LIGHTNING SIMULATION STUDY ON LINE SURGE ARRESTERS AND PROTECTION DESIGN OF SIMPLE STRUCTURES

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ABSTRACT

There was a recent incidence where a direct lightning strike on the earth shielding conductor of a 275/132kV quadruple circuit transmission line had caused the breakage of the conductor at four points. Three short conductors connecting the line arrester installed on the 132kV line were not affected. The location of the affected arrester was not at the nearest tower to the point of strike but at the adjacent tower. The arresters at the nearest tower were not affected. This phenomenon was studied using ATP-EMTP simulation. Transmission tower is modeled according to the multi storey tower proposed by Masaru Ishii which was validated through theory and calculation. Simulation results show that the phenomenon cannot be conclusively reproduced within the ATP-EMTP simulation. Study indicating the fact that the phenomenon may be a one-off special case event. Overhead line is modeled by applying the PI subroutine file. This project also study the protection of simple structures from lightning strikes. The most common and simplest form of lightning protection is by using a vertical rod which has the function of intercepting a lightning stroke before it can strike a nearby object it is protecting, and then discharging the current to ground. In this simulation study, 1500 strokes were applied in a square plot ground area of 1km^2 and the number of flashes to ground per square kilometer per year (Ng) is 15 strokes/ km^2/year. A Monte-Carlo technique is used to manipulate the statistical distribution of lightning strokes. The program is written in C-language using MATLAB simulation.

ABSTRAK

Baru-baru ini, satu kejadian telah berlaku di mana panahan petir pada talian bumi, talian penghantaran atas 275/132kV litar berkembar empat (quadruple circuit) telah menyebabkan talian bumi terputus kepada empat bahagian. Penangkap kilat pada bahagian bawah talian 132kV pada menara talian penghantaran yang berdekatan tidak berfungsi, sebaliknya penangkap kilat pada menara bersebelah yang berfungsi. Menara penghantaran dimodel berdasarkan kepada model bertingkat yang dicadangkan oleh Masaru Ishii. Model disahkan melalui kiraan dan teori. Keputusan daripada simulasi kajian yang dijalankan tidak dapat membuktikan kejadian ini berlaku melalui ATP-EMTP. Aturcara Simulasi ATP-EMTP telah digunakan dalam mengkaji panahan petir terhadap litar berkembar empat. Talian atas dimodelkan dengan menggunakan model PI yang sedia ada dalam EMTP. Simulasi menunjukkan fenomena di atas tidal dapat ditunjukkan melalui simulasi dan ia mungkin merupakan kes terpencil. Projek ini juga mengkaji perlindungan daripada struktur yang mudah terhadap panahan kilat. Struktur yang asas dan mudah untuk perlindungan petir ialah dengan menggunakan rod tegak dimana ia berfungsi memintas penahan petir sebelum ia memanah kawasan sekitar yang dilindungi dan kemudian menyahcas arus ke bumi. Untuk kajian simulasi ini, 1500 panahan telah dikenakan pada segiempat sama yang berukuran 1km^2 panjang dan lebar kawasan bumi. Bilangan panahan ke bumi per km^2 per tahun (Ng) adalah sebanyak 15 panahan. Teknik Monte-Carlo telah digunakan untuk manipulasi statistik taburan panahan petir. Program ini menggunakan bahasa C dalam Simulasi MATLAB.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Introduction

High overvoltage transients caused by lightning is considered a major source of disturbances in high voltage transmission line systems. There is a consensus that lightning starts from the charge separation process (positive and negative), which is due to transportation of lightweight particles to higher regions by the rapid updrafts of moist air, usually in hot humid areas. This charge separation is known as the vertical thunderstorm dipole. It can be performed within the cloud or between the cloud and the earth which creates electric fields that eventually bring out the breakdown known as *lightning*. The overvoltage introduced by lightning have traditionally been estimated using conventional and simplified methods. More involved calculations become possible with digital computer programs such as Electromagnetic Transients Program (EMTP). In such a program, each power system component can be modelled in great detail.

The characteristics of lightning surges on overhead transmission lines, which result from lightning strokes, depend on how there are caused. They can be broadly divided into four types:

a) Tower/ground wire surge - The stroke terminates on the tower structure/ground wires without any flashover to the phase conductors.
b) Shielding failure - The stroke passes through the protective zone of the ground wires and terminates on the phase conductors.
c) Back flashover - The same as a), but followed by a flashover to the phase conductors. This type of flashover is called back flashover.
d) Shielding failure flashover – The same as b), but followed by a forward flashover to the ground/ground wires or tower.

1.2 Problem Statement

Part 1: Lightning Simulation Study on Line Surge Arresters.

A recent incidence from direct lightning strike on the shielding conductor of a 275/132kV quadruple circuit transmission line had caused the breakage of the conductor at four portions. This incident happened between transmission line Pulu to Serdang(275kV) and Balakong to Serdang(132kV). Figure 1.1 shows a direct stroke on the earth wire between two towers has caused the wire to snap into 4 portions. Line arresters are installed on the 132kV lines. The location of the affected arrester was not that closest to the point of strike but rather further down at the next tower. The arrester at the nearest tower was not effected. Figure 1.2 shows the tower locations.

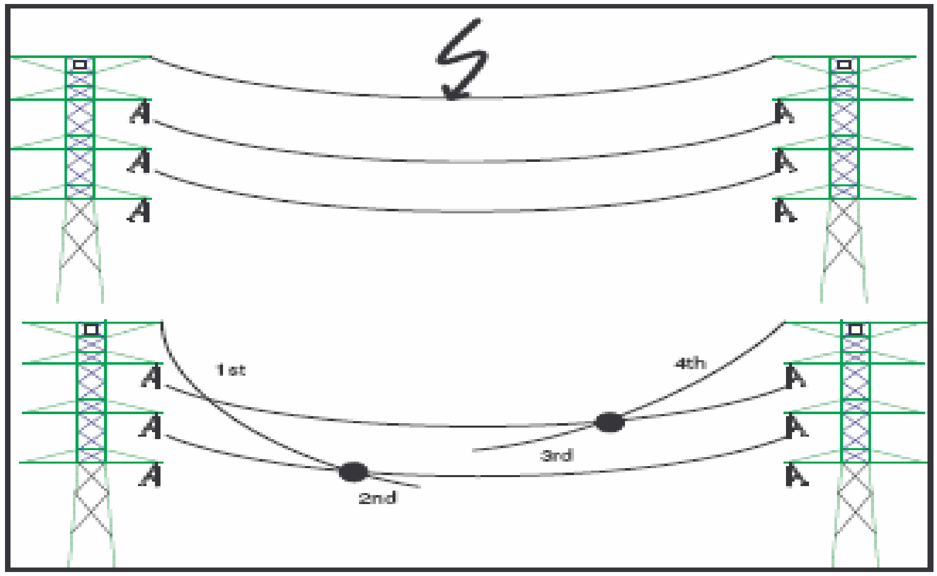

Figure 1.1 Transmission line had caused the breakage of the conductor at four portions[1]

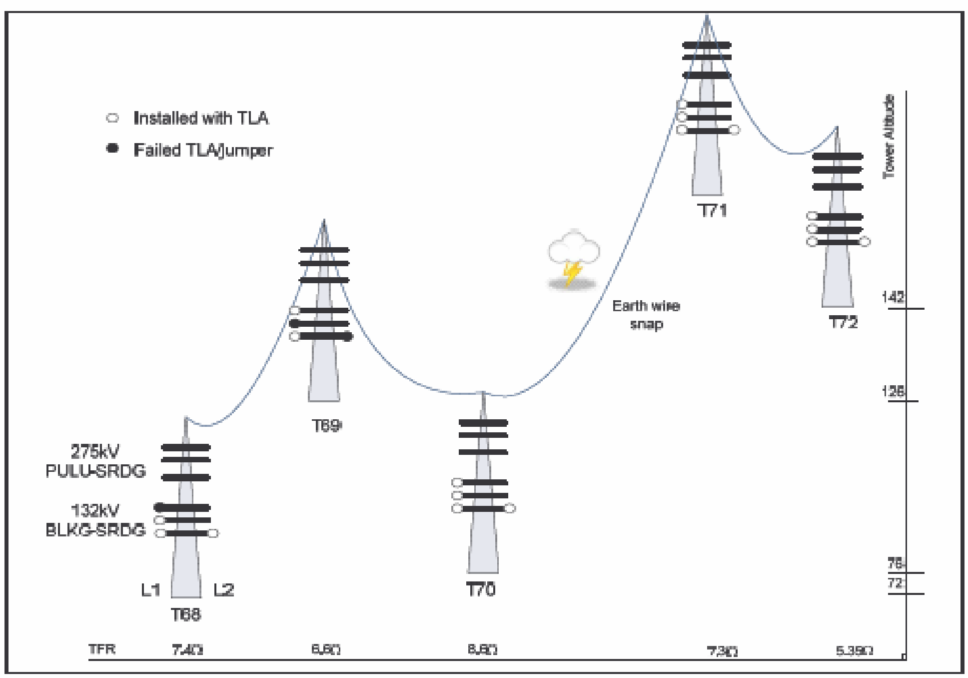

Figure 1.2 The direct stroke on shield wire between T70-T71 affected three TLAs installed at T69 and T68 [1]

Part 2: Protection Design of Simple Structure

There are standard methods to design and install the lightning protection devices for structures. Among the concepts used is the rolling sphere method which determines the exposed areas to lightning strikes. Lightning rods, usually the conventional Franklin rods, are installed on top of buildings and structures is protect the exposed areas from lightning threats. The rolling sphere method described above is based on a number of assumptions such as the average lightning peak current, which may limit the protection reliability to a certain condition only. This simulation work aims to consider all possible lightning current magnitudes and the corresponding ground flash density. The simulation is run for long time (teens or hundreds of years) and this is possible using a computer simulation. The performance of the designed lightning protection can then be studied.

1.3 Objective

The objectives of this project are:

1) To study and investigate a recent incident where a direct lightning strike on the earth shielding conductor of a 275/132kV quadruple circuit transmission line as below:

   a) Arrester at the nearest to the point of strike is not effected rather further down at the next tower.
   b) Lightning strike at shielding wire caused the breakage of conductors at four points.

2) To develop a program to simulate the probability nature of lightning strike using Monte Carlo Simulation and to simulate the lightning protection of simple structures.

1.4 Scope of Project

Design and analysis:

- Modeling 275/132kV Quadruple Circuit Transmission Line use ATP-EMTP Simulation
- Monte Carlo Simulation using MATLAB

1.5 Organization of Thesis

The thesis is organized in the following manner. Chapter 2 describes the literature review of the project which includes the lightning strikes phenomenon on transmission line and transmission tower, and the protection design of simple structures. Chapter 3 describes on the methodologies used. Results and discussion are described in Chapter 4 followed by conclusions in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Lightning Problem for Transmission Line

Lightning strokes to transmission line and tower of 275/132kV quadruple circuit are classified into two groups which are direct stroke and induced voltage. Direct stroke is the phenomenon of thunder cloud directly discharge into transmission line and it is considered the major source of disturbance in transmission line system [3]. Induced voltage is introduced when the thunderstorm generates negative charges and the earth objects develop induced positive charges. When cloud discharges to some earthed objects other than the transmission line, the line is left with a huge concentration of charge (positive) which cannot leak instantaneously. The transmission line and the ground will act as a huge capacitor charged with a positive charge and hence overvoltage occurs due to these induced charges [3,6]. This phenomenon is not so critical for system voltages more than 66kV.

2.2 Effects on Transmission Line Protection

When a direct lightning stroke occurs, lightning current of large amplitude will be injected into the transmission line. Lightning can strike on transmission lines in many ways. However, only the lightning strokes, which can cause transients on phase conductors of the transmission line, may influence the surge arrester. They are: direct stroke to a phase conductor and strike to the overhead shield wire or tower, which then flashes over to the phase conductor [10].

2.2.1 Backflashover

When lightning strikes a tower, a traveling voltage is generated which travels back and forth along the tower, being reflected at the tower footing and at the tower top, thus raising the voltage at the cross-arms and stressing the insulators. The insulator will flashover if this transient voltage exceeds its withstand level (backflash). Backflashover voltages are generated by multiple reflections along the struck tower and also along the shield wire for shield lines at the adjacent towers. The backflashover voltage across insulator for the struck tower is not straight forward. The peak voltage will be directly proportional to the peak current [7].

2.3 Travelling Wave

Traveling wave occurs when lightning strikes a transmission line shielding conductor, phase conductor or tower. A high current surge is injected as the lightning strikes. The impulse voltage and current waves divide and propagate in both directions from the stroke terminal at a velocity of approximately 300 meters per microsecond with magnitudes determined by the stroke current and line surge impedance [6].

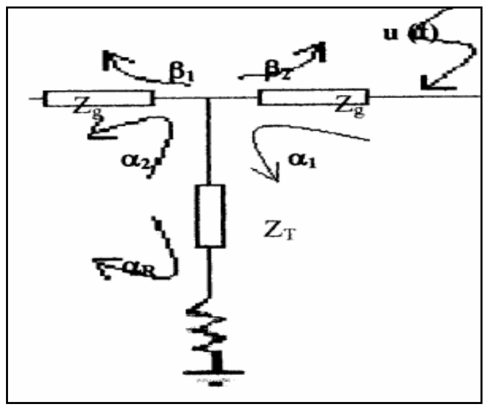

Figure 2.1 Reflection and refraction at tower after lightning strike

2.4 Lightning Current

Wave shape and amplitude of lightning current are influenced by some stochastic factors, including geographic location, geologic conditions, climate and weather, etc. Thus, they change every time. But investigations show that although the lightning currents differ every time in waveform and magnitude, all exhibit the basic characteristics of a double-exponent wave. It can be given by:

$$I = I_0\left(e^{-\alpha t} - e^{-\beta t}\right) \qquad (2\text{-}1)$$

where:

I, is the amplitude of the lightning current; ***α,*** *ß* are attenuation coefficients. [8]

2.4.1 Characterization of The Lightning Discharge

The lightning discharge current is defined by its shape and characteristic parameters. Given the random nature of lightning, the parameters identifying each stroke follow probabilistic laws which have to be considered. IEEE guidelines consider a triangular shape, it can be shown in Figure 2.2. The current amplitude follows a probabilistic law given by the cumulative probability of exceeding the amplitude I, P_I: [12]

$$P_I = {}^{1}\!\Big/_{1 + \left({}^{I}/_{31}\right)^{2.6}} \qquad (2\text{-}2)$$

where I is given in kA.

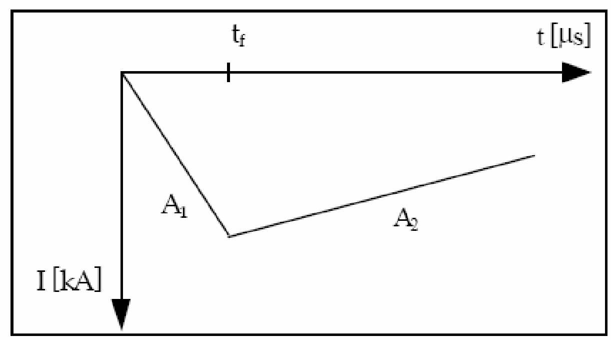

Figure 2.2 Lightning current shape, according to IEEE guidelines (negative polarity)

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Peak current amplitude (lightning) and rise time of lightning stroke can effect to the overvoltage that occur in transmission line because the higher peak current magnitude and shorter front time will increase the overvoltage. It can be shown in Figure 2.3 and Figure 2.4. This will lead to backflashover [11].

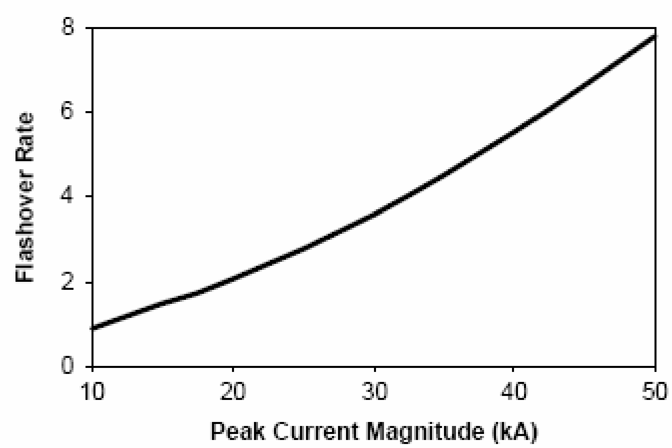


Figure 2.3 Peak current magnitude (kA) versus flashover rate

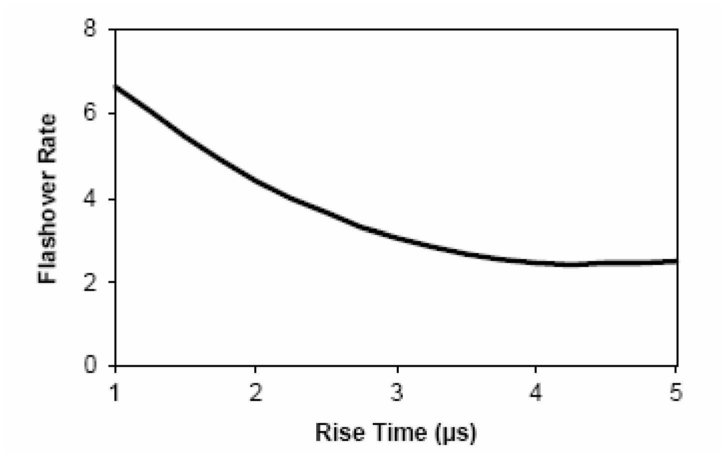


Figure 2.4 Rise time lightning current versus flashover rate

2.5 Line Insulation Flashover Model

The leader propagation model is used to represent line insulation flashovers[14]:

$$V_l = 170d\left(\frac{u(t)}{d-l_l} - E_0\right)e^{0.0015\frac{u(t)}{d}} \qquad (2\text{-}3)$$

where:

V_l- Leader velocity (m/s)

d - Gap distance (m)

l_l - Leader length (m)

u(t) - Applied voltage (kV)

Eo= 520 (kV/m)

The critical flashover voltages $U_{50\%}$ of 275 kV and 132kV circuits are 1120 kV and 880kV respectively. Flashover voltage of all line insulators in the simulated section is randomly varied, according to the normal distribution. Standard deviation for the line insulation flashover voltage was 3% [2].

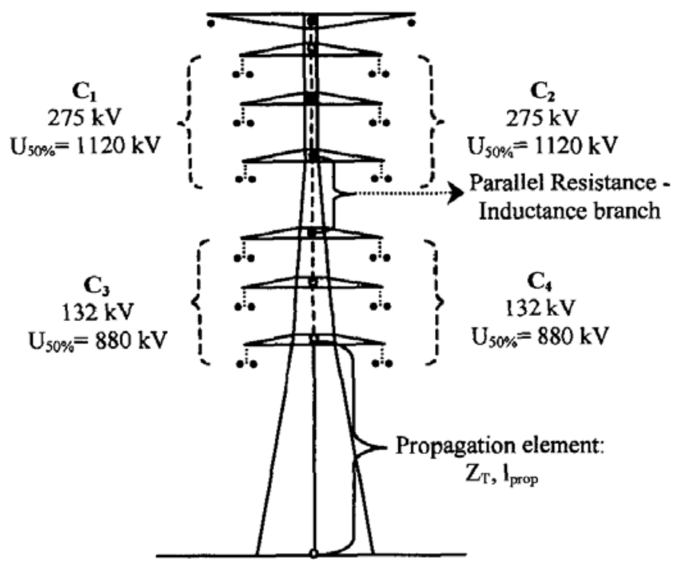


Figure 2.5 Critical flashover voltage for 275/132kV transmission line

Line insulators from tower to conductor can be represented as a capacitor. The tower to conductor has equivalent capacitance of about 80 pF for 132kV lines [12]. The transient-voltage withstands level of a power apparatus is not a unique number. An apparatus may withstand a high transient voltage which has a short duration even it has failed to withstand a lower transient voltage with longer duration. This characteristic of the insulator is known as the volt-time characteristic of the insulation. However, a simplified expression for the insulator voltage withstand capability can be calculated as below [12]:

$$V_{fo} = K_1 + K_2/t^{0.75} \tag{2-4}$$

where:

V_{fo} - a flashover voltage (kV),

K_1 - 400*L,

K_2 - 710*L,

t - elapsed time after lightning stroke, µs.

The back flashover mechanism of the insulators can be represented by volt-time curves. When a back flashover might occur, a parallel switch is applied. If the voltage across the insulator exceeds the insulator voltage withstand capability, the back flashover occurs. The back flashover is simulated by closing the parallel switch. Once the back flashover occurs, the voltage across insulator goes down to zero. Figure 2.6 and Figure 2.7 show the insulator model and the waveform of voltage across insulator, when back flashover occurs at 4 µsec [4].

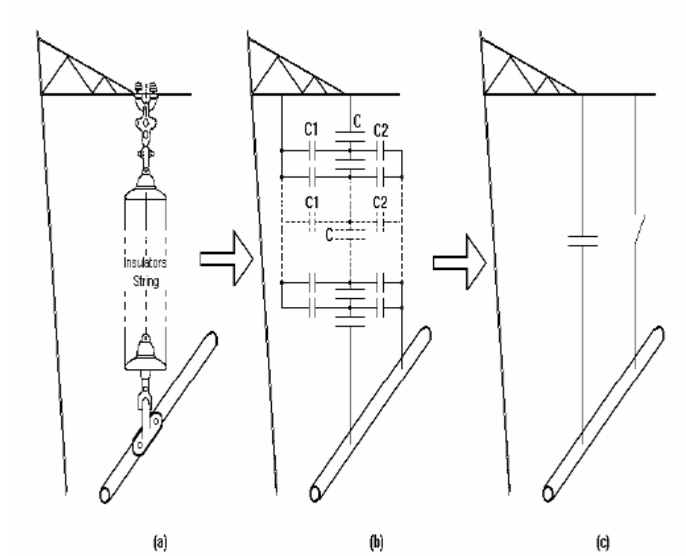


Figure 2.6 Model used for string of insulator up 275/132kV.

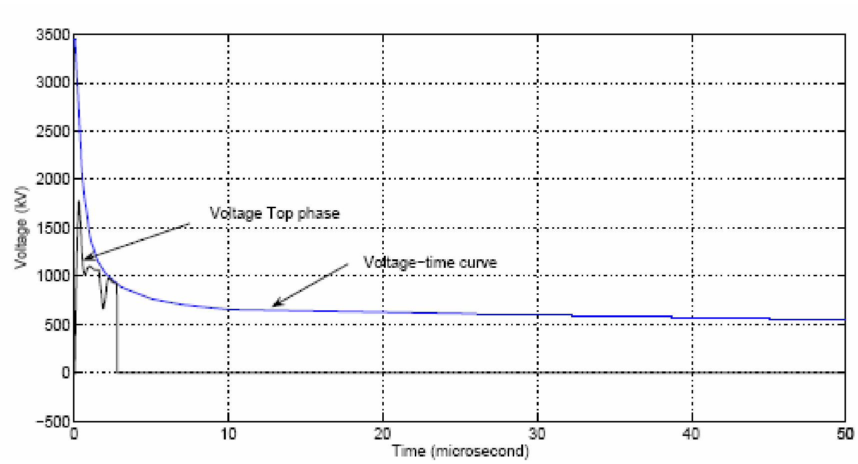


Figure 2.7 The back flashover mechanism

2.6 Ground Flash Density

The Ground Flash Density, Ng, has a linear effect on lightning outage rates. There have been important developments in measurements of Ng, in the 1980s. Based on a power-law regression between CIGRE Lightning Flash Counter readings and local thunder days (*TD)* values for the same period [8]. *Ng* is given as:

$$Ng = 0.04\ TD^{1.25} \quad (2\text{-}5)$$

The flash/100km/year, Na, is used to calculate total hit on the transmission line which is given by:

$$Na = \frac{Ng}{10}\left(4h^{1.09} + b\right) \quad (2\text{-}6)$$

where:

h = average conductor height, m

b = overhead ground wire separation distance, m

Ng = ground flash density, flashes/km^2/year

Na = flashes/100km/year

2.7 Tower Footing Resistance

The tower footing behavior is characterized by a lumped resistance. This resistance is constant according to IEEE guidelines, while in CIGRÉ the effect of soil ionization is taken into account. The decrease of the tower footing resistance when the lightning current amplitude exceeds a critical value I_g is given by [9]:

$$R_i = R_0 \Big/ \sqrt{1 + I/I_g} \qquad (2\text{-}7)$$

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, using the equation:

$$I_g = E_g \rho \Big/ 2\pi (R_o)^2 \qquad (2\text{-}8)$$

where:

Ro = low current footing resistance (Ω)
Ri = tower footing resistance (Ω)
ρ = soil resistivity (Ωm)
I = impulse current (kA)
Ig = soil ionization limit current (kA)
Eg = soil ionization critical electric field (kV/m)
[Eg = 400 (kV/m]

2.8 Transmission Line Tower

A direct stroke to a transmission line is very rare and most of the lightning strikes to the top of a transmission tower. As a result, in calculation of lightning, tower models have been developed using a theoretical approach or an experimental work. The accurate representation of the transmission tower has been the subject of much discussion. In lightning surge simulations, the tower model used can range from simple lumped inductances or resistance to complicated nonuniform transmission line circuits. Representation of the tower as a lumped element is only valid if surge current rise time is long compared to surge travel time in the tower. So for a steep-front wave the tower must be modeled as a distributed parameter element [4].

2.8.1 Development of Tower Model

Several formulas for the tower surge impedance have been used in the past. Wagner's and Hileman's model indicates that the tower impedance varies as the wave travels from top to bottom, being lowest at the tower top and increasing as the wave travel down the tower [9]. Kawai later performed measurements on isolated tower (without ground wires connected) and obtained similar result, although the magnitudes were appreciably lower [9]. Later on Chisholm et al. performed some experiments and found that the tower response to a horizontal current, resulting from a midspan stroke, is different from the response to a vertical surge, where the tower impedance decrease from top to bottom [9]. All these result are obtained considering the tower alone, without ground wires connected [9].

Next, Ishii et al, measured the surge response of the typical double circuit 500kV transmission tower, with ground wires, for vertical stroke current. Based on this measurement, they developed a multistorey transmission tower model to be used in the multiconductor analysis with ElectroMagnetic Transients Program (EMTP). The multistorey transmission tower model consists of distributed parameter lines representing tower surge impedance and parallel R-L circuits representing an attenuation of a travelling wave along the tower [5].

2.8.2 Tower Model

The surge impedance expression proposed by Sargent [5] has been widely used as a tower model for traveling wave calculation. According to this expression, the tower under measurement is approximated by a cone, and a surge impedance of 170Ω is obtained for this shape. In this case, it is treated that the velocity of surge propagation in the tower is equal to the velocity of light (300 m/μs) and there is no surge attenuation. On the other hand, a surge impedance of 100Ω to 115Ω, a surge propagation velocity of 210 to 240 m/μs and a surge attenuation coefficient of 0.8 to 0.9 obtained by Kawai et al. through experiments on an actual tower used as second model [5].

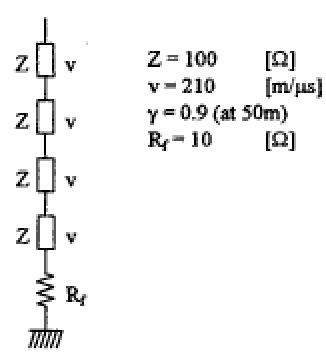


Figure 2.8 Kawai tower model [5]

In the new model an inductance is connected parallel with the resistance determining the attenuation coefficient, enabling a more accurate approximation of the characteristic of the wave tail. This inductance is a parameter to determine the shape of the wave tail, and has nothing to do with the lumped inductance often used to represent the tower itself. The damping resistance is determined from the resistance per unit length of a transmission line calculated from the postulated surge attenuation coefficient of a tower [13].

The transmission line tower model, used in simulation is presented in Figure 2.9. The value of R can be obtained by calculating and dividing the tower into upper and lower truncated cones as shown in Figure 2.10. Section of the tower from the bottom crossarm to the ground is represented as propagation element, which is defined by the surge impedance Z_T and wave propagation speed on the tower was taken to be equal to the velocity of light. Sections on the tower top [between tower top and top crossarm and between crossarms] modeled as inductance branches. Branch inductance is determined according to the section length, tower surge impedance and the propagation velocity. In the parallel to the inductance branches a damping resistors are introduced [19].

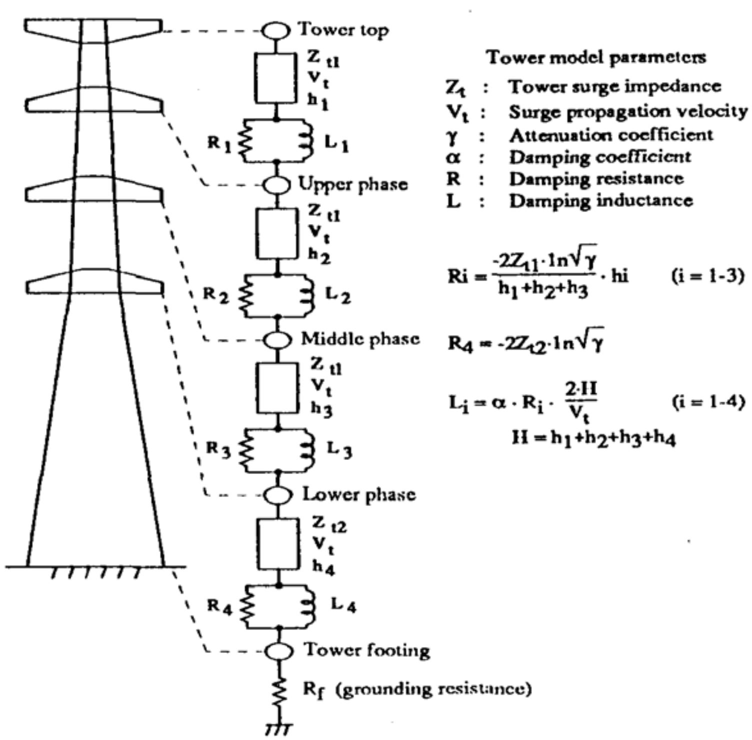


Figure 2.9 Mathematical calculation for multistore tower model

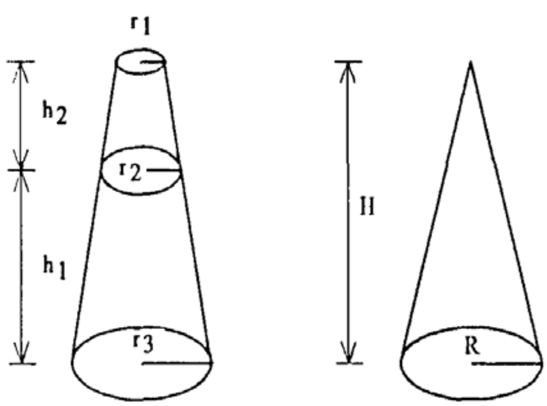


Figure 2.10 Tower equivalent model

2.9 Surge Arrester

Four general classes of devices that have been used to limit over voltage and permit low (more economical) insulation levels of equipment [7]:

- Spark gaps
- Expulsion-type arresters
- Gapped valve-type arrester
- Gapless-Metal oxide arrester

Overvoltage protective devices use spark gaps connected in series made with a nonlinear silicon carbide (SiC) material. The spark gaps provided high impedance during normal conditions. Nowadays, the physical construction of modern high voltage surge arrester consists of metal oxide discs inside a porcelain or polymer insulator.

The use of line surge arresters to improve transmission line lightning performance or to avoid double circuit outages has increased over the last decade. Many line surge arresters are in service today and substantial service experience has been accumulated. The majority of line surge arresters are installed on lines having nominal voltages between 44kV and 138kV, but the application of this type of technology has been extended to the distribution lines and also to the transmission lines up to 500kV.

Line surge arresters are installed on 132kV lines, mainly to reduce double circuit outage rate. Line surge arresters are normally installed on all phase conductors of one circuit of the double circuit line. Arresters are installed on all towers of the considered 132kV line as shown in Figure 2.11. With this arrester installation configuration, double circuit outages are eliminated, but there exists possibility to have flashovers on the circuit without arresters [2].

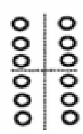
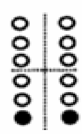
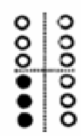
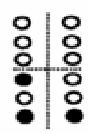
Figure 2.11 Line arrester installed on 275/132kV

Lightning stroke performance of the line without line surge arresters is presented in Table 1 (per circuit flashovers). As expected, the majority of the flashovers happen on 132kV circuits. Line lightning performance strongly depends on the tower footing resistance. For the tower footing resistance less than 10**Ω,** zero flashover rate is obtained (line is equipped with two shield wires with a negative shielding angle) [2].

Table 2.1 Flashover rate for different circuit without line surge arrester (flashover/100km/year). Refer to Figure 2.6 for location of C1, C2, C3 and C4.

$R_T(\Omega)$	$C_1(275)$	$C_2(275)$	$C_3(132)$	$C_4(132)$
10	0	0	0	0
15	0	0	0.78	2.14
20	0	0	5.66	4.88
25	0	0.19	12.69	10.92
30	0.19	0.39	20.69	20.69
35	0.19	0.58	29.67	33.58
40	0.19	0.19	42.55	46.85

Table 2 Line double circuit flashover rate different arrester installation configuration (Flashover/100km/year)

R_T				
10	0	0	0	0
15	0	0	0	0
20	2.14	0	0	0
25	5.07	0.19	0	0
30	8.19	0	0	0
35	14.64	0.58	0	0.19
40	22.84	1.17	0	0.39

○ Without LSA
● LSA Installed

The number of double circuit flashovers depends on the tower footing resistance, and may reach value of 35 % of the line total flashover rate, for the tower footing resistance of 40Ω. The number of the triple circuit flashovers (simultaneous flashovers on two 132kV circuit and on one 275kV) is very low. The best improvement in the line total flashover rate is obtained by the installation of the arrester on the bottom conductors of both 132kV circuit and on the one top conductor of one 132kV circuit (the best three arrester installation configuration) [2].

When line surge arresters are installed on all phase conductors of one 132kV circuit, double circuit flashover are completely eliminated (actual installation on the considered transmission line). But, it is to note that with this arrester installation configuration line total flashover rate remains high. Arrester installation configuration with the arresters on the bottom conductors of both 132 kV circuits and on the one top conductor of one 132 kV circuit is very attractive, because this configuration substantially reduce line total flashover rate, reducing in the same time line double circuit flashover rate [2].

2.10 Transmission Line Model

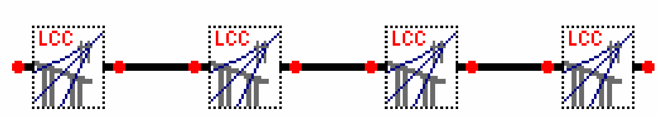


Figure 2.12 Transmission line model

There are five types of the line/cable in ATP (EMTP) which are[16]:

1. Bergeron: Constant parameter KCLee or Clark models
2. PI: Nominal PI-equivalent (short lines)
3. JMarti: Frequency dependent model with constant transformation matrix
4. Noda: Frequency dependent model
5. Semlyen: Frequency dependent simple fitted model.

J.Marti is a suitable model to represent the multiphase transmission line. This model considers frequency attenuation, the geometrical and material of the conductor including skin effect and conductor bundling and the corresponding electrical data are calculated automatically by ATP-EMTP program. It also generates high order frequency dependent model for overhead line and cables.

2.11 Monte Carlo Simulation

A Monte Carlo method is a technique that involves using random numbers and probability to solve problems. The term Monte Carlo Method was coined by S. Ulam and Nicholas Metropolis in reference to games of chance, a popular attraction in Monte Carlo, Monaco. It is a method for *iteratively* evaluating a deterministic model using sets of random numbers as inputs. This method is often used when the model is complex, nonlinear, or involves more than just a couple uncertain parameters. Monte Carlo technique can be used in order to build the computer program for the evaluation of the performance of overhead lightning shielding system. Analysis of atmospheric overvoltage in power plants or transmission line there was always a problem how to determine amplitude of the lightning current which is striking the protected object and cause overvoltage. Development a computer program to represent an algorithm which will determine the mentioned amplitude in same range for entered protected object is necessary. The program is based on a statistical Monte Carlo analysis on the 3-dimensionally simulated system.

2.11.1 The 3-Dimensional Electrogeometric Model

The basic feature of the 2-dimensional electrogeometric model of Whitehead is the simple criterion of shortest path (from the leader tip) determines the target point in protection on structure. This target point of the lightning stroke is determined when the tip of the descending leader reaches a point when the distance from the leader tip to the protective target point equals the striking distance. The field of influence of any structure to a descending lightning leader is hence described by arcs with centers at the various parts of the structures having a radius equal to its striking distance [17].

2.11.2 3-Dimensional Simulation of Fields of Influence

To extend the 2-dimensional EG model to a 3-dimensional system, fields of influence of a structure described by its space of influence whose extreme radius is defined by its striking distance are now considered. For example, the field of influence of a vertical rod can be described by a vertical cylinder with a hemispherical top, both having a radius equal to its effective striking distance r as illustrated in Figure 2.13.

Similarly, the fields of influence of a horizontal wire above ground can be represented by a horizontal cylinder (Figure 2.14). Figure 2.15 also illustrates the fields of influence of a rectangular block above ground which can be used to represent a building structure or a patch of trees, etc. In all cases, the field of influence of the ground plane is represented by a horizontal plane at its effective striking distance rs above the ground. The termination point of the lightning stroke is determined on the basis that an object will be struck if its field of influence is meet first by the leader tip on its way to ground. As in the case of the example given in Figure 2.13, stroke A will terminate on the rod and stroke B will terminate on the ground [17].

2.11.3 3-Dimensional modeling of the Lightning Stroke

The lightning stroke is characterized principally by the lightning leader approach angle and stroke current magnitude. The probability density function of the vertical angle of approach of the lightning stroke is given by [17]

$$g(\theta) = \frac{4}{\pi} cos^2\theta \qquad (2\text{-}9)$$

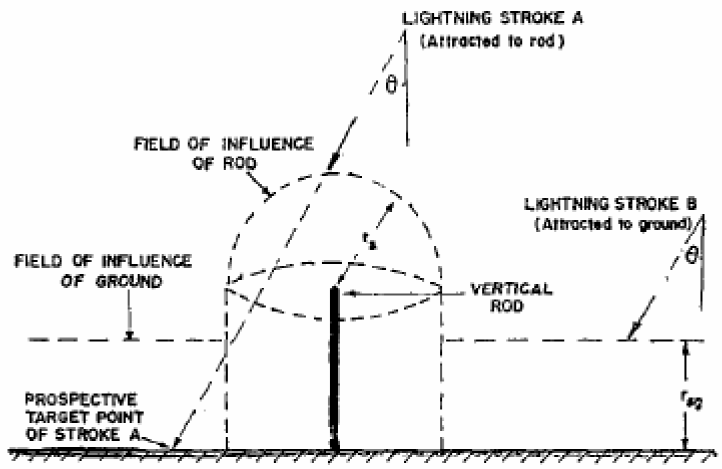


Figure 2.13 Fields of influence of a vertical rod and ground. R_s and r_{sg} are the effective striking distances of the vertical rod and ground respectively [17]

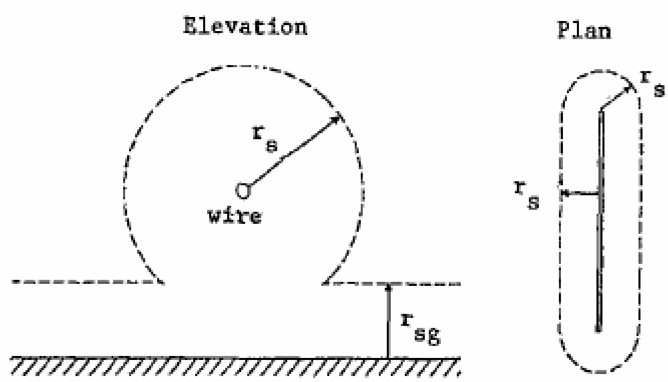


Figure 2.14 Fields of influence of horizontal wire and ground [17]

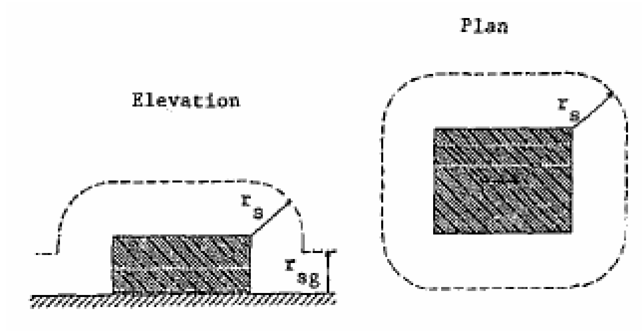


Figure 2.15 Fields of influence of rectangular block and ground [17]

To fully describe the stroke in 3 dimensions, a horizontal angle θ having a uniform probability distribution of between 0 and 360 degrees is incorporated. The AIEE current distribution used is represented by an array with **250** current values stored in a data file. The IEEE WG distribution is given by [17]

$$P(I) = 1 / 1 + (I/31)^{2.6} \tag{2-9}$$

where I is the stroke current in kA and P(1) is the probability of current exceeding I. Striking distance is related to stroke current magnitude.

$$r_s = 8.0\ I^{0.65} m \tag{2-10}$$

where I is in kA and r_s is in meters.

2.11.4 Ground Flash Density

The frequency of strokes to an area under study is determined by the ground flash density which is the number of ground discharges per square kilometer per year. The shielding failure rate of a shielding system is a function of the ground flash density. The distribution of all prospective ground discharges within the area of study is taken to be uniform as there is no reason to consider otherwise [17].

2.11.5 Shielding Effect of a Vertical Rod

The most common and simplest form of lightning protection is using a vertical rod which has the function of intercepting a lightning stroke before it can strike a nearby object it is protecting, and then discharging the current to ground [17].

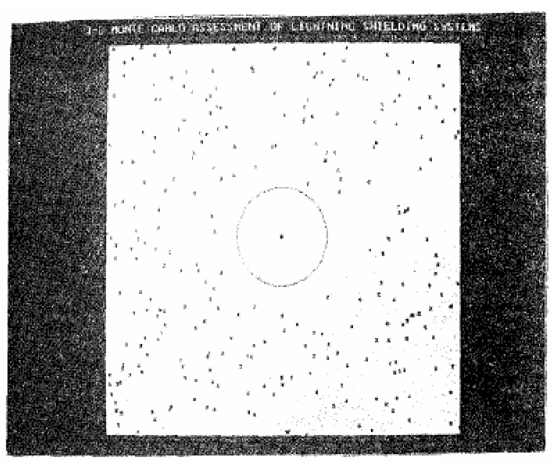


Figure 2.16 Display of lightning strokes (represented by dots) terminating structure (vertical rod) and surrounding ground - plan view [17]

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