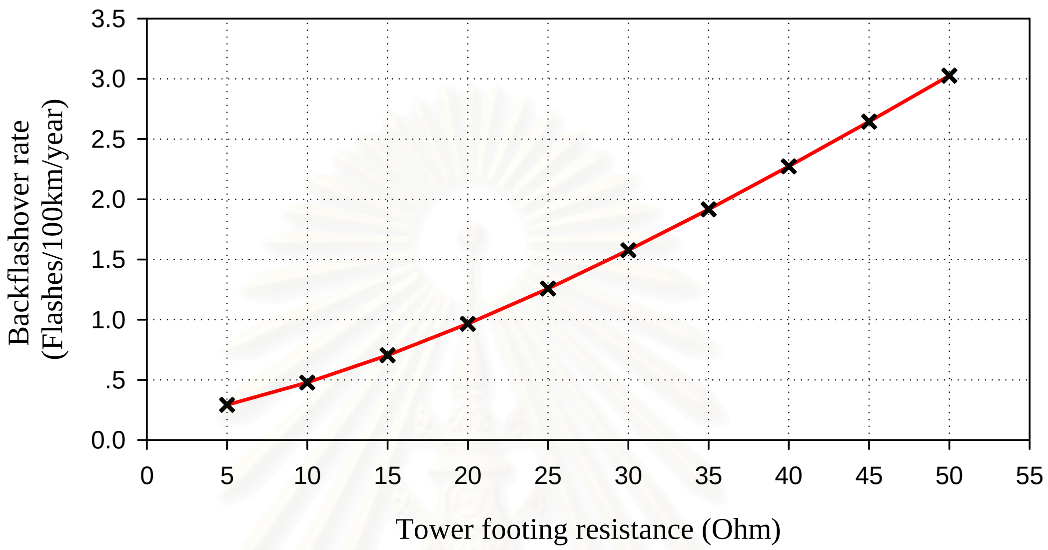


Figure 5.3 Effect of tower footing resistance

5.3 Effect of Shielding Angle (OHGW Position)

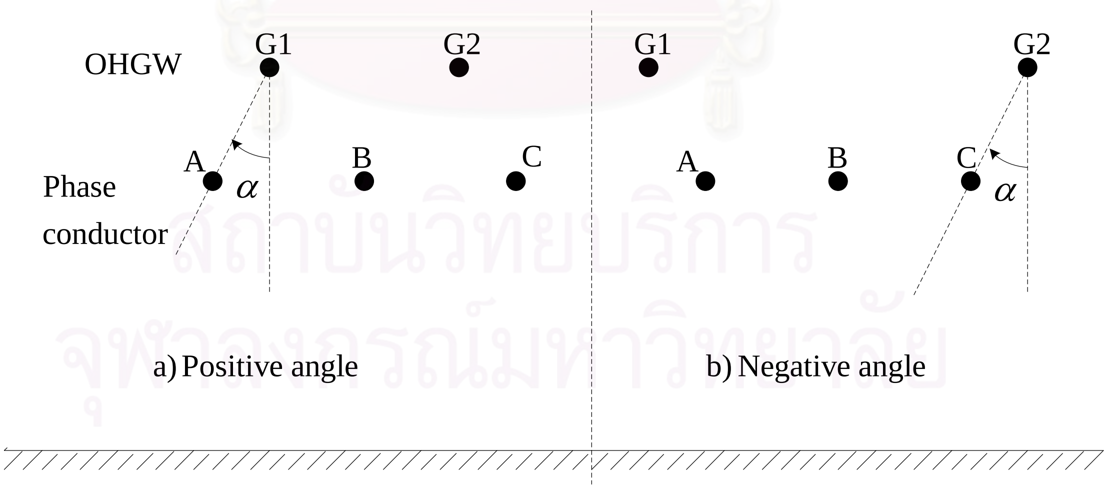


Figure 5.4 Definition of physical shielding angle

One important task of transmission line designer is to locate the OHGWs. Well-planned geometry will reduce the probability of lightning striking the phase conductors to an acceptable level. The proper placement of the OHGW around the phase conductors is usually defined by the physical shielding angle, as shown in Fig. 5.4. The physical shielding angle is negative if the OHGWs are horizontally disposed outside the phase conductors.

The placement of OHGW position is necessary because it can help to reduce the shielding failure flashover rate of overhead transmission lines. In this study, the OHGW position is varied in horizontal direction. The result of study is shown in Fig. 5.5 to Fig. 5.7. The OHGW position is the distance from the center of tower. From Fig. 5.5, it can be seen that OHGW position involves with the number of lightning strikes. A suitable OHGW position can reduce the physical shielding angle (see Fig. 5.6), resulting in the decrease of shielding failure flashover rate (See Fig. 5.7).

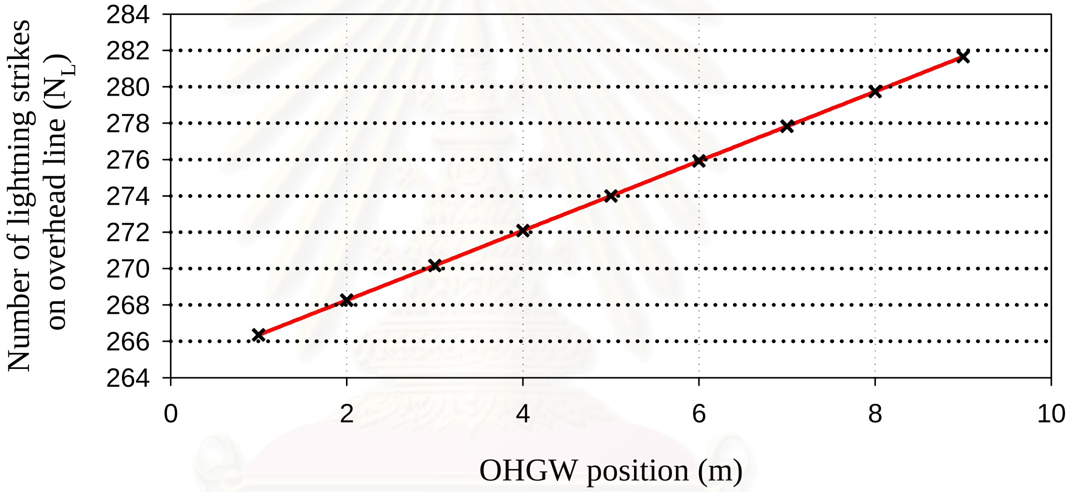


Figure 5.5 Effect of OHGW position on the number of lightning strikes on line

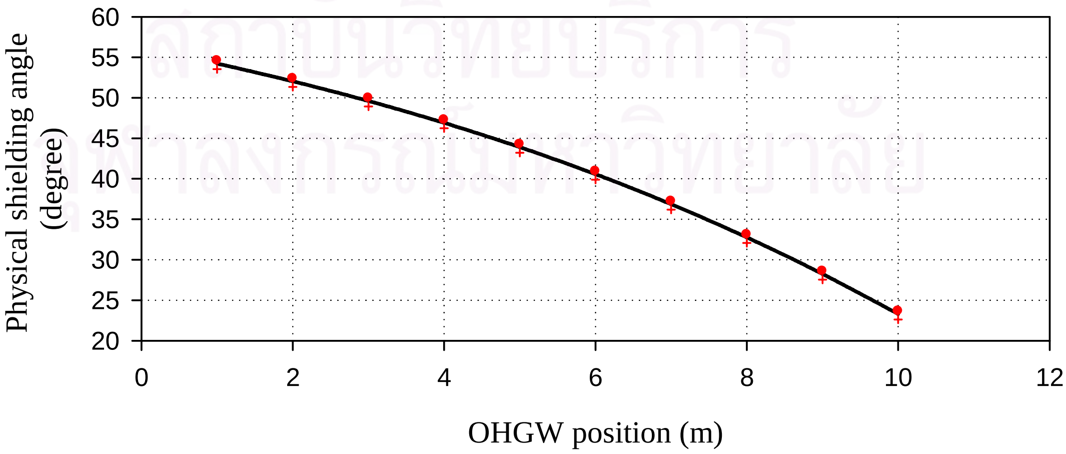


Figure 5.6 Effect of OHGW position on physical shielding angle

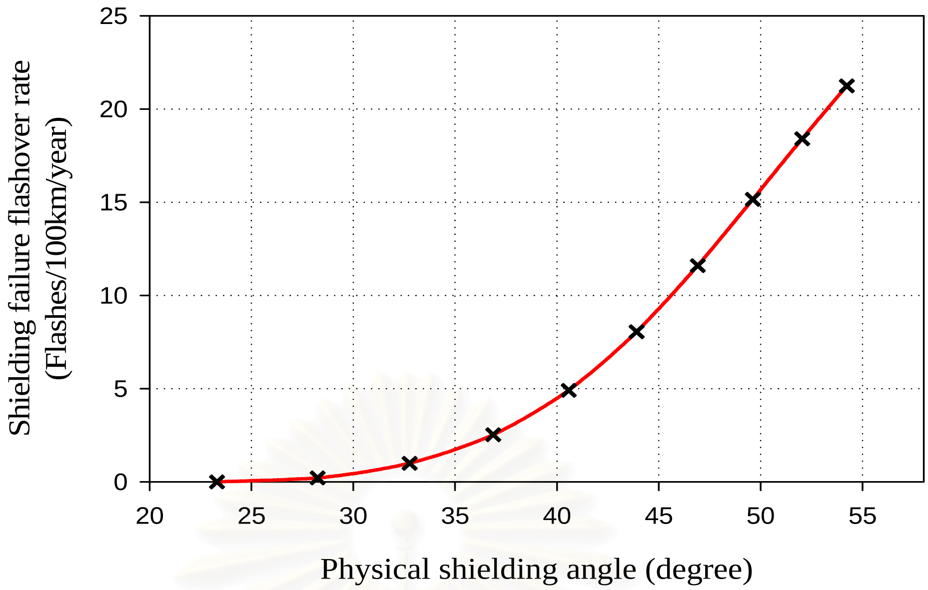


Figure 5.7 Effect of physical shielding angle on SFFOR

5.4 Effect of Insulation Level

Breakdown characteristic of the insulator is one of the main factor that can affect lightning performance of overhead transmission lines. This characteristic depends on insulator length (the number of insulator disk). The number of standard disk insulator (146 mm x 254 mm) [4] used in typical insulator string for 500 kV system voltage is about 22 disks to 28 disks (3.212 m – 4.088 m). Therefore, in this study, the insulator length is varied from 3.2 m to 4.4 m with a step 0.2 m. The effect of the insulator length is shown in Fig. 5.8 and Fig. 5.9.

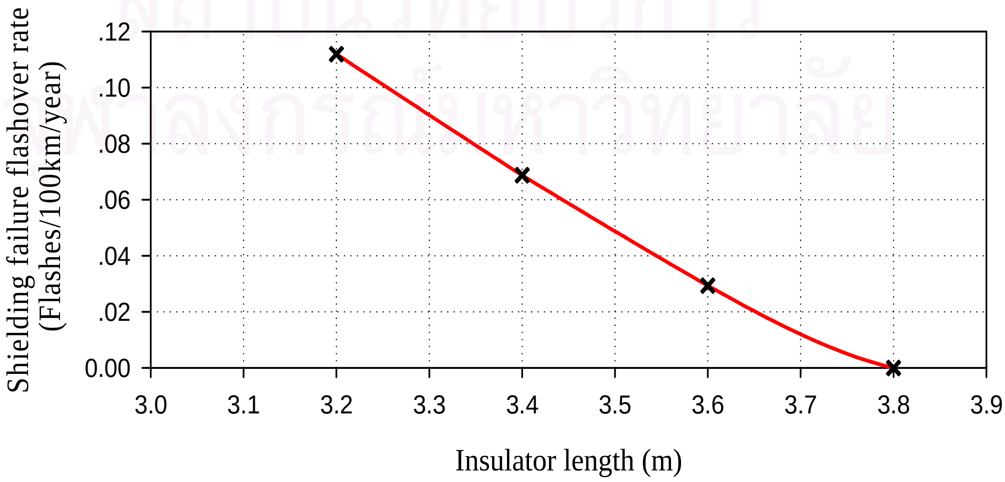


Figure 5.8 Effect of insulator length on SFFOR

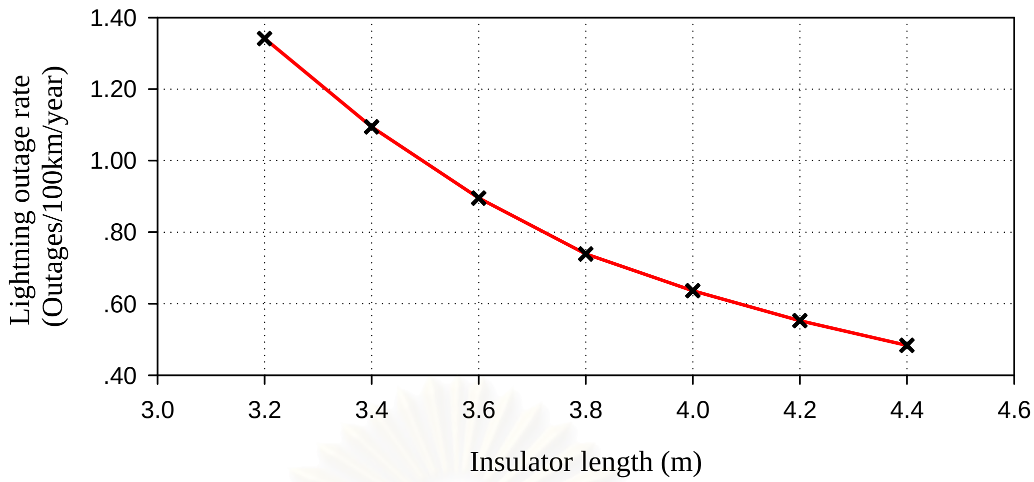


Figure 5.9 Effect of insulator length on lightning outage rate

From Fig. 5.8, the shielding failure rate decreases rapidly with increasing insulation level or insulator length. The lightning outage rate also decreases with increasing insulation level or insulator length as shown in Fig. 5.9. Therefore, it is a choice for improvement of lightning performance of overhead lines. However, the side effect from increasing insulation level such as insulation coordination should be considered and investigated.

5.5 Effect of Ground Flash Density

The ground flash density (N_g) is an important parameter that has an effect on lightning performance of transmission lines. This parameter is normally defined by the thunderstorm days per year (T_d) from record data and statistics as shown in Fig. 5.10.

From Fig. 5.10, we can see that the thunderstorm days per year in the world are different in each geography. This information is very important for calculating ground flash density. Many researchers have proposed the equations to calculate ground flash density as follows:

According to [2], the ground flash density is given by

$$N_g = 0.12T_d \tag{5.1}$$

According to [5], the ground flash density is given by

$$N_g = 0.04T_d^{1.25} \tag{5.2}$$

According to [6], the ground flash density is given by

$$N_g = 0.04T_d^{1.35} \tag{5.3}$$

According to the collection data of Electricity Generating Authority of Thailand (EGAT) [17], the ground flash density is given by

$$N_g = 6.5\times10^{-5}T_d^{2.277} \tag{5.4}$$

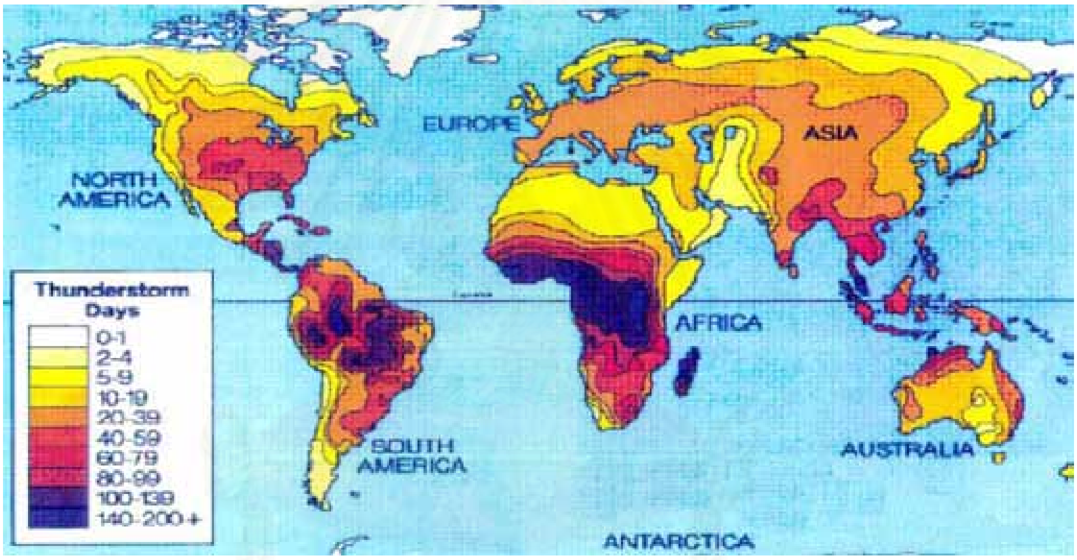


Figure 5.10 Thunderstorm days per year (Td) in the world

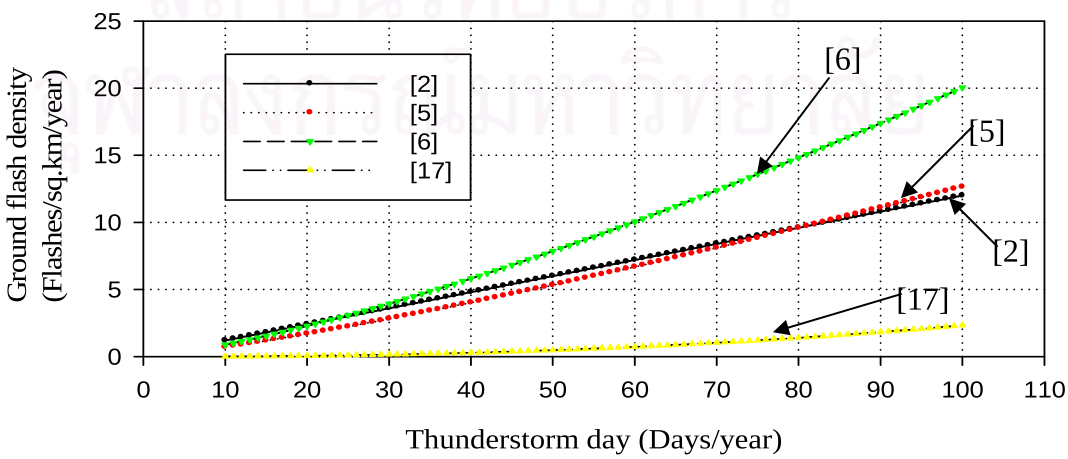


Figure 5.11 Ground flash density as a function of thunderstorm day

Fig. 5.11 shows the comparison of ground flash density obtained from equations (5.1)-(5.4). The effect of ground flash density obtained from different equations is shown in Fig. 5.12.

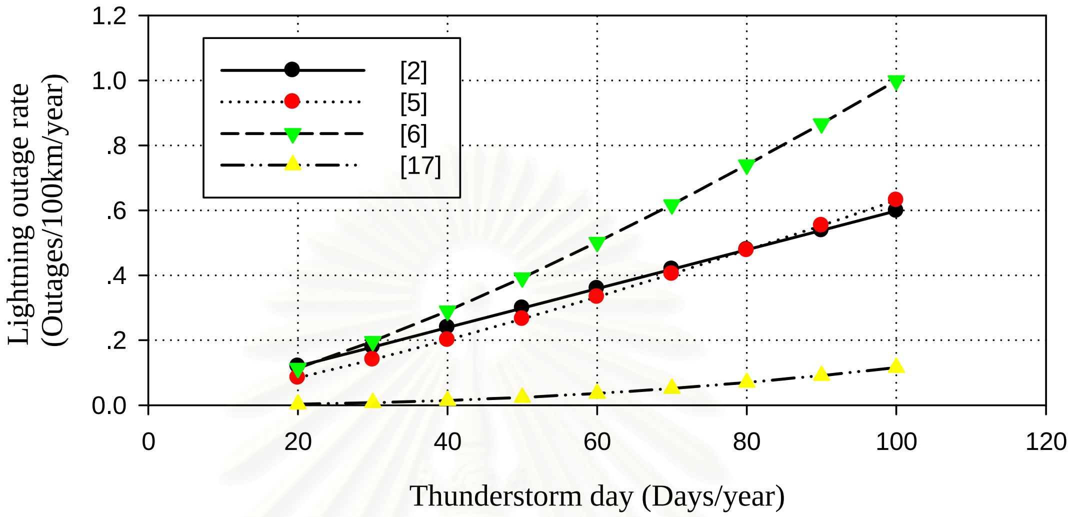


Figure 5.12 Lightning outage rate as a function of thunderstorm day

From Fig. 5.11 and Fig. 5.12, we can see that the high ground flash density results in high number of lightning strikes and high lightning outage rate. Therefore, one important thing that should be considered is the equation to compute the ground flash density. From the comparative results of lightning performance presented in Fig. 5.11 and Fig. 5.12 using equations (5.1), (5.2), (5.3) and (5.4), it can be summarized as follows:

1) The calculated results calculated by equation (5.4) show the considerable low values of both the ground flash density and lightning outage rate.

2) If the thunderstorm day is less than $40\, Days/year$, equations (5.1), (5.2) and (5.3) give the similar ground flash density, resulting in the similar lightning outage rate.

3) If the thunderstorm day is greater than $40\, Days/year$, equations (5.1) and (5.2) still give the similar ground flash density, resulting in the similar lightning outage rate. In contrast, equation (5.3) gives the highest ground flash density and the highest lightning outage rate. For example, if $T_d = 100\, Days/year$, using equation (5.1) or (5.2) to determine ground flash density gives the lightning outage rate of about one-half in comparison with using equation (5.3).

Therefore, in the area with high lightning activity like Thailand, the actual data of ground flash density is important for estimating lightning performance of transmission lines.

5.6 Effect of Stroke Current Distribution

The severity of lightning stroke current is its magnitude. This value is normally defined by the probability distribution of stroke current as described in section 2.1.4 of chapter 2. In lightning performance estimation, the exact value of this parameter is required. There are many researchers who collected the lightning data and proposed the probability distribution function of stroke current magnitude in the form of cumulative probability distribution function as shows in Table 5.3. This function (P_I) is the probability that the magnitude of lightning current will exceed the value I .

Table 5.3 Summary the equations of the probability

Reference	Equations
CIGRE guidelines [3]	$P_i = 1 - 0.31e^{\frac{-z^2}{1.6}}$ for $3 < I < 20kA$ $P_i = 0.50 - 0.35Z$ for $20 < I < 60kA$ $P_i = 0.278e^{\frac{-z^2}{1.7}}$ for $60 < I < 200kA$
Anderson –Eriksson [2]	$P_i = \dfrac{1}{1+(I/31)^{2.6}}$
Thailand data [17]	$P_i = \dfrac{1}{1+(I/40)^{3.09}}$

Where Z is , as before,

$$Z = \frac{\ln(I/M_I)}{\beta_I} \tag{5.5}$$

Where $I < 20kA,\ \ M_I = 61.1kA,\ \ \beta_I = 1.33$

$$I > 20kA, \quad M_I = 33.3kA, \quad \beta_I = 0.605$$

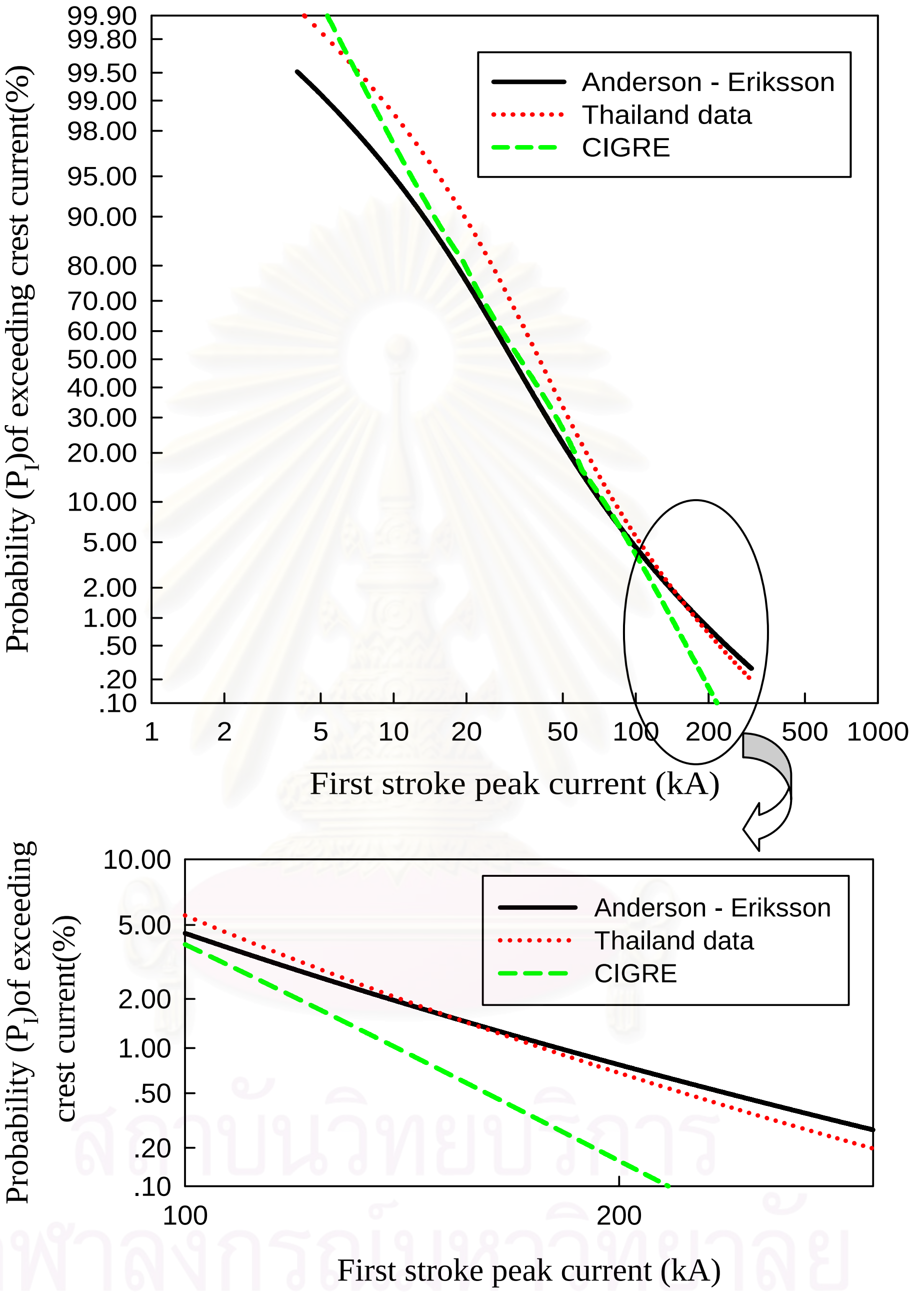


Figure 5.13 Comparison of cumulative probability distribution of stroke current

Fig. 5.13 shows the plot of cumulative probability distribution of stroke current magnitude. It reveals that the lightning current in Thailand shows a tendency to have higher magnitude than others. Figure 5.14 shows the lightning outage rates obtained from the calculation with different cumulative probability distribution function. The critical stroke current required to cause backflashover is about 280 kA in this case. As shown in Fig. 5.13, Anderson – Eriksson equation shows the highest probability that the magnitude of lightning current will exceed 280 A, resulting in the highest lightning outage rate. On the other hand, the equation of CIGRE guidelines shows very low probability the magnitude of lightning current will exceed 200 A. Therefore, the lightning outage rate obtained by using this probability function is very low.

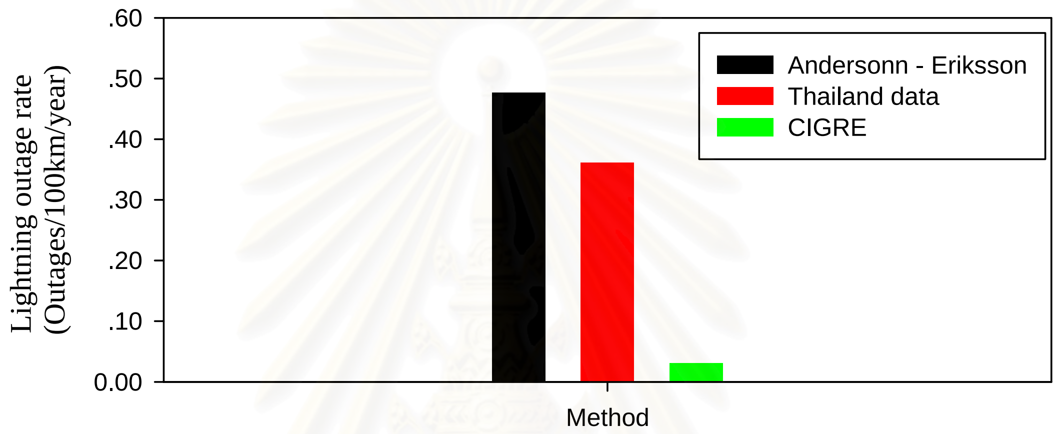


Figure 5.14 Effect of probability distribution of lightning current on lightning outage rate

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis concerns with the development of software programs for estimation of lightning outage rate of overhead transmission lines. There are many complicate and statistical parameters which involved in computation. Therefore, a simplified method and/or simulation method is required for convenient solution.

This thesis consists of six chapters. Chapter 1 gives the over view of this project. It presents the objective and benefit of this project as well as the research procedure.

Chapter 2 described the general theories of the lightning parameters, number of lightning strikes to power line, circuit elements involved in computation of flashover performance, shielding failure computation, backflashover computation. The Electromagnetic Transient Program (EMTP) is also introduced for using in simulation. Many models of elements in power system such as transmission line, tower and insulator are explained.

Chapter 3 presents the structure of two software programs for the evaluation of lightning performance of transmission lines. Procedures for calculating critical lightning current required to cause flashover are spilt into two groups, i.e. the method based on simplified two-point method proposed by EPRI and the method bases on EMTP simulation. Therefore, they are named as STPM and I-EMTP programs, respectively. Both software programs have the same procedure for calculation of flashover rate.

Chapter 4 explains the user manual of both programs. The verification of both programs was done by comparison against the result obtained from a reference book and also comparison against a commercial program, TFlash. The STPM program is easy to use without in-depth knowledge of the details and methodologies for estimating lightning outage rate of overhead transmission lines. The I-EMTP program is expected to give more accurate result, but the procedure is complicate because the user must model the power system to simulate the critical lightning current. Moreover, the used models may have effects on the result.

Many parameters which influence the lightning outage are studied in chapter 5 using the STPM program. The results can be summarized as follows:

1) Tower configuration: Tower high and conductor position have effects on the lightning outage rate.
2) Tower footing resistance: this factor is a very important parameter which affects the backflashover rate. The increasing tower footing resistance will increase backflashover.
3) Insulation level: The increase in insulation level or number of insulator can reduce the lightning outage rate.
4) OHGW position: the placement of OHGW position is a very important choice in the improvement of lightning performance, because it has an effect on shielding angle.

6.2 Recommendations for Future Works

The software program developed by using a simplified two-point method is very useful tool for estimating lightning performance. In this software program, some parameters are simplified or not considered. Thus, for more accurate results, the future works that can improve the software program are:

1. Improvement of the tower model
2. Improvement of the tower footing resistance model
3. Improvement of the insulator voltage breakdown model
4. Adding more the tower configurations
5. Comparison of the result with the field data of overhead transmission lines

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APPENDICES

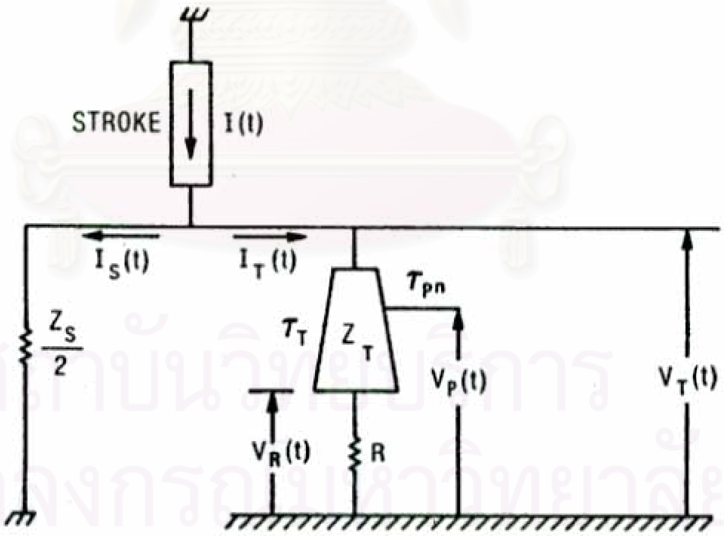
Appendix A

A.1 Derivation of the Fundamental Traveling Wave Equation for Tower Top Voltage

The equivalent circuit in the development of tower top voltage due to a flash to the tower is shown in Fig A.1. Before deriving the traveling wave equation for $V_T(t)$, the classical current reflection and refraction coefficient off the tower top and the tower base must be defined as following:

$$\beta_R = \frac{Z_T - R}{Z_T + R} \tag{A.1.1}$$

$$\beta_S = \frac{2Z_T - Z_S}{2Z_T + Z_S} \tag{A.1.2}$$



$Z_s / 2$ = combined shield wire surge impedances

Z_T = tower surge impedance

R = tower footing resistance

$I(t)$ = stroke current source

$V_T(t)$ = tower top voltage to earth at a select time t

τ_T = travel time for a current wave to travel from the tower top to its base

$V_R(t)$ = footing resistance voltage

τ_{pn} = travel time from the tower top to a tower crosssarm n

$V_p(t)$ = crossarm voltage to ground

Figure A.1 Equivalent circuit for calculating tower top voltage

And

$$\alpha_T = \frac{4Z_T}{Z_S + 2Z_T} \quad \text{(A.1.3)}$$

Where β_R is the portion of a current wave traveling down the tower that is reflected toward the tower top

β_S is the portion of an upward traveling current wave in the tower that is reflected toward to the tower base from the top

α_T is the portion of an the combined shield wire surge impedance

In intrinsic impedance Z_I which is the impedance any element of stroke current encounters the instant it reaches the tower top, also needs to be defined. This impedance is parallel combination of the tower impedance Z_T and the net shield wire surge impedance $Z_S/2$ or

$$Z_I = \frac{Z_S Z_T}{Z_S + 2Z_T} \quad \text{(A.1.4)}$$

Finally. A stroke current refraction coefficient needs to be defined. It is

$$\delta_T = \frac{Z_S}{Z_S + 2Z_T} \quad \text{(A.1.5)}$$

Where δ_T is the portion of the total stroke current $I(t)$ that enters the tower top and starts its trip toward the base (the remainder travels out the shield wire). At any selected time t, the stroke current $I(t)$ entering the intrinsic impedance Z_I creates a component $V_I(t)$ of voltage at the tower top such that

$$V_I(t) = Z_I I(t) \tag{A.1.6}$$

At the same instant that $V_I(t)$ is being created, another component $V_I(t)$ is also being created at the tower top. This component is due to the current that entered the tower at a previous time $t-2\tau_T$. This current traveled down to the base, reflected off R and arrived back at the tower top at time t where a portion of it enters $Z_S/2$ creating the voltage component $V_I(t)$ from tower top to ground. The magnitude of this component of current entering $Z_S/2$ is

$$I(t-2\tau_T)\delta_T\beta_R\alpha_T$$

Therefore,

$$V_1(t) = -I(t-2\tau_T)Z_S\delta_T\beta_R\alpha_T / 2 \tag{A.1.7}$$

The negative sign is necessary, because if the current entering the tower indicated positive on an ammeter, then the current arriving back at the tower top enters the opposite and of the ammeter and drives it in the opposite direction.

Depending on time, another component $V_2(t)$ will appear owing to the current that entered the tower top at a previous time $t-4\tau_T$. This component made two round trip down and up the tower, finally refracting into $Z_S/2$ exactly at time t. This component may be written as

$$V_2(t) = -I(t-4\tau_T)Z_S\delta_T\beta_R^2\beta_S\alpha_T / 2 \tag{A.1.8}$$

If the stroke current existed at a previous time $t-6\tau_T$, then a three round trip component of voltage may exist and it is

$$V_3(t) = -I(t-6\tau_T)Z_S\delta_T\beta_R^3\beta_S^2\alpha_T / 2 \qquad \text{(A.1.9)}$$

The simultaneous arrival of these components can perhaps be best visualized by tracing all their flight paths directly on a ramp function, stroke current wave feeding into the top of the equivalent circuit as shown in Fig A.3. Only seven components may exist in this example for this time t. The history of the current component that entered the equivalent circuit at a time $t-6\tau_T$ is traced in equation (A.3) through (A.9) until one reaches the origin of the current wave. At that point, the summation must end. These component may then be written as summation equation:

$$V_T(t) = V_0(t) + V_1(t) + V_2(t) + ... + V_n(t)$$

Or

$$V_T(t) = Z_I I(t) - \frac{Z_S}{2}\delta_T\beta_R\alpha_T\sum_{n=1}^{N} I(t-2n\tau_T)(\beta_R\beta_S)^{n-1} \qquad \text{(A.1.10)}$$

However, $\frac{Z_S}{2}\delta_T\beta_R\alpha_T$ has dimension of impedance and it may be reduced to an equivalent impedance Z_w where

$$Z_w = [\frac{2Z_S^2Z_T}{(Z_S+2Z_T)^2}][\frac{Z_T-R}{Z_T+R}] \qquad \text{(A.1.11)}$$

A term φ may be defined as the coupling factor for the waves and it may be equated to $\beta_R\beta_S$. Thus

$$\varphi = \beta_R\beta_S$$

Or

$$\varphi = \left(\frac{2Z_T - Z_S}{2Z_T + Z_S}\right)\left(\frac{Z_T - R}{Z_T + R}\right) \tag{A.1.12}$$

The fundamental equation for tower top voltage is then

$$V_T(t) = Z_I I(t) - Z_w \sum_{n=1}^{N} [I(t - 2n\tau_T)\varphi^{n-1}] \tag{A.1.13}$$

A.2 Traveling Wave Equation for the Voltage at The Tower Base

Referring to Fig A.1 in Appendix A.1, the conventional assumption is made that the surge impedance per unit length is constant at any point on the tower. Appendix A.1 made use of current components, but in this derivation, voltage components are used for simplicity because the signs of the components will be less confusing. The tower voltage reflection coefficients are defined as

$$\bar{\beta}_R = \frac{R - Z_T}{Z_T + R} \tag{A.2.1}$$

And

$$\bar{\beta}_S = \frac{Z_S - 2Z_T}{Z_S + 2Z_T} \tag{A.2.2}$$

A voltage refraction coefficient $\bar{\alpha}$ must also be defined. It represents the proportion of a downward traveling voltage wave that appear across the footing resistance R:

$$\bar{\alpha} = \frac{2R}{Z_T + R} \tag{A.2.3}$$

If one draws the lattice diagram and goes through the procedure of tabulating voltage components appearing across R, in a manner similar to that done in Appendix A.1, the voltage $V_R(t + \tau_T)$ across the fooling resistance becomes

$$V_R(t+\tau_T) = \bar{\alpha}_R Z_I I(t) + \bar{\alpha}_R Z_I I(t-2\tau_T)\varphi + \ldots + \bar{\alpha}_R Z_I I(t-2N\tau_T)\varphi^N \quad \text{(A.2.4)}$$

And using summation sign

$$V_R(t+\tau_T) = \bar{\alpha}_R Z_I \sum_{n=0}^{N} I(t-2n\tau_T)\varphi^n \quad \text{(A.2.5)}$$

Where

$$Z_I = \frac{Z_S Z_T}{Z_S + 2Z_T}$$

$$\varphi = \bar{\beta}_R \bar{\beta}_S$$

N is the largest whole number $\leq \dfrac{t}{2\tau_T}$

Appendix B

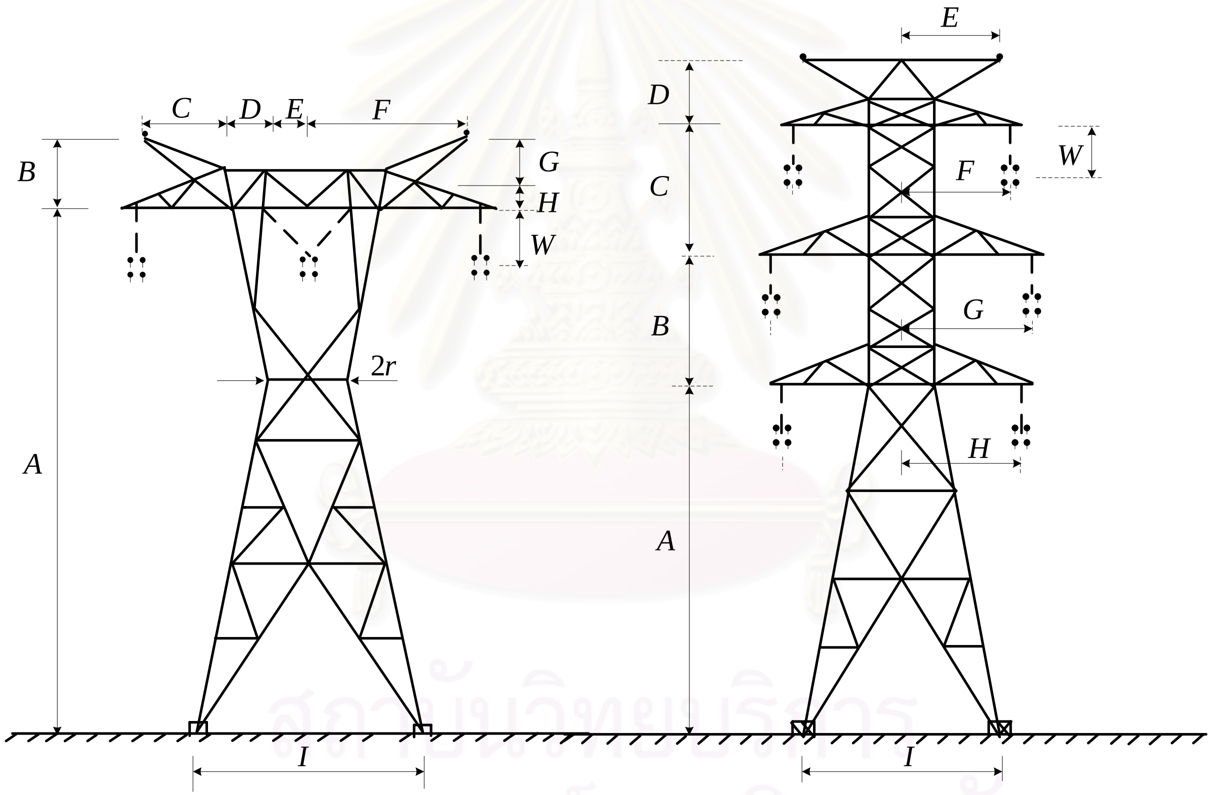


Figure B.1 A typical tower configuration of 500 kV lines (all dimension in meters)

Table B.1 Tower configuration

Nam No.	System voltage	Tower type	Number and size of conductor per phase	A	B	C	D	E	F	G	H	I
1	500kV	$DM\ (0^{\circ}-3^{\circ})$	4x1272 MCM ACSRGA	38.4	11.0	11.0	5.0	6.60	8.14	10.24	11.34	16.18
2	500kV	$SLV\ (0^{\circ}-3^{\circ})$	4x795 MCM ACSRGA	40.4	5.0	6.8	2.7	4.55	10.65	4.17	1.44	9.46

Table B.2 Insulator string and sag

Nam No.	System voltage (kV)	Tower type	Number and size of conductor per phase	Insulator string length W (m)	Bundle spacing (mm)	Sag conductor (m)	Sag OHGW (m)	Rating span length (m)
1	500	$DM\ (0^{\circ}-3^{\circ})$	4x1272 MCM ACSRGA	4.429	457	15.7	10.4	390
2	500	$SLV\ (0^{\circ}-3^{\circ})$	4x795 MCM ACSRGA	4.429	457	18.5	12.3	490

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Appendix C

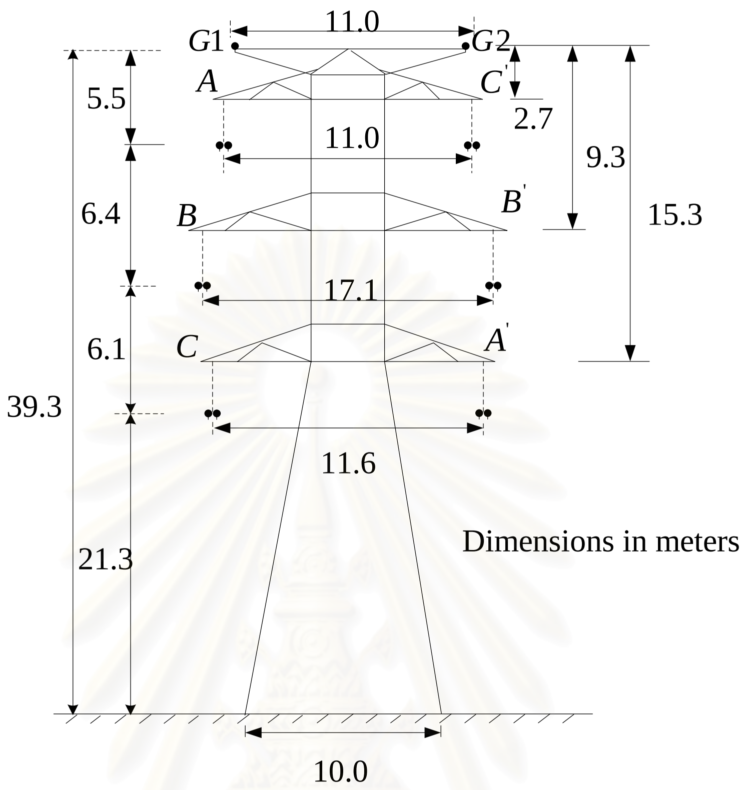

Figure C.1 345 kV, vertical double circuit, two overhead ground wire

Table C.1 Conductor positions and conductor parameters

Conductor	Function	Phase coordinates		Conductor	Bundle	Operating	Phase angle
No		X(m)	Y(m)	radius(cm)	spacing(cm)	p-p(kV)	degree
1	shielding	-11	63.9	0.4572	-	0	-
2	shielding	11	63.9	0.4572	-	0	-
3	A	-9.6	52.9	1.386	45.7	500	0
4	B	-9.8	41.9	1.386	45.7	500	-120
5	C	-10	30.9	1.386	45.7	500	120
6	C'	9.6	52.9	1.386	45.7	500	120
7	B'	9.8	41.9	1.386	45.7	500	-120
8	A'	10	30.9	1.386	45.7	500	0

OHGW and Phase conductor sags: 7.0 m; Span distance: 335 m

BIOGRAPHY

Somvang Tipphavongxay was born on 13 April in 1981 Xiengkhouang province, Lao P.D.R. After graduating in 2005 from the Department of Electrical Engineering, Faculty of Engineering, National University of Laos (NUOL), he worked as assistance lecturer in the field of electrical power in 2005-2006 and his continue studying in Master of Electrical Engineering, Department of Electrical Engineering, Chulalongkorn University, Thailand in 2006-2008 under the AUN/SEED-Net scholarship program.