ADDIS ABABA UNIVERSITY

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SCHOOL OF GRADUATE STUDIES

Study and Evaluation of Lightning Over voltages for Protection of Transmission Lines:

Case Study of GERD-Diddesa-Holeta transmission line

BY

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A Thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the Degree of Master of Science in Electrical Power Engineering

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Declaration

I, the undersigned, declare that this thesis comprises my own work. In compliance with internationally accepted practices, I have dually acknowledged and referenced all materials used in this work. I understand that non-adherence to the principle of academic honesty and integrity, misrepresentation/fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the university and can also evoke penal action from the source which have not been properly cited or acknowledged.

Signature ____________________________________

Adugna Edosa

Date _______________________________

DEDICATED

TO

MY MOTHER

Acknowledgement

I would like to forward the deepest of my appreciation and gratitude to my advisor Dr.Ing Getachewu Biru (PhD) for his patience and constructive advice throughout the course of the thesis. Not only did he help me with invaluable advice, I have also learned a lot from him. The brotherly treatment he accorded me has served as an inspiration for the completion of this study.

I am in a position where I cannot take the sole credit for the completion of this study. I credit every piece of strength of this study to my advisor and any weakness to myself.

I also owe a great deal of gratitude to my family and my friends for their moral support.

Abstract

Lightning is one of the most significant sources of over voltages in overhead transmission lines. The lightning over voltages could lead to failure of the devices connected to the transmission line. A fundamental constraint on the reliability of an electrical power transmission system is the effectiveness of its protective system. The role of the protective system is to safeguard transmission system components from the effects of electrical overstress. Shield wire and surge arresters are an important means of lightning protection in transmission and distribution systems. Therefore, it is necessary to analyze the influence of over voltages caused due to lighting.

This research is aimed at study and evaluation of the protection level of transmission line by using shield wire and line surge arresters against lightning overvoltage.

The increase in voltage due to lightning is in investigated by using the MATLAB software. Direct and induced, types of lightning strokes are considered. The model of a 500kV three-phase overhead power transmission line is developed considering the RL circuit. The simulations are performed based on a time domain analysis.

Also numerical analysis is made for 500kV tower structure transmitting power over 620km from GERD to Dedesa and then to Holeta being protected by shield wire. Probability of lightning stroke going to shield wire and phase conductor is analytically determined in each cases. Accordingly the effective area of the lightning stroke that goes to phase conductor per 100km per year is $0.0301\mathrm{m}^2$and that goes to shield wire per 100km per year is$0.399\mathrm{m}^2$. Probability of failure and failure rate is obtained to be 31% and 0.0024respectively which means it takes 413.18failures per year years between .

Key words: *lightning, Modeling, transmission line, protection*

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List of Abbreviations and symbols

BFOR	Back Flashover Rate
CIGRE	International Council on Large Electric System
GERD	Grand Ethiopian Renaissance Dam
IEEE	Institute of Electrical and Electronics Engineers
I_f	Peak value of lightning current
kA	kilo Ampere
kV	kilo volt
m	meters
km	kilo meters
TC	Technical Committee
SFFOR	Shielding Failure Flash over Rate
CG	Cloud-to-Ground
η	Nano (10ex9)
μ	Micro (10exp6)
t_h	time to half
I_{max}	maximum current
IN	Induction
SF	shielding failure
BF	back flashover
m/s	meter per second
F/m	Farad per meter

I_{m1}	*maximum value of first current peak, A,*
I_{max}	*maximum value of current, A,*
t_{10} *s,*	*time interval between instants corresponding to 10% and 90% of first peak value,*
t_d	*front duration according to* t_{10} *s,*
t_{30} *s,*	*time interval between instants corresponding to 30% and 90% of first peak value,*
S_{10}	*average front steepness between 10% and 90% value point of first peak,* $A\ s^{-1}$,
S_{30}	*average front steepness between 30% and 90% value point of first peak,* $A\ s^{-1}$,
TAN-10	*rate of current rise at to 10% value point of first peak amplitude,*
TAN-G	*the maximum front steepness or rate of rise in the front wave,*
t_f	*front duration* ($t_f = 1.25\ t_{10}$)
BIL	*Basic insulation level*
H_{CL}	*Height of cloud*
SW	*shielding wire*
PC	*phase conductor*
d_{FO}	*horizontal displacement of phase conductor and shielding wire*
r_c	*radius to conductor in the electrogeometric model*
d_s	*Distance between shielding wires,*
δ	*The protection angle of the tower,*
h_t	*distance between shielding wire and earth,*
y	*Distance between phase conductor and earth*
V_{rms}	*Root mean square value of voltage*

Chapter 1 Introduction

1.1 Background

From the earliest days of the power industries, lightening faults on lines as well as equipment fault have been the major cause if interruption of service. With the growing importance of electric power to both industrial and residential customers, attention was increasingly directed towards protective system and devices to improve service continuity. At an early stage, the source of over voltage was believed to be induction from the electric charge of the thundercloud, and this led to installation of grounded conductors usually erected above the power conductors to divert some of the induced charge from them.

A reliable operation of the transmission and distribution systems requires detailed analysis of stresses to which these systems are exposed. The main part of the transmission lines stresses, defining requirements for the power system insulation and crucial for its reliable operation are over voltages. The particularly high over voltages, whose maximal values may be many times higher than the rated voltage, result from lightning discharges and are responsible for the basic hazard of the insulation breakdown.

Lightning is one of the main causes of electric power system fault. The entire power system consists of power plants, substations, transmission lines, distribution feeders and power consumers. Generally, the power grid or electric power network referred to that part of the electric power system except the power plants and consumers. All components of the power system form dynamic balance in operation. The system frequency, voltage, tie-line flows, line currents and equipment loading must be controlled and kept with limits determined to be safe. Lightning, especially Cloud-to-Ground (CG) lightning could damage power transmission lines, distribution lines, substations and power plants. Furthermore, such hazard may lead to loss of the system stability and uncontrolled separation of power network even threatens the whole electric power grid [1].

1.2 Statement of Problem

Since transmission lines are usually shielded by one or several wires, lightning over voltages can be caused by strokes to either a shield wire or a phase conductor. The stroke to shield wire can produce a flashover if the back flash overvoltage exceeds the insulator strength. Over voltages caused by a shielding failure, that is, by a stroke to a phase conductor, are more dangerous, but their frequency is usually very low due to the shielding provided by sky wires.

Due to the random nature of lightning flashes, the analysis of the lightning performance of transmission lines must be based on a statistical approach. Based on this, the flashover rate of a transmission line can be divided into the backflashover rate (BFOR) and the Shielding Failure Flashover Rate (SFFOR). Backflashover rate occurs when lightning strikes the tower (or the overhead ground wires), the current on the tower and ground impedances causes the rise of the tower voltage. A small fraction of the tower and shield wires voltage is induced in the phase conductors due to the electromagnetic coupling, nevertheless the tower and shield wires voltage becomes much larger than the phase conductors voltages. Shielding Failure Flashover Rate is a stroke that terminates on a phase conductor, in spite of the presence of poorly located overhead ground wires. To obtain these two quantities, it is important to develop a model that can represent the nature of lightning strokes to shield wires, to phase conductors and those to ground wire.

1.3 Objective

1.3.1 General objective

The general objective of this thesis is to study and evaluate the overvoltage caused due to lighting.

1.3.2 Specific objective

The specific objectives of this research are:

- To study background of lightning phenomenon
- To analysis the effect of lightning on transmission line
- To Study protection system of transmission line from lightning
- To Study lightning protection system of GERD-Diddesa-Holeta transmission line
- To simulate lightning transient phenomenon

14 Methodology

The methodology used to complete this research is described by figure 1.1

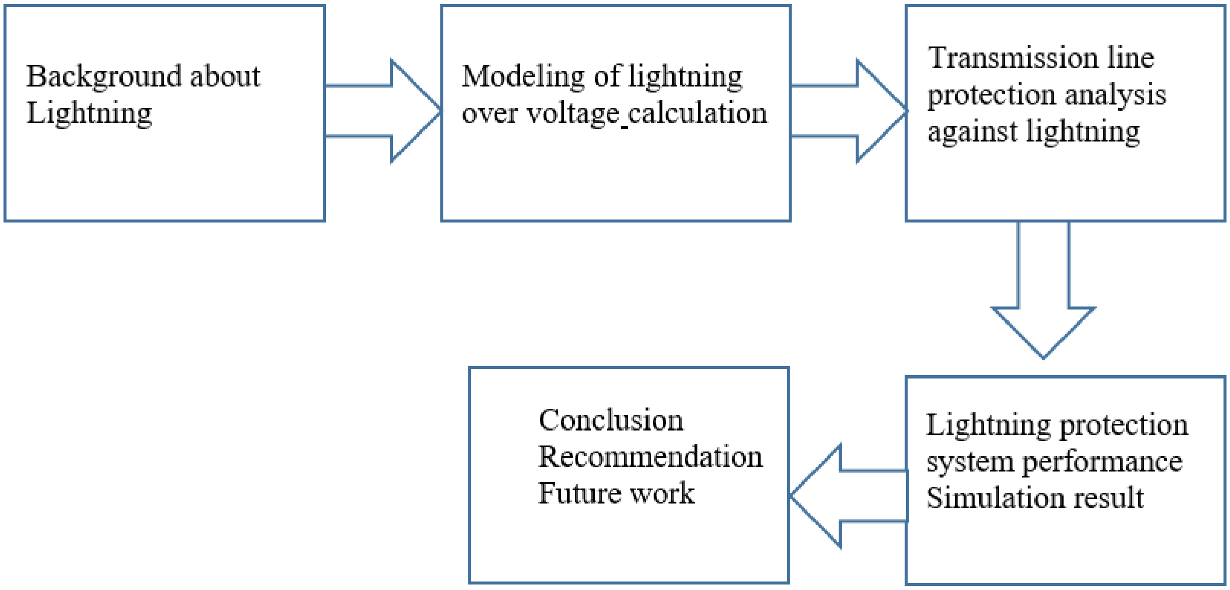


Figure 1-1 methodology

1.5 Literature Review

Frequency distribution of lightning current

The frequency distribution of first return-stroke lightning current peaks adopted by International Council on Large Electric System (CIGRE) has been derived from the available measurements of 338 negative downward flashes, collected in several parts of the world on various structures (76 flashes on lines and 262 on masts and chimneys) of different heights, in general, less than about 60 m. One-hundred twenty–five measurements are taken from those recorded at the Berger's tower. The lowest current value contained in the data sample is 3 kA. The cumulative distribution of these peak current peaks has a median value of about 34 kA. The analytical expression of the density function of such a distribution is the following [2]

$$f(I) = \frac{1}{\sqrt{2\pi}\sigma_1 I} e^{\frac{-(ln(\frac{I}{\mu_1}))^2}{2{\sigma_1}^2}} \qquad 1.1$$

Where

$f(I)$ is density function of peak current.

$\mu_1$is the median value,

σ_1 is the logarithmic standard deviation.

As noted by Anderson and Eriksson [1980], a lognormal distribution can be better represented by two sub-distributions that divides, in a first approximation, in to the shielding failure and backflashover domains. Shielding failure domain is the measure of ineffectiveness of protecting work which determines the number of strokes to the phase conductors per year where as backflashover domain is the measure of number of strokes to the shield wire per year

Table 1.1 reports the median and the logarithmic standard deviation of these two sub-distributions.

Table 1.1 Parameters of the first stroke distributions adopted by Cigré. [2]

Parameter of (1)	Shielding failure domain I<20 Ka	Backflashover domainI>20 kA
Median value [kA]	61	33.3
Logarithmic standard deviation	1.33	0.605

The majority of the currents, however, were measured on tall telecommunication towers. The well-known experiments were carried out on two 40 m high telecommunication towers in Italy on a 248 m high telecommunication tower near St. Christiana, Switzerland and on a 160 m high telecommunication tower located on the mountain Peissenberg near Munich, Germany. The highest towers were the 540 m high Ostankino tower in Moscow, Russia and the 553 m high Toronto Canadian National Tower, Canada. The most important current data, however, stem from the experiments of Prof. Berger, who had been recording the lightning currents during about 30 years on a telecommunication tower situated on the mountain San Salvatore near Lugano, Switzer-land. [3]

The lightning currents are preferably studied on elevated structures due to increasing probability of the strike with the height. In former lightning research they were measured with magnetic links installed on various locations as power lines, masts, chimneys and high buildings. Because only the current peak proportional to the maximum magnetic field strength is captured with this method, nowadays oscilloscopes are mainly employed for the recording of the current waveform. One of the first important experiments was carried out on the Empire State Building in New York City, USA. Similar experiments were performed on a 60 m high mast in South Africa and in Japan, where the currents measured in winter thunderstorms. In Russia even captive balloons connected with ground by a steel wire were used. [4]

TC 81 decided as one of the first steps to define the lightning threat as a common basis to any protection measures. The lightning treat is mainly derived from the measurement of Berger performed on two 70m towers on the mountain San Salvatore in Switzerland. Up to now the result published in CIGRE Electra in 1975 and 1980 represents the most complete data base of lightning current and their relevant parameters. [5]

1.6 Significance of the work

In designing of transmission line, care should be taken to its protection against over voltage which can be arise due lightning. Therefore every structure of transmission line should be designed, analyzed and simulated so as to withstand this overvoltage. This thesis provides the method used to give detail analysis on the effectiveness of transmission line protection system toward lightning overvoltage.

1.7 Thesis description

This thesis has five chapters in general. Chapter one includes introduction part in which background of the thesis, statement of problem, general and specific objective, methodology and significance of the thesis are covered.

In chapter two analysis of lightning over voltages in electric power systems is discussed. Areas covered under this chapter are: lightning discharge phenomenon, lightning stroke characterization, modeling of lightning impulses and lightning overvoltage calculations.

In chapter three modeling and protection of transmission line against lightning overvoltage is discussed. Accordingly transmission line protection analysis against lightning, simplified electro geometric model, lightning performance estimation of 500kV GERD-Dedesa-Holeta transmission line , procedure to design electro geometric model, failure probability calculation for 500kV GERD-Dedesa-Holeta transmission line are studied

In chapter four the result of the thesis is analyzed in MATLAB software.

In chapter five conclusion, recommendation and future work is presented.

Chapter 2 Analysis of Lightning Overvoltage in Electric Power Systems

2.1 Introduction

Lightning is a conducting channel of air plasma. It is caused due to electrostatic charges accumulated in clouds during thunderstorms [5].

2.2 Lightning Discharge Phenomenon

The phenomenon of generation and propagation of lightning during a thunderstorm event is discussed here. Strong winds moving in upward direction carries water droplets upward where they are cooled between temperatures of-10 to -20 degree Celsius. The collision of the super cooled water droplets with ice crystals forms a soft ice-water mixture. The collisions result in positive charge on ice crystals and a negative charge on soft ice-water mixture. The ice crystals are less heavy and therefore carried on the top portion of the cloud whereas the soft ice water mixture being heavier stays at the bottom of the cloud. This causes a charge separation within the cloud with positive charge at top of the cloud and negative at the base of the cloud. The negative charge at the bottom of the cloud produces a positive charge on the earth ground beneath it. Due to the separation of the charge within the cloud and between cloud base and earth, electric field is generated. The following figure shows the phenomenon [6].

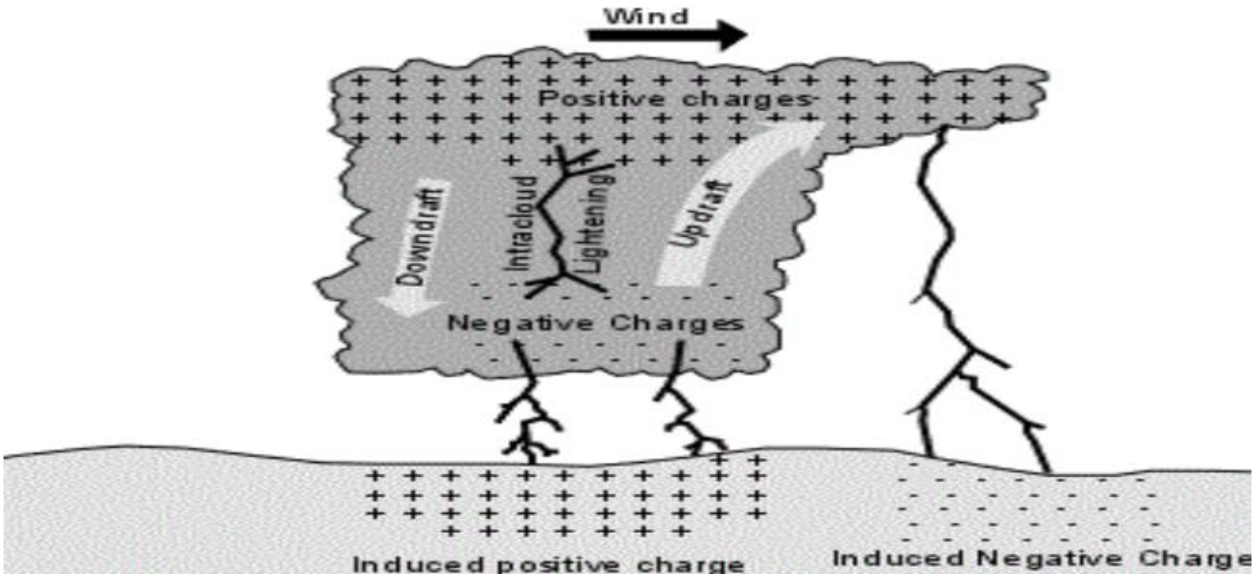


Figure 2-1 Charge Distributions in Cloud and Ground during Lightning

As the charge builds up in the cloud and on the earth due to cloud, a point is reached where strength of electric field is sufficient to cause air breakdown which has breakdown strength of approximately 30kV/centimeter. This field generates electron avalanche which joined together forms streamer. When tip of the leader exceeds thermal ionization threshold it propagates with high speed. The streamer propagates as its head charges continuously seeking least resistance path. Streamers move 30-100 meters and stops and some successful streamers move towards earth in series of steps. Due to this structures on the ground produce upward streamers. When this two discharges are joined together, an ionized path is formed which leads to a high magnitude of current from earth to the cloud. This is the current that causes damage to the structures as it superheats the air to plasma generating a shock wave of thunder [7].

2.2.1 Types of lightning to the ground

Based on the type of charge that is transferred to earth by lightning phenomenon there are two types of lightning. The flashes that transfers negative charges to the ground are termed as negative lightning while those that transfer positive charge to ground are referred to as positive lightning [3].

Since we are concerned with lightning strikes to objects and structures on the surface of the earth and nearly 85-95%of all ground strikes are negative cloud to ground lightning, for the purpose of this discussion only negative cloud-to-ground lightning is described.

Due to their initiating leader process lightning flashes are further classified in to down ward lightning and upward lightning [15].

2.2.1.1 Downward lightning

In this type of lightning flash, the lightning discharge starts with a leader inside the thundercloud propagating down toward ground. The negative downward lightning has a negative down ward leader while positive downward lightning has a positive downward leader. Small objects up to about 100m are almost exclusively struck by down ward lightning because in this case the discharge starts from the cloud and propagates downward to ground object. But for tall objects the discharge starts at ground objects and propagates upward to cloud. This is very rare case.

When the downward propagating leader approaches ground the electric field at grounded object increases due to the charge contained in the downward leader channel. As soon as the electric field exceeds a certain level, connecting leaders start from the grounded objects making the final connection between the objects at ground and the down ward leader. This is the beginning of the return stroke phase, where the return stroke current flows through the struck object [12].

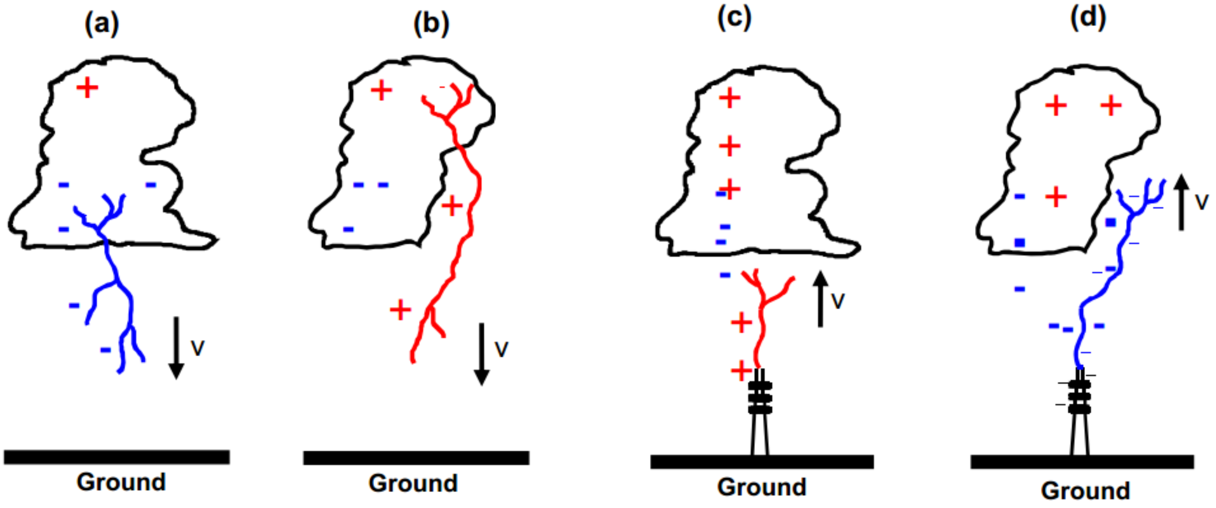


Figure 2-2-2 types of lightning flashes to ground

a. negative down ward

b. positive down ward

c. positive up ward

d. negative up ward lightning

Figure 2.3 shows two examples for the current of the first positive and first negative return stroke. The peak values are typically in the range of several 10kA. Especially positive first stroke may exhibit high peak currents exceeding the value of 100kA. The impulse currents of the return strokes have a fast rising front with a front time ranging from 100η up to more than $10\mu_s$ and slowly dropping decay. The currents of the negative first return stroke typically cease after some $100\mu_s$ while currents of the positive strokes may last significantly longer up to more than $2m_s$. Due to longer duration the positive return stroke current transfer more charges to ground compared to the negative first return stroke current [2].

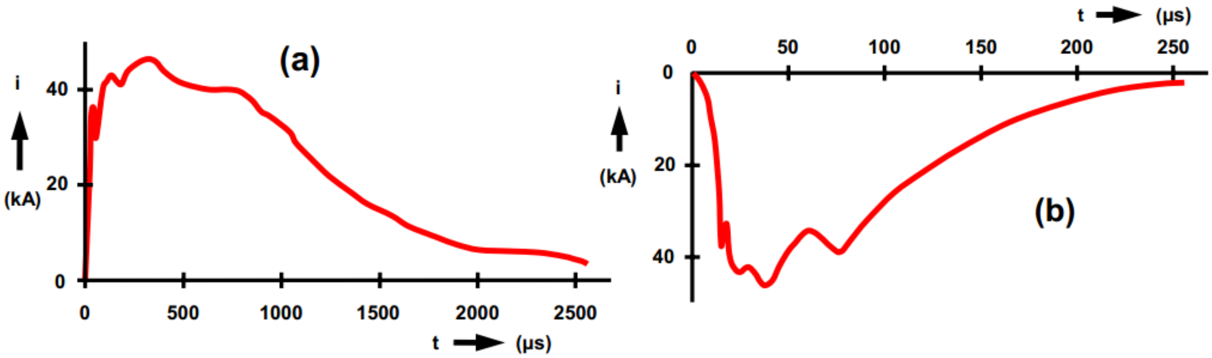


Figure 2-2-3 Return stroke currents of first positive and negative downward lightning

a. positive stroke current
b. negative stroke current

Upward lightning

In this type of lightning flash, the discharge starts from the ground object and propagates upward to the thundercloud. Most of the time, it happens to tall objects.

The electric field at the top of a structure increases with the object height. At tall buildings the electric field may be enhanced to such an extent that an upward leader starts from the top of it. To exceed the critical electric field strength, the object must have a height of about 100m at minimum. The upward propagating leader is associated with an initial continuous current flow through the object [11].

2.3 Lightning Stroke Characterization

2.3.1 Parameters of Lightning Strokes

The evaluation of the lightning performance of both transmission and distribution lines is one of the key issues for power engineers dealing with lightning protection of power systems. The need for improved power quality is nowadays more and more imperative, and this the reason for the permanent increasing interest on the assessment of lightning impact on power systems by researchers and engineers [5].

Lightning being assumed to be a current source, the magnitude and shape of the return stroke current wave play a significant role in the estimation of outage rates of power systems caused by lightning. The return-stroke current rises to its peak in a few microseconds and slowly decays after reaching the peak. The time to peak is called the front time, t_f, and the time duration from t = 0 to the instant when the current subsequently decays to the 50% value of the peak is called the time to half value (tail time) t_h. The time to half value t_h being many times longer than t_f, does not play a significant role in the severity of lightning-caused transient overvoltages. However, the influence of the peak of the current wave I_{max} and t_f is very significant.

2.3.2 Characteristic of Parameters of Lightning Strokes

The lightning flash is categorized by the polarity of the cloud and the direction of propagation of the flash leader. Hence, there are four categories of lightning flash to ground in which the developed leader is followed by a return-stroke current impulse. On average, at least 90% of downward flashes are negative polarity, with some 45 - 55% of flashes consisting of only one stroke. Multiple stroke flashes seldom involve more than 10 strokes (less than 5%), and generally average three strokes per flash, typically at intervals of less than three strokes per flash, per stroke. Upward flashes occur mainly in very tall towers. The majority of transmission line structures is only moderate height (typically less than 60-100 m) and will not in general be subject to upward flashes. The many lightning flash contain several lightning strokes whereby the first steeped-leader/return-stroke sequence is followed in shortly succession by a series of one or more subsequent strokes. Each stroke comprises a dart-leader and return-stroke sequent that generally follows the breakdown path of the first-stroke. Lightning protection systems for transmission line must be capable of withstanding the effects of a series of lightning strokes to the same location within a short period of time. Each lightning stroke is considered an ideal current source of infinite source impedance and the parameter contained within the incident impulse current wave shape determine the transmission network response. This wave shape parameter includes the peak-current (crest value), time to crest, steepness and duration. Also the polarity, time interval and number of incident strokes within each lightning flash are very important. Basic parameters values of lightning discharge can be subjected to distribution variation [6].

The most important aspects to be considered for a full characterization of lightning flashes is detailed below.

Polarity

The polarity of the lightning strike has same meaning as any battery that has a + (positive) or – (negative) sign. The sign represents the type of charge that comes from that end. With lightning this means there is a transfer of a negative charge from the cloud to the ground in negative lightning strikes and there is a transfer of positive charge from the cloud to the ground in positive lightning strikes. Most lightning flashes are of negative polarity. 90-95% of all lightning is negatively charged. It is very dangerous and a typical negative charged bolt is about 300,000,000 volts and 30,000 amps of power. Typical household lighting bulb is about 120V and 12A. The incidence of positive flashes increases during winter, although very rarely their percentage exceeds. It is necessary to know polarity of lightning stroke so as to understand its nature and consequences there by identifying to which type the transmission line most probably be exposed.

Multiplicity

Negative flashes can consists of multiple strokes, while positive flashes have usually a single stroke. Very different percentages of single-stroke flashes have been reported in the literature, see. Less than 10% of positive flashes have multiple pulses; however, since the number of recorded positive flashes is too low, it is usually assumed they are single-stroke flashes.

2.3.3 Return-Stroke Waveform

A concave waveform, with no discontinuity at t=0, is an accurate representation of the wave front of a negative return stroke. Several expressions have been proposed for such a form, being the so-called Heidler model one of the most widely used, see figure below. It is given by the following expression: [13]

$$i(t) = \frac{I_p}{\eta}\frac{k^n}{1+k^n}e^{-t/\tau_2} \qquad 2.1$$

Where

I_p is the peak current,

I is a correction factor of the peak current,

n is the current steepness factor, $k = t/\tau_1$

τ_1 τ_2 are respectively time constants determining current rise and decay time [13].

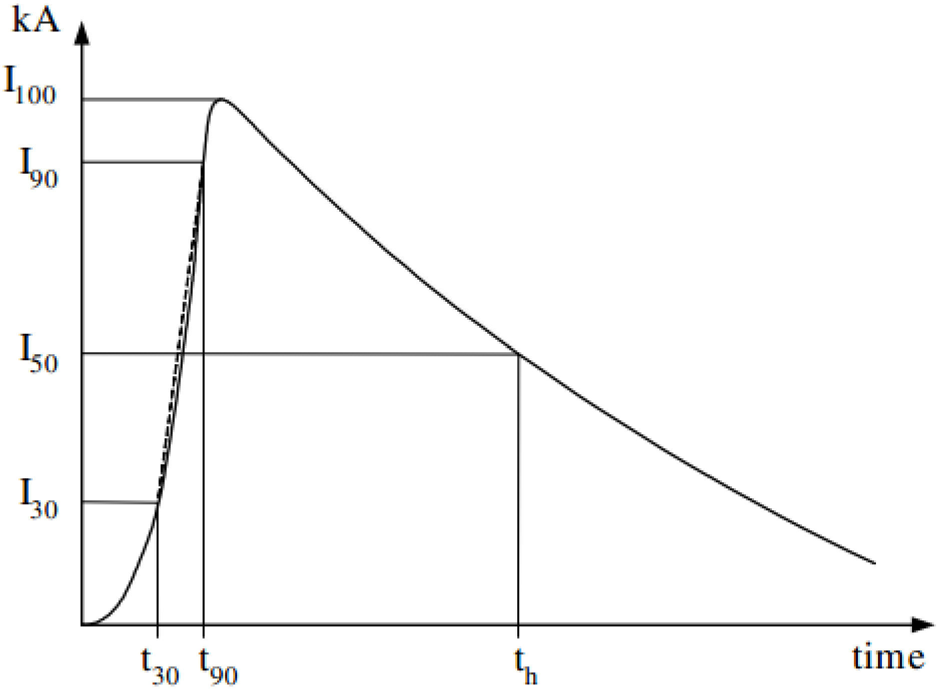


Figure 2-2-4 Parameters of a return stroke – Concave

Main parameters used to define this waveform in the present work are the peak current magnitude, I_{100}, the rise time, t_f (= 1.67 (t_{90}– t_{30})), and the tail time, t_h, i.e. the time interval between the start of the wave and the 50% of the peak current on tail.

2.3.4 Probability Distribution of Return-Stroke Parameters

The statistical variation of the lightning stroke parameters can be approximated by a log-normal distribution, with the following probability density function [11].

$$P(x) = \frac{1}{\sqrt{2\pi} x \delta_{\ln x}} \exp\left[-\frac{1}{2} \left(\frac{\ln x - \ln x_m}{\delta_{\ln x}} \right)^2 \right] \qquad 2.2$$

Where $\delta_{\ln x}$ the standard deviation of lnx and xm is the median value of x.

The joint probability density function of two stroke parameters can be expressed as follows

$$P(x, y) = \frac{\exp\left[\frac{-0.5}{1-\rho_c^2} \left(f_1 - f_2 + f_3 \right) \right]}{2\pi xy \delta_{\ln x} \delta_{\ln y} \sqrt{1-\rho_c^2}} \qquad 2.3$$

Being

$$f_1 = \left(\frac{\ln x - \ln x_m}{\delta_{\ln x}} \right)^2 \qquad 2.4$$

$$f_2 = 2\rho_c \left(\frac{\ln x - \ln x_m}{\delta_{\ln x}} \right) \left(\frac{\ln y - \ln y_m}{\delta_{\ln y}} \right) \qquad 2.5$$

$$f_3 = \left(\frac{\ln y - \ln y_m}{\delta_{\ln y}} \right)^2 \qquad 2.6$$

And ρ_c the coefficient of correlation

If x and y are independently distributed, then ρ_c =0, and $p_{(x, y)}$ =p(x) p(y).

2.4 Modeling of Lightning Impulse

2.4.1 Analytical Representation of Lightning Impulse

Accurate knowledge of lightning current parameters is essential for the appropriate analysis' of the risks the overhead electric devices as overhead transmission lines, power substations or buildings encounter during lightning. The properties of lightning have statistical character, thus, a number of measured values are needed to determine their statistical distribution. However, to collect sufficient data, measurements of lightning must be made on high objects where a high frequency of lightning strikes may be expected [5].

2.4.2 Lightning Current Wave shape

The wave shape of lightning current has very important influence on time courses and maximum values of overvoltages which are generated in overhead lines. The following basic parameters should be known when determining of the lightning current:

- Current peak value,
- Maximum of the current steepness,
- Charge transfer at the striking point [9]

A typical course of lightning currents of negative polarity is presented in Figure 2.5

I_{m1}- maximum value of first current peak, A,

I_{max}- maximum value of current, A,

t_{10} - time interval between instants corresponding to 10% and 90% of first peak value, s,

t_d- front duration according to t_{10} s,

t_{30}- time interval between instants corresponding to 30% and 90% of first peak value, s,

t_{d30} - front duration according to t_{30}, s,

S_{10}- average front steepness between 10% and 90% value point of first peak, A s^{-1},

S_{30}- average front steepness between 30% and 90% value point of first peak, A s^{-1},

TAN-10 - rate of current rise at to 10% value point of first peak amplitude,

TAN-G - the maximum front steepness or rate of rise in the front wave,

t_f- front duration ($t_f = 1.25\ t_{10}$)

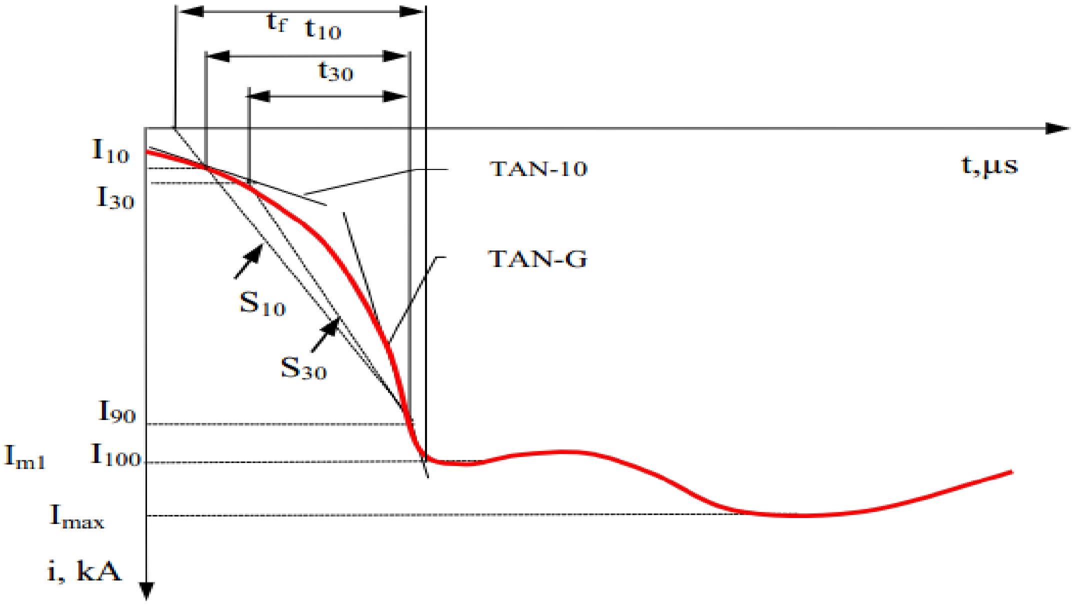


Figure 2-2-5 Lightning current wave form

The frequency distribution of impulse front parameters is summarized in Table 2.1, assuming a log-normal distribution of variables, where the general equation for the probability density for any particular parameter x is given by [10]:

$$f(x) = \frac{1}{\sqrt{2\pi}\beta x} e^{-\frac{z^2}{2}} \qquad 2.7$$

$$\text{Where } z = \frac{\ln \frac{x}{M}}{\beta} \qquad 2.8$$

Where

M - Median parameter value,

β - Slope parameter or logarithmic standard deviation

The mean value of any parameter ma y then is expressed as:

$$\mu = Me^{\frac{\beta^2}{2}} \qquad 2.9$$

2.4.3 Analytical Representation of the Current Shape

A lightning flash can result in significant overvoltage on overhead line insulation systems if substantial stroke current and charge are injected into the line conductor. If the first contact of lightning return stroke current is with the line, then it is modeled as a transient current generator feeding into a system of transient surge impedance representing the line conductors and the tower, and then the overvoltages are calculated using travelling wave technique. The Wave shapes parameters include the peak current amplitude (crest value), time to crest, steepness, duration, polarity and time interval.

To calculate the lightning overvoltages in overhead lines it is necessary to simulate the concave front in the lightning stroke current representation. Three points are needed to establish such simulation:

- The correct maximum value (peak) of the current,
- The highest steepness close to the peak value,
- For first strokes, the correct average steepness expressed as the front time passing through the 30% and the 90% values of current.

This front time should be larger than the current maximal value divided by the maximum steepness, thus resulting in the concave shape. For subsequent stroke this parameter may be neglected. Many mathematical expressions may meet these requirements and the one given here is only one proposal. Disadvantageously, the current front and the current tail are not described by a single expression, but are separated into two parts, one describing the front up to 90% of the maximal value, the other, the maximum value on the tail.

The Current Front

The current front for first strokes can be expressed as: [4]

$$i = At + Bt^n \qquad 2.10$$

Where: A, B - constants.

The basic assumption is that the current shape reaches the instant of maximum steepness (90% amplitude) at a time t_n dependent on exponent n in principle, both variables have to be evaluated by an iterative solution of the generalized equation:

$$(1-\frac{3x}{2S_N})(1-x)^n = x\frac{n-1}{2S_N}+\frac{1-3x_n}{2S_N}(1-x) \qquad 2.11$$

With

$$S_N = S_m\frac{t_f}{I_{\max}} \quad x = 0.6\frac{t_f}{t_n} \qquad 2.12$$

Where:

I_{max}- maximal value of current, A,

S_m- maximum steepness, A s^{-1}(Fig. 2.1).

However, a sufficiently accurate solution is given by:

$$n = 1 + 2(S_N - 1)(2 + 1/S_N) \qquad 2.13$$

$$t_n = 0.6 t_f \frac{3 S_N^{\ 2}}{1 + S_N^{\ 2}} \qquad 2.14$$

The constants then are:

$$A = \frac{1}{n-1}(0.9 \frac{I}{t_n} n - S_m) \qquad 2.15$$

$$B = \frac{1}{t_n^n (n-1)}(S_m t_n - 0.9 I) \qquad 2.16$$

For subsequent strokes the current front is given by:

$$I_{\max} = S_m t_f \qquad 2.17$$

Where: t_f- front time, s.

The current tail

The fundamental requirements for the current tail are:

- To have the maximum steepness at its beginning, thus providing a steady transition from one part to the other,
- To reach correct peak value,
- To describe the current tail.

A suitable mathematical expression for current tail is given by:

$$i = i_1 e^{\frac{t - t_n}{t_1}} - i_2 e^{\frac{t - t_n}{t_2}} \qquad 2.18$$

Where:

t_1, t_2 - time constants, in sec,

i_1, i_2 - constants, A,

t_h– wave tail, time to half value, s.

The constants are:

$$t_1 = \frac{t_h - t_n}{\ln 2} \qquad 2.19$$

$$t_2 = \frac{0.1I}{S_m} \qquad 2.20$$

$$i_1 = \frac{t_1 * t_2}{t_1 - t_2}\left(S_m + 0.9\frac{I}{t_2}\right) \qquad 2.21$$

$$t_2 = \frac{t_1 * t_2}{t_1 - t_2}\left(S_m + 0.9\frac{I}{t_1}\right) \qquad 2.22$$

It was proposed in [5] that the lightning current course might be approximated with the use of:

$$t_f = \frac{I_{\max}}{S_m / I_{\max}} \qquad 2.23$$

Where $S_m / I_{\max}$ is conditional distribution of steepness

Table 2.1 Parameters of the first negative lightning downward strokes [5]

Parameter	Lightning current stroke			
	3 kA ≤ I ≤20 kA		I > 20 kA	
	M	B	M	B
I_{max}- final crest current, Ka	61.1	1.330	33.3	0.605
S_m - maximum front steepness, kA μs^{-1}	24.3	0.599	24.3	0.99
$t_m = I_{max}/S_m$ - minimum equivalent front, µs	2.51	1.230	1.37	0.670
S_m/I_{max} - maximum rate of rise of current conditional distribution, kA μs^{-1}	$12.0 I_F^{0.171}$	0.554	$6.50 I_F^{0.376}$	0.554
t_m / I_{max} , µs	$0.0834 I_F^{0.828}$	0.554	$0.154 I_F^{0.624}$	0.554
t_h - wave tail time to half value, µs	77.5	0.557	77.5	0.557
ρ_c - correction factor between t_m and I_{max}	0.89		0.56	

2.5 Lightning Overvoltage Calculation

2.5.1 Overvoltages in Electric Power Systems due to Lightning

Lightning overvoltages are caused either by direct strokes to the phase conductor or as a result of strokes to earth very close to the line which produces induced lightning surges. The overvoltage, by which substation insulation is stressed, is a function of the line construction and the system configuration. For instance the surge impedance of a wave propagating with wave speed of v (m/s) through the tower having capacitance of C (F/m) is given by

$$Z_t = \frac{1}{C*v} \qquad 2.24$$

Where Z_t is tower surge impedance in ohm

C is the tower capacitance (F/m)

v is the speed of propagation of the voltage wave through the tower (m/µs).

The capacitance of towers has a behavior in which its value grows with ground proximity, so that at the point of contact of the tower with the ground, its value tends to infinity. In contrast, the impedance surge takes an opposite behavior, i.e. it assumes high values in its top and decreases with proximity to the ground until a null value [2].

The surge impedance of transmission towers is closely related to geometric shapes and dimensions. The variety of structures with different shapes and sizes results in the lack of a general equation covering all cases.

In order to simplify the calculations and represent the various types of towers, equations were developed from simple geometric shapes, such as cylinders and cones [3]. The so-called cylindrical and conical models are shown in figure 2-6

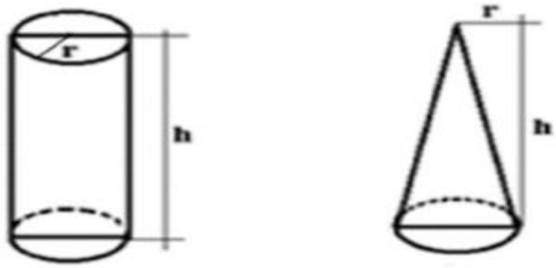


Figure 2-2-6 Cylindrical and conical models to calculate surge impedance of a tower

In cases in which the tower is similar to the cylindrical and conical shapes, the equations (2) and (3) are used, respectively, to calculate the surge impedance [4].

They are

$$Z_t = 60\ln[\sqrt{2} * \left(c * \frac{t}{r}\right)] \qquad 2.25$$

Where c is the wave propagation speed.

Further the expression can be written as

$$Z_t = 60\ln[{}^{c\sqrt{2(h^2+r^2)}}/_{r}] \qquad 2.26$$

t is propagation time

r is radius of the cylindrical shape

h is height of the cylindrical shape

In addition to the cylindrical and tapered models there are other more complex models, created with the purpose of approaching the actual shape of the towers. These models are shown in Figure 2.7

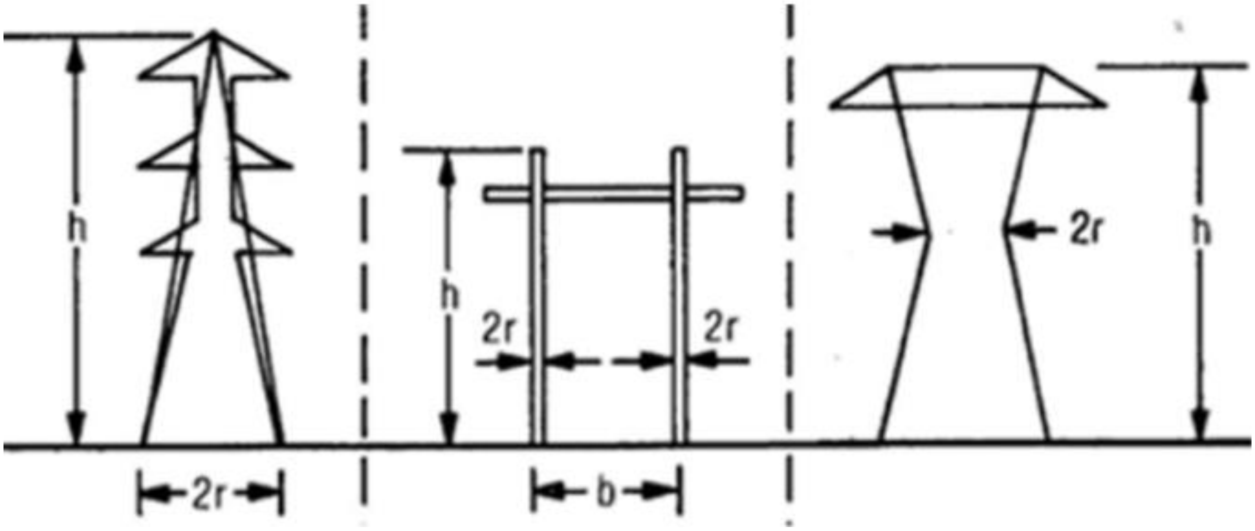


Figure 2-2-7 model to calculate surge impedance of a tower

$$Z_t = 30\ln[\frac{2(h^2+r^2)}{r^2} \qquad 2.27$$

$$Z_t = 0.5[Z_s + Z_m] \qquad 2.28$$

Where

$$Z_s = 60\ln\left(\frac{h}{r}\right) + 90\left(\frac{r}{h}\right) - 60 \tag{2.29}$$

And

$$Z_m = 60\ln\left(\frac{h}{b}\right) + 90\left(\frac{b}{h}\right) - 60 \tag{2.30}$$

$$Z_t = 60[\ln\left(\sqrt{2} * \frac{2h}{r}\right) - 1] \tag{2.31}$$

These models are used to determine the approximate value of the surge impedance of towers. For different types of tower geometry, we have different surge impedance which also varies the value of lightning overvoltage that may occur.

Overvoltage induced by indirect lightning on overhead lines can cause damage to the power system.

The scheme of an influence of lightning strokes on overhead transmissions lines in power systems is presented in Figure 2.8 [13].

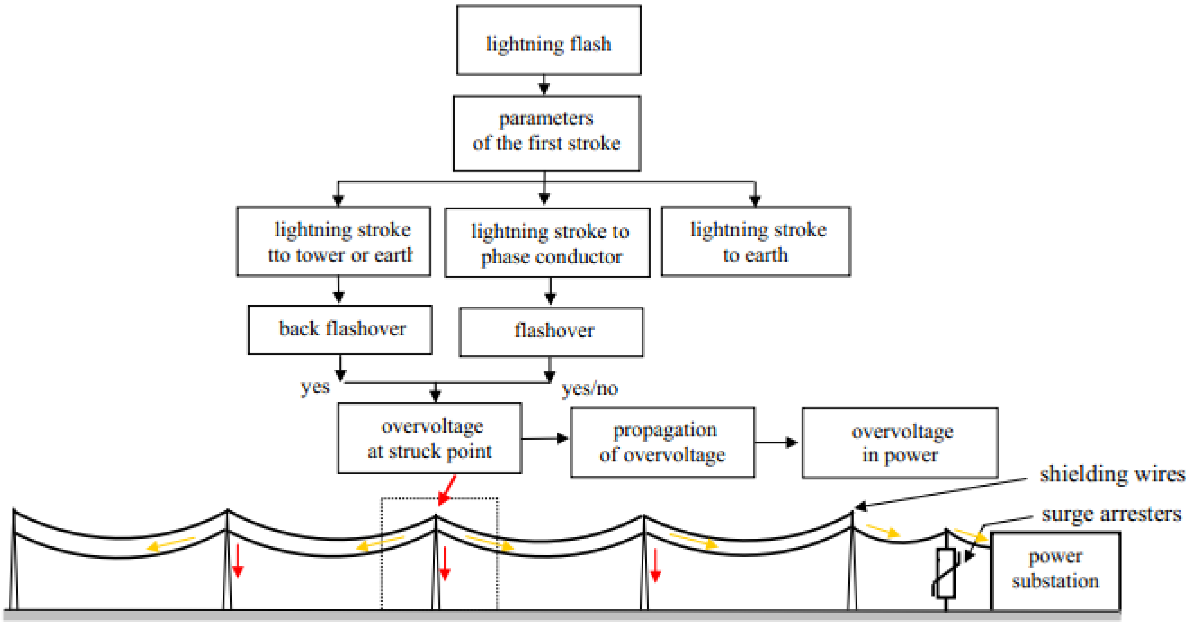


Figure 2-2-8 General scheme of lightning overvoltages in power systems

Moreover, due to its more frequent occurrence, indirect lightning constitutes a more important cause of micro-interruptions than the direct strike. Their estimation is therefore crucial for the correct operation coordination of overhead lines and, as a consequence, has been the object of various studies since many years. The majority of lightning strokes takes place from clouds which have positively charged upper regions with the rest negatively-charge except for some localized positive charge in part of the cloud base. The lightning stroke consists basically of two components, a leader stroke from the cloud which initiates an upward streamer from some irregularity on the earth and a conducting channel along which a return stroke then passes. In many cases the stroke is multiple with a number of leaders and return strokes.

The return stroke, in the course of which the current reaches its peak, may have a current as low as hundreds of amperes, but is more frequently between a few, kilo-amperes and about 100 kA. The current waveform is generally a unidirectional pulse rising to a peak value in about 3 μs and falling to small values in several tens microseconds.

2.5.2 Indirect stroke

When the lightning current stroke contacts the line, the voltage wave starts to be formed as shown in figure 2.9

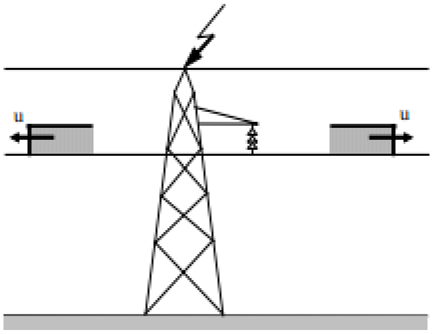


Figure 2-2-9 Voltage wave formed as a sequence of a lightning stroke

Suppose that lightning has struck a tower. More often, this is actually not a tower but rather an overhead grounded wire connected to it. Due to the lightning current$i(t)$, the potential at this point,φ_A, will differ from the zero potential of the earth by the voltage drop in the grounding resistance R, and in the tower inductance L between the tower base up to the point A [4]:

$$\varphi = R_g * i + L_s \frac{di}{dt} \qquad 2.32$$

However, the power wire potential will practically remain the same (in this qualitative description, we ignore all inductances between the power wires, tower and grounded wire). The power wire potential is due to the operating voltage source of the power line:$\varphi_w = U_{op}$then, the insulator string voltage will be

$$U = U_{op} - R_g i - L_s \frac{di}{dt} \qquad 2.33$$

Note that the lightning current and operating voltage may have different polarities. As a result, the overvoltage U may prove to be the sum of the three terms.

The inductance component of the overvoltage$L_s \frac{di}{dt}$ has short life time. It acts about as long as the lightening current rises. For this reason, this component makes the principal contribution to the insulation flashover.

2.5.3 Direct stroke

Suppose now the lightning conductor has proved unreliable, and a discharge has struck the wire as sown in figure 2.10

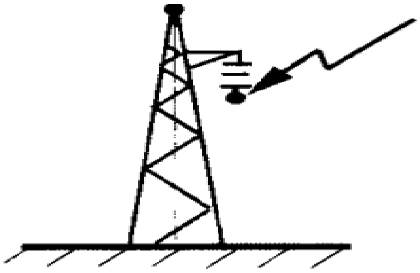


Figure 2-2-10 direct stroke

At the point of the stroke, the current will branch to produce two identical waves of the amplitude ${}^{I_M}\!/_{2}$. The two waves will run toward the ends of the line with a velocity nearly equal to vacuum light velocity. The wire potential relative to the ground will rise to

$$U_M = \frac{U_M * Z}{2} \qquad 2.33$$

Where Z is wave impedance given by

$$Z = \sqrt{\frac{L_1}{C_1}} \qquad 2.34$$

And it varies slightly between 250 and 350 Ω, with the height and the wire radius. So the average lightning current with amplitude 20kA will raise the wire potential up to

$$U_M = \frac{20kA * 250}{2} \ to \ \frac{20kA * 350}{2} = 2500kV \ to \ 3500kV$$

The tower potential will practically remain unchanged and equal to zero, so the insulation overvoltage will be close to the calculated value of U.

2.5.4 Indirect Strokes Induced Overvoltage

Even if lightning strikes near an object, tower, phase conductor, it can be a cause of overvoltage. Such surges are produced by induction. These arise in two different ways, one by electrostatic induction and other by electromagnetic induction. The return stroke of the lightning discharge is responsible factor for the induced voltages.

Calculation of such induced strokes can be done in two parts:

i. The return stroke model with its associated electric field effects. This is a model of return stroke current in time and space. The return stroke is assumed vertical
ii. The voltage induced on phase resulting from the interaction of above model. For calculating induced voltages, coupling models are used. The Rusck's model is used for calculating induced voltages flashover rate.

The distance within which a cloud-to-ground lightning discharge can cause an induced voltage flashover is generally within 200 meters of the stroke.

The Rusck's formula is given by [11], for calculation of induced voltage is as follows,

$$V_{max} = \frac{Z_0 I_0 h}{y}\left(1 + \frac{V}{\sqrt{2} * V_0 \sqrt{1 - \frac{1}{2}(\frac{V}{V_0})^2}}\right) kV \qquad 2.35$$

Where $Z_0 = 30 ohms, I_0$is the lightning peak current in kA, h is the average height of the power line over ground, y is the distance between line and the lightning strike in meters, v is return stroke velocity and v_0 is speed of light in free space in m/sec. Generally assumed value of V varies between 0.3 and 1.5 m/s.

The number of induced flashovers decreases as a function of BIL. Also major factor while considering induced overvoltage is steepness of the pulse. Such overvoltage can cause phase-to-ground or phase-phase flashover.

Chapter 3 Modeling and protection of Transmission Line against lightning over voltage

3.1 introduction

With the significant in power generation to meet growing demand, the transmission system has to be augmented to transfer the bulk power generated to the load center. The general transmission lines gets very much affected by lightening thunder (leader stroke) while working steadily at its normal working period. Lightening effects on transmission line have always been a matter of concern in studies of power distribution, transmission and up gradation of transmission system. The magnitude and shape of the lightening on transmission line will be in undetermined and unpredictable form. It takes place for some microseconds to milliseconds and as it arises (immerges on object), it causes–serious damage to the system where it immerges [4]. The analysis of lightening leader (strokes) arising in distribution and transmission system is assuming increased importance. This is mainly because such studies yield necessary information about the possible damage on different component which will determine their proper design as well as their persistence protection strategies. Height dependent model is universally accepted standard for both distribution and transmission systems protection level analysis [13].

3.2 Transmission line protection analysis against lightning

There are two methods that are employed to protect transmission line against lightning stroke risk. The first one is by installing shield wire at the top most above phase conductors so as the stroke will not hit the phase conductor. This method protects the line from direct stroke. The second method is by incorporating surge arrester. This will protect the transmission system from indirect stroke [5].

3.2.1 The Simplified Electro Geometric Model (EGM)

Shielding wires are used for the protection of high voltage overhead transmission lines against direct lightning strokes. Protective wires are strung above phase conductors on transmission lines. Shielding wire is connected directly to line towers at the top to protect the phase conductors from a direct lightning strike. Lightning strikes will hit shielding wires rather than phase conductors. If the lightning stroke the phase conductors, a short circuit to the ground might occur, which could result in a wide-spread power outage. Phase conductors of transmission lines are connected to the towers by insulators. Line insulators must be strong enough to support the line conductors and they are a part of insulation systems of overhead lines.

For analyzing the transmission line protection against direct lightning strokes with the use of shielding wires, a simplified concept of the electrogeometric model will be used. As the down leader approaches the earth, a point of discrimination is reached. At this point the leader decides the object it will strike. The electrogeometric model portrays this concept with the use of the striking distance. If all striking distances to the shielding wire, to the phase conductor and to earth are equal, the stroke would terminate on the closest object. However, these striking distances are in general not considered equal and therefore some alternative considerations are required. In general, the striking distance is of the form [2]:

$$r = Ai^{b} \tag{3.1}$$

Where:

A, b – constants, dependent on the object, i.e. the phase conductor, the shielding wire or earth,

i - stroke current

Values of constants A and b are presented in Table 3.1

The usual model of phase conductors and shielding wires of overhead lines is presented in figure 3.1 and is illustrated for one specific value of stroke current. The arcs of the circles are drawn centered at the phase conductors and the shielding wire, having radius of r_c.

In transmission line design, the specification of the shielding wire location is usually given by the shielding angle δ. If the shielding wires are horizontally disposed beyond the phase conductors, the shielding angle is defined as negative [1].

The electro-geometric model is depicted in figure 3.2 for the one specific value of the stroke current. The striking distances, r_c are shown as arcs of circles from the phase conductors and shielding wires and a horizontal line is constructed parallel to the earth at height of r_g. Downward leaders or strokes reaching the arc between B and C will terminate on the shielding wire. Those reaching the arc between A and B will terminate on the phase conductor, and those beyond A will terminate on the earth [1]

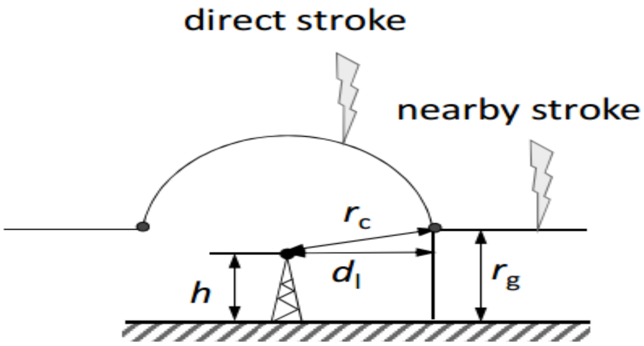


Figure 3-1 Simplified representation of the electrogeometric model for a vertical structure of height h

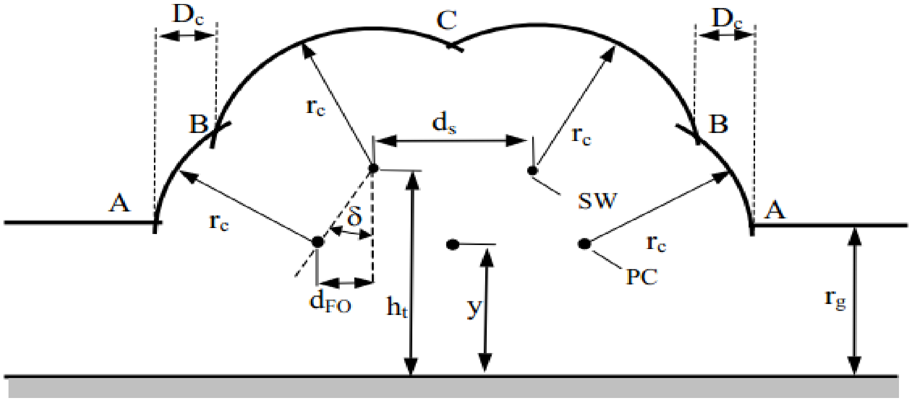


Figure 3-2 Electrogeometric model representation of phase conductors and shielding wires

SW - shielding wire,

PC - phase conductor,

d_{FO}- horizontal displacement of phase conductor and shielding wire,

r_c -radius to conductor in the electrogeometric model

d_s- Distance between shielding wires,

δ- The protection angle of the tower,

h_t-distance between shielding wire and earth,

y - Distance between phase conductor and earth

From figure 3.2, the general expression of r_c and r_g are given by

$$r_c = A_{rc} I^b \tag{3.2}$$

$$r_g = A_{rg} I^b \tag{3.3}$$

Where

r_c -radius to conductor in the electrogeometric model

A_{rc}, b – constants,

The value of the ground striking distance r_g can be also expressed as follows:

$$r_g = kr_c \qquad 3.4$$

Therefore, taking into account both attractive conductor and ground attractive radii, lateral attractive distance (d_l) becomes:

$$d_l = \sqrt{r_c^2 - (r_g - h)^2}\,,\ for h < r_g \qquad 3.5$$

$$d_l = r_c,\ for h \geq r_g \qquad 3.6$$

Table 3.1summarizes the values experimentally inferred and adopted in the literature. [18]

Sources	A		B
	r_c	r_g	
Young et al. [1963]	27 for h<18m $27(\frac{444}{462-h})\ for h > 18m$	27	0.32
Armstrong and Whitehead [Cigré WG 33-01, 1991]	6.7	6	0.8
Brown and Whitehead [1969]	7.1	6.4	0.75
Love [1973]	10	10	0.65
Andersson IEEE WG [1985]	10	6.4 for UHV 8.0 for EHV, 1 for others	0.65
IEEE T&D Committee [1981]	8	$8\frac{22}{y}\ for 4.8 < r_g < 7.2$	0.65
IEEE T&D Committee 1992 [IEEE Std. 1243, 1997]	10	3.6+1.7ln(43-h), for y<40m 3.6+1.7ln(43-40),for y>40m	0.65
IEEE substation Committee [1995]	8	8	0.65

3.2.2 Lightning Performance Estimation

3.2.2.1 Shielding failure flashover rate

The procedures for the calculation of the shielding failure flashover rate (SFFOR), make reference to the electrogeometric model (EGM). In this model for a specific value of stroke current, arcs of radii r_c are drawn from the phase conductors and from the shield wires, also the horizontal line at a distance r_g from the earth can be drawn. By referring to this model, shielding failure is a stroke that terminates on a phase conductor, in spite of the presence of overhead ground wires [12].

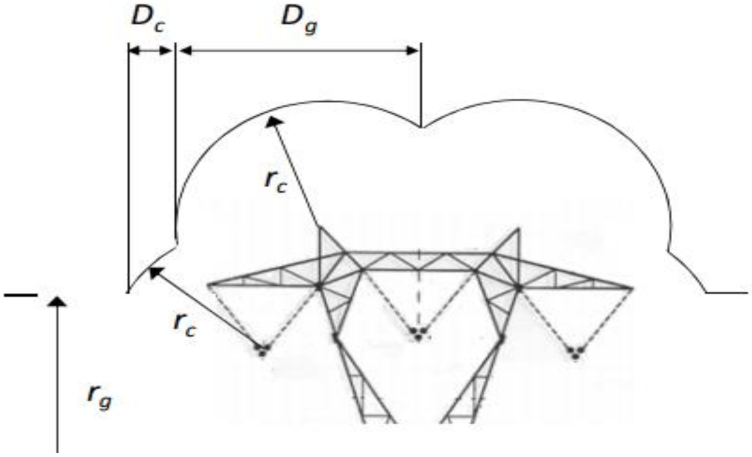


Figure 3-3 Geometry adopted in [Cigré WG 33-01, 1991] and [IEEE Std. 1243, 1997] for the calculation of the shielding failure rate (SFR)

For such geometry it is possible to determine the flash collection rate as:

$$N_s = 2N_g L\int_{\mathrm{Im}in}^{\infty}[D_g(I)+D_c(I)]f(I)dI \qquad 3.7$$

Where L is the line length (typically 100 km), f (I) is the density function of the lightning current amplitude distribution.

Unreliability of shielding wire is dependent on the distance Dc and ground flash density Ng. When Dc and N_g are constant for line with length l_L then the differential of probability dP_f of lightning stroke with maximum value of current I to the external phase conductor is expressed by formula:

$$dP_f = N_g l_L D_c(I) f(I)dI \qquad 3.8$$

Where: f (I) - probability density f unction of crest current of the first stroke, Ng- ground flash density N_g calculated with the use of equation:

$$N_g = 0.04Td^{1.25} \quad 3.9$$

Where: Td - number of thunderstorm -days.

By integrating only the exposure area of the phase conductors (the one corresponding to Dc we obtain the so-called shielding failure rate (SFR). The ineffectiveness of protecting work is characterized by the coefficient of shielding failure rate (SFR) which determines the number of strokes to the two external phase conductors a year:

$$\mathrm{SFR} = 2N_g l_l \int_{I_{min}}^{I_{max}} D_c(I) f(I) dI \quad 3.10$$

Where: Ng - ground flash density, flashes/km^2/year,

l_l- line length, km,

I_{min} - minimum lightning current, 2-3 kA

D_c - horizontal exposed distance of the phase conductor, m,

f (I) - probability density function of crest current of the first stroke.

The integration limits of the above equation can be determined in view of the following. As shown in the figure by increasing the lightning currents the value of Dc decreases until a point at which all three striking distances meet and Dc becomes zero. This point defines the I_{max} value the equation.[18]

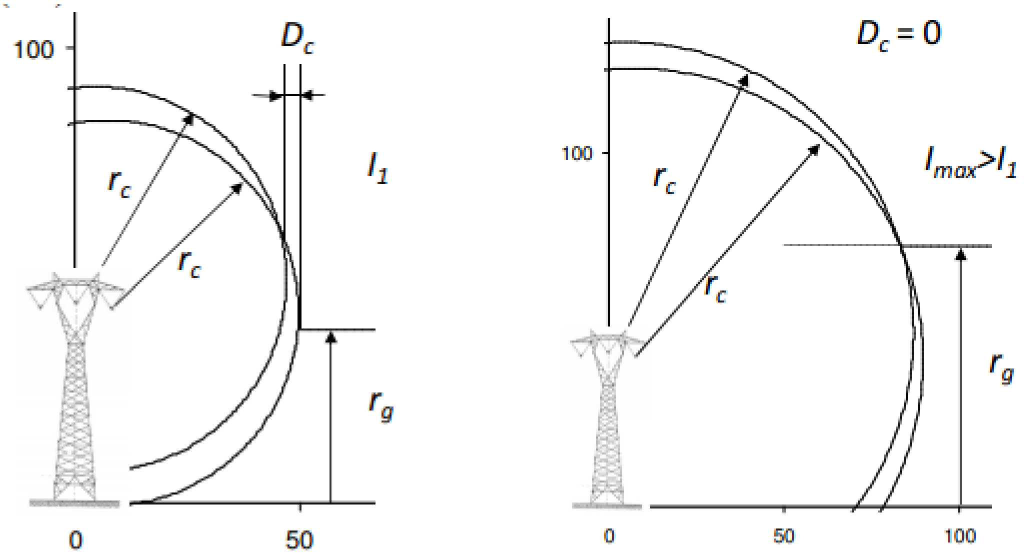


Figure 3-4 Geometry adopted in [Cigré WG 33-01, 1991] and [IEEE Std. 1243, 1997] for the calculation of the Imax value of SFR

The shielding failure rate (SFR) provides the number of strokes that terminate on the phase conductor. Not all of these will result in flashover. However, if the voltage produced by a stroke to the conductor exceeds a critical voltage value, a flashover occurs. Thus the SFR includes both the strokes that cause flashover and those that do not.

Therefore the number of flashovers caused by unreliability of shielding wires is determined with the use of the shielding failure flashover rate, SFFOR written as follows:

$$SFOR = 2N_g l_l \int_{If}^{I_{\max}} D_c(I) f(I) dI \qquad 3.11$$

Where: I_f– minimum peak value which cause of flashover.

As noted from this equation, the SFFOR becomes zero if I_{max} is equal to or less than I_f [14].

The maximum stroke current I_{max} is defined as the maximum current beyond which no stroke can terminate on the conductor. At I_{max} distance Dc is zero.

As an approximation, the maximum value of r_g is:

$$r_{g\max} = \frac{(h_t + y)}{2}(1 - \frac{r_c}{r_g}\Gamma \sin\delta) \qquad 3.12$$

$$\text{Where } \Gamma = \frac{r_c}{r_g} \qquad 3.13$$

From geometry:

$$D_c = r_c[\cos\theta - \cos(\beta - \delta)] \qquad 3.14$$

Where δ - the protection angle of the tower

$$\beta = \sin^{-1}[d_{FO}{}^2 + (h_t - y)^2 * \frac{0.5}{2r_c}] \qquad 3.15$$

$$\theta = \sin^{-1}[\frac{(r_g - y)}{r_c}] \qquad 3.16$$

At higher transmission voltages a shielding failure with a low current may not necessarily cause a flashover. The minimum or critical current required for a flashover would be:

$$I_c = {}^{2U_{50}}\!/_{Z_c} \qquad 3.17$$

Where: U_{50} – lightning impulse critical flashover, negative polarity, V,

Z_c - phase conductor surge impedance, Ω*[14,]*.

The maximum current which makes the exposure distance of the phase conductors Dc equal to zero, can be calculated as follows [6]:

$$I_{p\max} = [\frac{\sqrt{(d_{FO}{}^{2} + (h_t - y)^2} + 2y}{1.34(h_t^{0.6} - y^{0.6}\sin\delta)}]^{1.35} \quad 3.18$$

Where: h_t – shielding wire height, m

y - Average phase conductor height, m (Fig. 3.1).

It depends on the construction of the line towers, their dimensions and location of shielding wires.

To determine the shielding failure flashover rate SFFOR, is necessary to calculate the voltage across the line insulation. The IEEE procedure suggests to approximately calculate such a voltage as:

$$E = I\,\frac{Z_{surge}}{2} \quad 3.19$$

$$Z_{surge} = 60\sqrt{\ln\frac{2h}{r}\ln\frac{2h}{R_c}} \quad 3.20$$

In which h is the average phase conductors heights, r the phase conductor radius and R_c the corona radius of the conductor that refers to an electric field of 1500 kV/m.

If the voltage E of above is set to the Critical Flashover Voltage (CFO), negative polarity, then the critical current, at and above which flashover occurs can be determined. This value corresponds to the lower integral limit I_{min} of equation for SFR.

$$I_{\min} = 2\frac{CFO}{Z_{surge}} \quad 3.21$$

In the IEEE procedure, the CFO value is determined by making reference to the V-t curve of the line insulation and the CFO employed is usually assumed as the standard CFO, negative polarity, which is typically assumed equal to 605 kV/m times the strike distance of the insulator string.

3.2.2.2 Back flashover rate

As known, when lightning strikes the tower (or the overhead ground wires), the current on the tower and ground impedances causes the rise of the tower voltage. A small fraction of the tower and shield wires voltage is induced in the phase conductors due to the electromagnetic coupling, nevertheless the tower and shield wires voltage becomes much larger than the phase conductors voltages. If that voltage difference exceeds a critical value, a flashover occurs called “back flash” or “back flashover” and the corresponding minimum lightning current that produces such a flashover is called “critical current”. The term “back” refers to the fact that the highest voltage is on a part of the power system normally at ground potential, namely the line tower or the shielding wires.

The calculation of the critical current I_c depends, in general, to the following parameters:

- Wave shapes and amplitude of the lightning current;
- Tower model;
- Flashover criteria (e.g. volt-time characteristic or others);
- Transmission line models including all line conductors (electromagnetic-coupling);
- Tower grounding models;
- Presence of surge arresters;
- Representation of power system components (e.g. transformers);
- Possible representation of the soil ionization.

The procedure adopted by CIGRÉ for the calculation of the line Backflash overrates (BFR) is specifically aimed at calculating the critical current and the consequent BFR value. In particular, the CIGRÉ procedure analytically calculates the backflashover critical current by making reference to simplified representation of the travelling phenomena that take place for both cases of a lightning strike to a tower or to an overhead ground wire. Due to the typical front times of lightning current, in the order of 1-4 µs, longer than typical travelling times of transmission line towers, many models assume that the tower response is dominated by transverse electromagnetic wave mode.

In [CIGRÉ WG 33-01, 1991], the BFR is given by the probability of exceeding the critical current multiplied by the number of flashes to the shield wires, N_L. However, since the crest voltage and the flashover voltage are both functions of the time-to-crest t_f of the lightning current, the critical current previously determined is variable. Therefore, the BFR considering all the possible time-to-crest values is:

$$BFR = 0.6 N_L \int_0^\infty \int_{I_c}^\infty f(\frac{I}{t_f}) f(t_f) dI dt_f \qquad 3.22$$

Where $f(\frac{I}{t_f})$- is the conditional probability density function of the stroke current given the time to-crest and $f(t_f)$ is the probability function of the time-to-crest value.

Note that, in order to obtain the BFR for strokes to the tower and to the spans, the BFR obtained for strokes to the tower is multiplied by a coefficient, equal to 0.6 [Cigré WG 33-01,1991, Hileman,1999].

Another, more simplified procedure for the calculation of the BFR, is also illustrated in [CIGRÉ WG 33-01, 1991] as the BFR resulting from the application of the equation (3.22) can be obtained by using of an equivalent time-to-crest value T_e.

$$BFR = 0.6 N_L \int_{I_c}^\infty f(I) dI = 0.6 N_L P(I > I_c) \qquad 3.23$$

3.3 Procedure to design electrogeometric model (EGM)

- Calculate Surge Impedance Z_s from the geometry. For two heights, use the higher level heights
- Determine the value of critical flash over voltage (CFO) or Basic lightning impulse insulation level (kV)
- Calculate the value of stroke current (Is)
- Calculate the value of the striking distance

According to [22], Allowable Stroke Current (I_s):

$$I_s = \frac{BIL * 1.1}{\frac{Z_s}{2}} = \frac{2.2}{Z_s} * BIL \qquad 3.24$$

$$0.94 * \left(\frac{\mathrm{CFO}}{\frac{\mathrm{Z_s}}{2}}\right) * 1.1 = \frac{2.068}{\mathrm{Z_s}} * \mathrm{CFO} \quad 3.25$$

I_s- Allowable stroke current (kA)

BIL - Basic lightning impulse insulation level (kV)

Zs- Surge impedance (Ω)

CFO - Negative polarity critical flashover voltage (kV)

Surge impedance of a transmission line will be calculated as:

$$Z_s = 60\sqrt{\ln\left(\frac{2h}{R_c}\right)\ln\left(\frac{2h}{r}\right)} \quad 3.26$$

$$R_c \ln\left(\frac{2h}{R_c}\right) - \frac{V_c}{E_0} = 0 \quad 3.27$$

h - Average height of the conductor (m)

Rc- Corona radius (m)

r - Conductor radius (m)

Vc= Basic lightning impulse insulation level BIL (kV)

E_0 = Limiting corona gradient = 1500kV/m

According to [22] the value of Basic lightning impulse insulation level (kV) is given as summarized in table 3.2

Table 3.2 Basic lightning impulse insulation level (kV)

V_{rms}	BIL(kV)	V_{rms}	BIL(kV)	V_{rms}	BIL(kV)
362	950	525	1175	765	1675
	1050		1300		1800
	1175		1425		1950

The striking distance is calculated by

$$s = 8 * k * I_s^{0.65} \qquad 3.28$$

Where

S is the strike distance in meters

I_s is the return stroke current in kA

K=1 for strokes to wires or the ground plane

K=1.2 for strokes to a lightning mast

Failure Probability calculation for 500kV

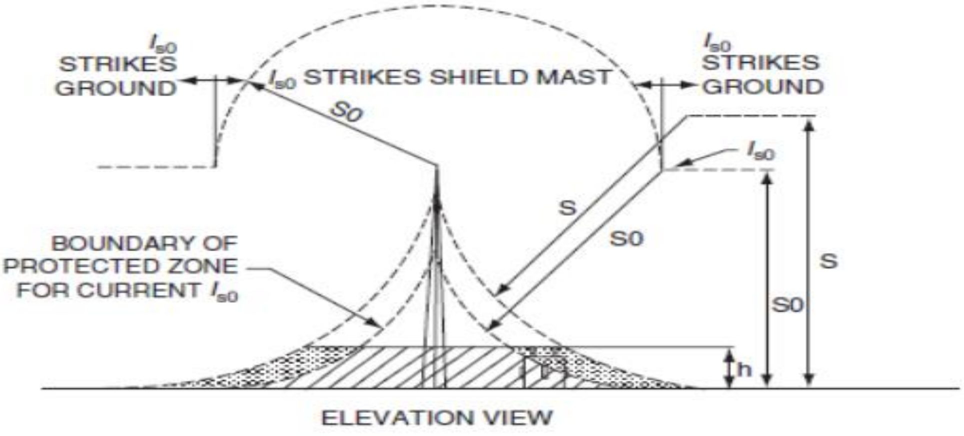


Figure 3-5 electro geometric model to calculate failure probability

Referring to figure 3.5 the distance S is the distance above which protection is required

And S_o is the distance corresponding to allowable stroke current.

From table 3.2 the value of BIL for 500kV (rms value) voltage level is 1175kV, and surge impedance of transmission line is 355 Ω.

Hence the allowable Stroke Current (I_s) is

$$\frac{2.2}{\mathrm{Z_s}} * \mathrm{BIL} = \frac{2.2 * 1175}{355} = 7.28kA$$

$$S_0 = 8 * k * {I_s}^{0.65} = 8 * 1 * 7.28^{0.65} = 29.07m$$

Now any value above S= 29.07m can be selected as the distance above which protection is required. For instance if we select S=54m (height of the top most phase conductor of the line understudy), the stroke current corresponding to this distance is

$$I_s = (\frac{S}{8k})^{\frac{1}{0.65}} = (\frac{54}{8*1})^{\frac{1}{0.65}} = 18.87kA$$

For this condition the exposed area or unprotected zone is given as

$$7.28kA < I < 18.87kA$$

Now the failure probability is calculated by first calculating the probability that a stroke current will exceed Is_0 and Is

These two probabilities are given by

$$P(I > 7.28kA) = \frac{1}{1+(\frac{I_{S0}}{24})^{2.6}} = \frac{1}{1+(\frac{7.28}{24})^{2.6}} = 0.96$$

$$P(I > 18.87kA) = \frac{1}{1+(\frac{I_S}{24})^{2.6}} = \frac{1}{1+(\frac{18.87}{24})^{2.6}} = 0.65$$

Now probability of failure is

$$P(I > 7.28kA) - P(I > 18.87kA) = 0.31 = 31\%$$

Failure Rate

According to electrogeometric for a specific value of stroke current, arcs of radii r_c are drawn from the phase conductors and from the shield wires to do performance analysis of transmission line. From this statement we can draw figure 3.6 [20]

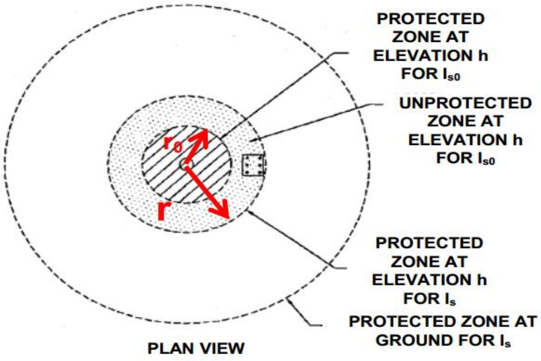


Figure 3-6 protected zone and exposed zone

In the case understudy, the value of r_o=29.07m and r=54m

As this arc form circular path, the unprotected area is

$$\pi(A_r^2 - A_{ro}^2) \rightarrow \pi(54m^2 - 29.07m^2) = 2070.7m^2 * 3.14 = 0.0065km^2$$

The isokeraunic level for the area understudy is 10 thunderstorm-days per year (Td= 10) [21]

$$\mathrm{N_k} = 0.12 * \mathrm{T_d} = 0.12 * 10 = 1.2\text{strokes per km}^2\text{per year}$$

The annual number of strokes expected to descend into the unprotected area is:

$$1.2\text{strokes per km}^2 \text{ per year} * \ 0.0065\text{km}^2 = 0.0078\text{per year}$$

The annual expected number of equipment failures due to direct lightning strokes, using the 31% probability [21]

$$0.0078\text{per year} * 0.31\text{failures} = 0.0024\text{failures per year}$$

$$= 413.18\text{years between failures}$$

3.4 Multistory Tower Model

According to this model, tower is composed of four sections that represent the tower sections between cross-arms. Each section consists of a lossless line in series with a parallel RL circuit, included for attenuation of the traveling waves.

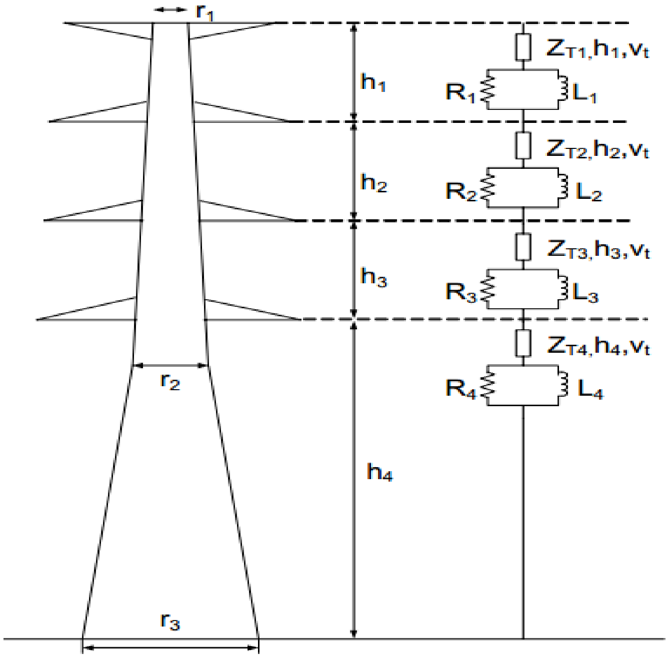


Figure 3-7 multistory model of HVTL

Where h_1 represents the tower dimension from the top most to the first cross arm from top and R_1, Z_{T1} and L_1 are the values of resistance, impedance and inductance corresponding to this section respectively, h_{12} represents the tower dimension from the top most to the second cross arm from top and R_2, Z_{T2} and L_2 are the values of resistance, impedance and inductance corresponding to this section respectively, h_3 represents the tower dimension from the top most to the third cross arm from top and R_1, Z_{T3} and L_3 are the values of resistance, impedance and inductance corresponding to this section respectively, V_t voltage of the tower under transient , and h_4 is height of the bottom conductor from the ground [18]

The electrical parameters of the line and the geometrical design for the tower are established as follows:

$$R_i = \Delta R_i * x_i = 2 * Z_t \frac{\ln(\frac{1}{\alpha})}{(h-x)} \quad 3.29$$

$$L_i = 2 * \tau * R_i \quad 3.30$$

$$\tau = \frac{h}{c_0} \quad 3.31$$

Where τ is the time of the travelling lightning wave along the tower height expressed in µs, R_i and Li are the values for resistance and inductance of each (RL) circuit of the tower,

h=63 m is the tower height, x is the distance between power distribution line phases

c_0 300m/μs is the light speed in free space,

$\alpha = 0.89$ is the attenuation coefficients along the tower [19]

3.5 Analytical Model of generally used Transmission Line Tower

Shielding failure flashovers can be reduced to rare events by providing properly shielding conductors. Even popularly located shield wires failed to intercept some of the strokes having prospective currents to earth above minimum. The design problem then consists of steps required to locate the shield wires so as to intercept strokes having prospective currents to earth above minimum amplitude. It is convenient to develop an analytical model which exhibits the relations between the structural and electrical parameters of the problems. In such a model, the mean structural dimension of the line together with the mean of striking distance of the stroke constitutes the geometrical parameters.

The complete analytical model consists of geometry together with an associated set of basic assumptions and mathematical relations [10].

a. The mean conductor height Hg can be computed from the profile drawings or, alternatively, estimated for primary purposes from the following relation.

$$H_g = H_{gt} - (2/3)Sc \quad 3.32$$

Where H_{gt} is height of conductor at the tower and Sc Sag of the conductor;

Rolling profile

$$H_{gr} = H_{gt} \tag{3.33}$$

For mountainous

$$H_{gm} = 2H_{gt} \tag{3.34}$$

For all cases

$$H_g = H_p + \Delta \tag{3.35}$$

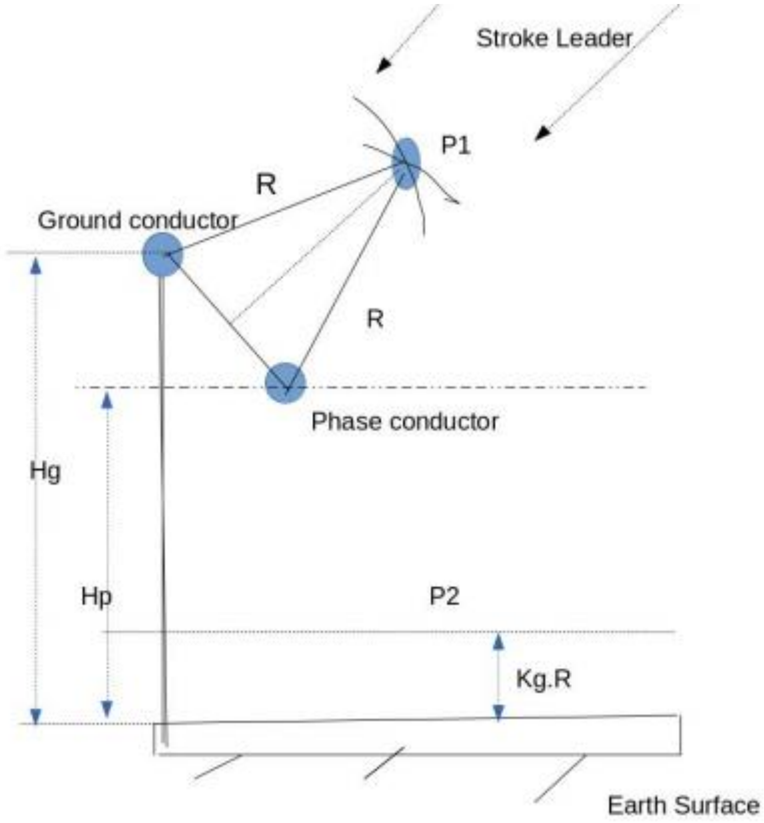


Figure 3-8 simplified HV tower structure for lightning performance analysis

b. The mean Spacing between the phase conductor and the shield wire can be estimated from a preliminary configuration. If none are yet available an estimate of

$$C = {U_{50\%}}/{145m}, \qquad 3.36$$

may be used for initial studies

c. The striking distance to be used is the value corresponding to prospective current to earth of

$$I_{oc} = {2.2U_{50\%}}/{Z_{cKA}} \qquad 3.37$$

U (50percentage) =critical impulse flashover voltage of the insulation (kV);

Zc = surge impedance of the conductor in the presence of shield wires (ohm).

d. The striking distances are given by (According to the standard IEEE model of Transmission line)

$$R = 10I_p^{0.65} \qquad 3.38$$

As leader immerges to transmission line, protective theory says that both ground wire and phase conductor produces protective arc around them. This protective arc cut each other in space at terminating point. The termination point of a lightning stroke to a transmission line can be a ground wire, a phase conductor, a metal tower or even the ground. According to the electro-geometrical model theory, it is able to determine the termination point, when the striking distance is known.

Figure 3.9 clearly explains the striking position of leader to various points. Now the following points can be considered with respect to the figure.

(1) The lightening strokes emerges before point P_1 will goes to ground wire i.e. the transmission line has been saved

(2) If lightening strokes goes between points P_1 and P_2 then it will immerges directly to the phase conductor i.e. it will cause damage to the transmission line and can harm to useful equipment.

(3) If lightening stroke immerges after point P_2 then it will goes to ground and transmission line will be saved.

From above conclusions point to be considered it is very important to reduce the area of gap between point P_1 and P_2

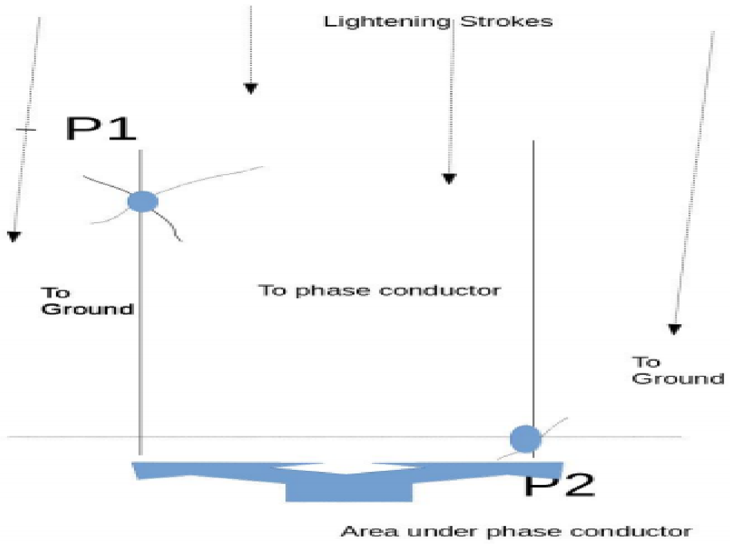


Figure 3-9 Area of region showing immerging lightening stroke

Derivation for estimating the co-ordinates of points P_1 and P_2

Figure 3.9 shows the upper portion of typical structure of the HV transmission tower

Here various physical parameters are as follows:

Hg = Height of ground wire from earth

Hp = Height of phase conductor from earth

If R= radius of protective arc produced by both conductor during lightening and θ Is Shielding angle between Ground wire and phase conductor now from the figure, we have;

$$AB = H_g - H_p = \Delta \text{, and} \quad (3.39)$$

$$BC = (H_g - H_p)\tan\theta = \Delta\tan\theta \quad (3.40)$$

Hence for the case under study, the shielding angle is 0degree

$BC = 19m * tan0° = 0m$

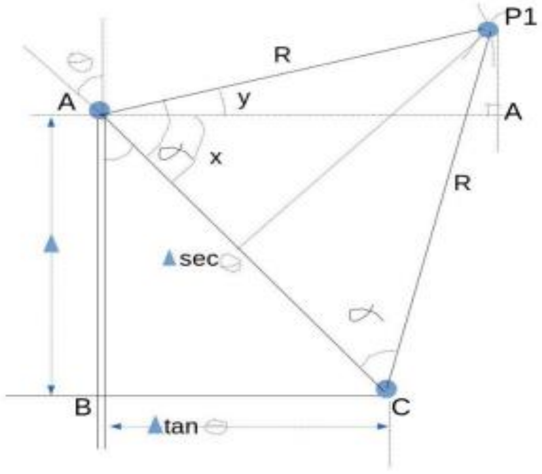


Figure 3-10 Fig for calculating co-ordinate of P1

And by Pythagoras theorem

$$AC = \sqrt{\Delta^2 + (\Delta^2 \tan^2(\theta)} = \Delta \sec\theta \qquad 3.41$$

Now co-ordinates of ground wire and phase conductor are

$$A(0, H_g), \quad \text{and } C(\Delta \tan(\theta), H_p)$$

Now triangle ACP1 is isosceles triangle. Then we have:

$$\alpha = \angle x + \angle y \qquad 3.41$$

$$\cos\alpha = \left(\frac{\Delta/_2 \sec\theta}{R}\right),$$

There fore

$$\alpha = \cos^{-1}\left(\frac{\Delta/_2 \sec\theta}{R}\right) \qquad 3.42$$

$$\alpha = \angle x + \angle y$$

$$\alpha = 90 - (\theta - y)$$

$$\alpha = \cos^{-1}\left(\frac{\Delta/2\,\sec\theta}{R}\right) = 90 - (\theta - y)$$

$$\frac{\Delta/2\,\sec\theta}{R} = \cos(90 - (\theta - y)$$

$$\frac{\Delta/2\,\sec\theta}{R} = \sin(\theta - y)$$

$$(\theta - y) = \sin^{-1}\left(\frac{\Delta/2\,\sec\theta}{R}\right)$$

$$y = \theta - (\sin^{-1}\left(\frac{\Delta/2\,\sec\theta}{R}\right) \qquad 3.43$$

Where

y is the deviation angle of P_1 in degree

θ is shielding angle in degree

R is striking distance

Hence co-ordinates of the point P1 will be

$$P1(R\cos(\theta), H_p + R\sin(\theta)) \qquad 3.44$$

R is found by taking peak value of lightening current as

$$R = 13.82 I_p^{0.55} \qquad 3.45$$

Hence coordinates of P1 will be

$$P1(Rcos\,\theta°, 44 + Rsin\,\theta° \qquad 3.46$$

And for finding co-ordinates of point P2 we can use generalized circle equation

$$(x - x1)^2 + (y - y1)^2 = R^2 \qquad 3.47$$

$$y = KgR \tag{3.48}$$

$$y1 = Hp \tag{3.49}$$

$$x1 = (\Delta \tan \theta) \tag{3.50}$$

Solving equation 3.47, 3.48, 3.49, 3.50 we get co-ordinate of P2

$$P2\left(\sqrt{R^2 - (0.5 * R - Hp)} + (\Delta \tan \theta), 0.5 * R\right) \tag{3.51}$$

In this way we get X distance of both co-ordinate so we can find the x distance (P2-P1) where lightning strokes can be immerged

If we are calculating the area for 100km Transmission line we can simply use following formula

$$a = \left(\frac{P_2 - P_1}{1000}\right) * 100 \tag{3.52}$$

Probability of the distribution of lightening over the given current range can be found by standard formula the cumulative Probability of II_f exceeding I is given by

$$\mathrm{P}(\mathrm{I_f} > \mathrm{I}) = \frac{1}{1 + (\frac{\mathrm{I}}{\mathrm{I_{first}}})^{2.6}} \tag{3.53}$$

Similarly we can calculate all the values of lightening strokes for ground wire in the same way.

Analytical Calculation for 500kV tower

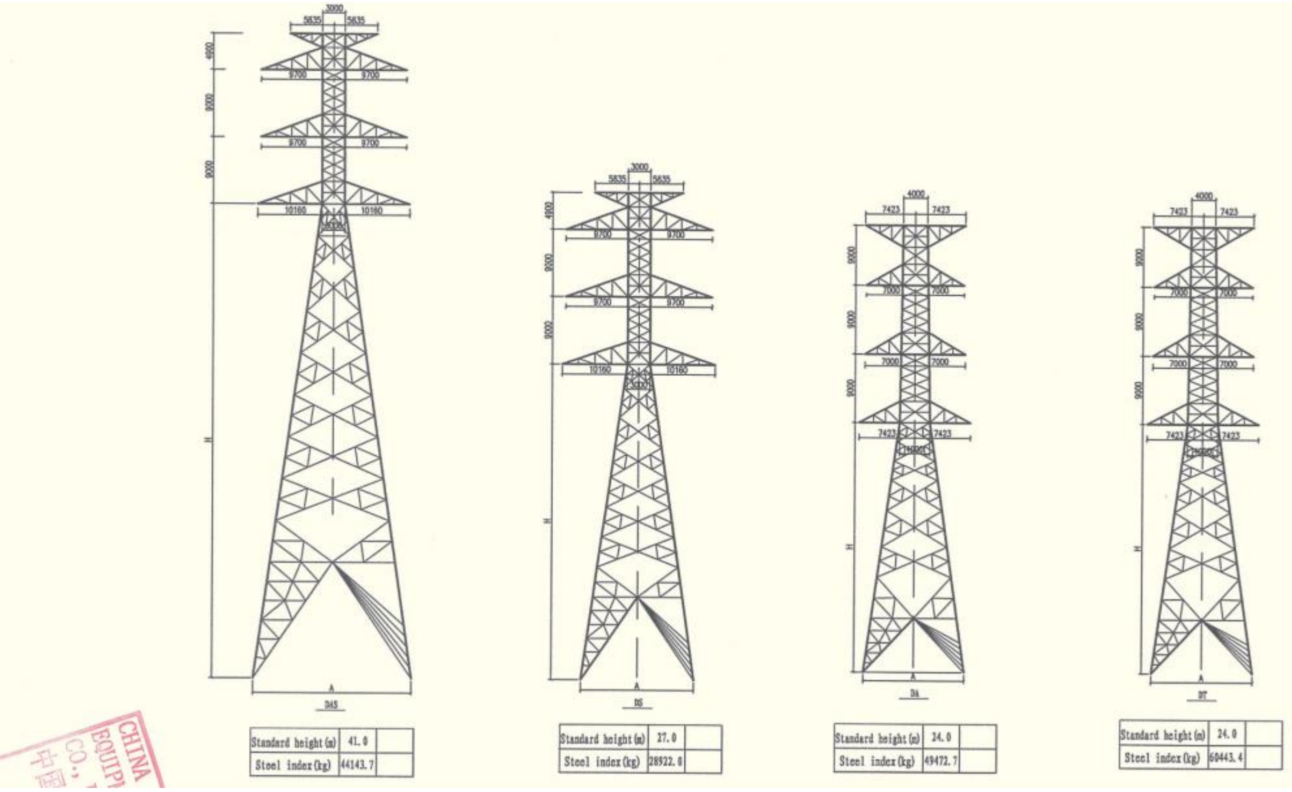


Figure 3-11 GERD-Diddesa-Holeta transmission line tower

We have the followings datum from GERD-Diddesa-Holeta transmission line contractor manual

Dh_p= minimum horizontal conductor distance = 14.0m

DV_pPhase to phase conductor vertical distance= 9.0m

H_p=height of phase conductor from ground=23.0m

H_g= maximum height of shield wire from ground = 63.0m

D_g= shield wire to conductor distance = 9.0m

Shielding angle 0 degree

$$H_p = 23 + 9 * 2 = 41m$$

$$\Delta = H_g - H_p = 63 - 41 = 22m$$

$$R = aI_p^b \ \rightarrow a = 13.82, b = 0.55$$

So the striking distance will be as

$$R = 13.82 I_p^{0.55}$$

Now we take peak value of leader current 20kA

So

$$R = 13.82 I_p^{0.55} = 13.82 * 20^{0.55} = 71.79$$

So starting point will be

$$x1 = Rcos(\theta - sin^{-1}\left(\frac{13\sec(\theta)}{2R}\right))$$

So

$$x1 = 71.79cos\left(0 - sin^{-1}\left(\frac{13*\sec(0)}{2*71.79}\right)\right) = 71.49m$$

The end point will be

$$x2 = (R^2 - \left(K_g R - H_g\right)^2)^{1/2} + (\Delta tan\theta)\ here\ K_g = 0.5$$

$$x2 = (71.79^2 - (0.5 * 71.79 - 63)^2)^{1/2} + (13tan\theta) = 66.47m$$

So area of lightning goes to phase conductor will be

$$a_p = \frac{(x_2 - x_1)*100}{1000} = \left(\frac{(71.49 - 66.47)*100}{1000}\right) = 0.502$$

And area of lightning goes to ground wire will be

$$a_g = \frac{(x_1 - x_0)*100}{1000}\ here\ x_0 = 0 \rightarrow \frac{(66.47 - 0)*100}{1000} = 6.647m$$

Probability distribution for considering current limit from 17.5kA to 22.5kA ($I_1 to\ I_2$) taking I_f 31kA

$$P\left(I_p > I_1\right) - (I_p > I_2)$$

$$\frac{1}{1+\frac{I_1}{I_f}}-\frac{1}{1+\frac{I_2}{I_f}}=0.64-0.58=0.06$$

So the effective area of lightening on phase conductor will be

$$a_{fp}=P*a_p \rightarrow 0.06*0.502=0.0301m^2$$

And the effective area of lightening on ground wire will be

$$a_{fg}=P*a_g \rightarrow 0.06*6.647=0.399m^2$$

3.6 Modelling Of Surge Arrester

Metal oxide surge arresters are fundamental elements of protecting systems of electric devices against overvoltages. They contain varistors, which main constituent is zinc oxide as well as small amounts of other metal oxides. Surge arresters are exposed to transient effect of overvoltages generated as a result of lightning discharges, switching and damage states in electric power systems.

Modelling of surge arresters being in transient states, in case of large currents' flow accompanying overvoltages has a practical importance. Analyzing the risks of electric insulation systems of protected devices while overvoltages are exerting their influence, it is essential to know the voltages of arresters. The voltages determine efficiency of overvoltage protection of devices. Theoretically, voltage-current dependencies in established operation conditions make it possible to determinate energy dissipated in arresters, as well as taking into consideration influence of the arrester on currents in the circuit into which is it connected [15].

3.6.1 Mechanism of current conductivity in metal oxide varistors

Surge arresters contain one or more varistors with various diameters and heights. Varistors are made of ceramic of non-linear voltage-current characteristic. It is a ceramal of zinc oxide with admixtures of other metal oxides – i.e. of cobalt, manganese and aluminum. Structure of the varistors' mass is in the shape of close-packed grains. A small part of the grains constitute admixtures inside the grains while others, mainly bismuth, are accumulated in outer layers. Resistivity of the grain inside is small as op -posed to resistively of outer layers. Non-linearity of the volt -age-current characteristic results from phenomena occurring just mainly on the boundary of the grains. Between grains appear potential barriers, which regulate intensities of cur -rents in dependence on voltage, as on the grain boundaries is considerable negative charge accumulated, being a result of existence of acceptor admixtures. With small voltage, volt -age-current characteristic remains in accordance with the Ohm's law, and depends on temperature. While increasing the voltage, energies of electrons can be high enough to pull electrons out of valence band. Electron-hole pairs of charges are created. Holes direct towards negatively charged boundary between grains, neutralizing considerably surface charge and contributing to decrease of potential barrier. Sudden decrease of this barrier results in rapid current increase in the varistors. In this work range is the characteristic strongly non-linear. The non-linearity decreases, however, with potent lightning currents flow. With high density of currents, voltage increase is revealed, as a result of rise of voltage drop on grain-inside resistance. Character of phenomena on the grain boundary is the same as with lower current density.

Dynamic properties of charges on inter-grain boundaries influence voltage-current dependencies. With very steep impulses, voltages on varistors increase faster than currents. Their maximal values are also higher for currents with shorter duration. These dependencies result from inertia of charge translocation in form of holes towards boundaries, decreasing barrier of potentials [16].

3.6.2 Characteristic of selected model of surge arresters

According to IEEE the standard model for arrester is shown in figure 3.12. It contains two nonlinear resistors $A_{0\,(i)}$ and $A_{1\,(i)}$ with various voltage-current characteristics, separated by a L_1-R_1 filter. A capacitor C represents capacitance of the arrester. To improve stability of calculations, a resistor R_0 is connected parallel to the inductance L_0. Parameters of linear elements and characteristics of non-linear resistors of the schema can be determinate from results of investigations of arresters, published in catalogues, as well as from elementary dimensions of the column of varistors.

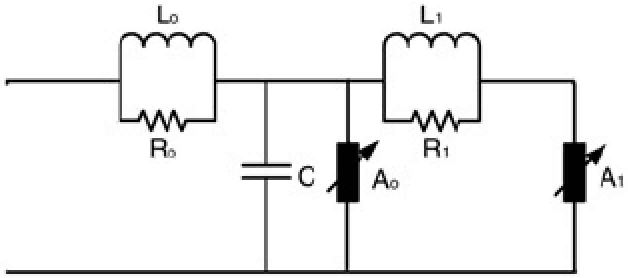


Figure 3-12 Model of Surge Arrester

Characteristics of varistors A$_0$ and A$_1$ of surge arresters with rated discharge current I$_r$ is represented by formulas [17]:

$$A_0 = A_{w0}\frac{U_{8/20};I_r}{1.6} = 1.55 * \frac{1065}{1.6} = 1031.72 \tag{3.50}$$

$$A_1 = A_{w1}\frac{U_{8/20};I_r}{1.6} = 1.22 * \frac{1065}{1.6} = 812.1 \tag{3.51}$$

Where $U_{8/20};I_r$ residual voltage with rated current impulse I$_r$ of times 8/20μs,

$$A_{w0} = c_0 i_{A0}^{0.051} = 1.378 * 10^{0.051} = 1.55 \tag{3.52}$$

$$A_{w1} = c_1 i_{A1}^{0.0507} = 1.083 * 10^{0.0507} = 1.22 \tag{3.53}$$

Where i_{A0}, i_{A1}densities of currents in varistorsA0andA1

c_0, c_1Constants$c_0 = 1.378\ and\ c_1 = 1.083$

Parameters of linear elementsL0, R0, L1, R1andCare expressed by dependencies:

$$L_0 = 0.2\frac{d}{n}[\mu H] = 0.2 * \frac{5.76}{2} = 0.576\mu H$$

$$L_1 = 15\frac{d}{n}[\mu H] = 15 * \frac{5.76}{2} = 43.2\mu H$$

$$R_0 = 100\frac{d}{n}[\Omega] = 100 * \frac{5.76}{2} = 288\Omega$$

$$R_1 = 65\frac{d}{n}[\Omega] = 65 * \frac{5.76}{2} = 187.2\Omega$$

$$C = 100\frac{d}{n}[\text{pF}] = 100 * \frac{5.76}{2} = 288\text{pF}$$

Where d- height of the column of varistors, m

n- Number of parallel varistors columns

A simplified version of substitute scheme of metal oxide surge arresters recommended by the IEEE is:

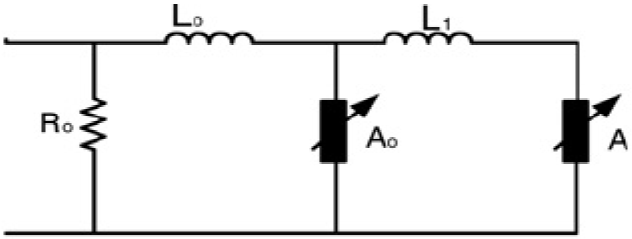


Figure 3-13 simplified model of Surge Arrester

Now parameters of Arrester are determined by the following equations

$$L_1 = \frac{1}{4}\frac{U_{r1/T2} - U_{r8/20}}{U_{r8/20}}U_n = \frac{1}{4}\frac{1550 - 1065}{1065} * 420 = 47.82\mu H$$

$$L_0 = \frac{1}{12}\frac{U_{r1/T2} - U_{r8/20}}{U_{r8/20}}U_n = \frac{1}{12}\frac{1550 - 1065}{1065} * 420 = 15.94\mu H$$

Chapter 4 Studies and Analysis of Results

4.1 Introduction

In this chapter transmission lines lightning performance will be studied under different lightning stroke cases. MATLAB Simulink software is used to carry out this study.

The tower is represented as discussed in section 3.1. The transmission line used is represented as lumped LC PI model found in Matlab Simulink block. It is Pi-model transmission line with length of 625km from the load. The lightning is assumed to strike tower nearest to Diddesa substation which 345km from the source and 275km from load to best determine the effectiveness of protective surge arrester that is employed to protect substation equipment.

The model consists of three phase AC source of 500kV representing the sending end of the line under study, 6000MW load to represent receiving end of the line under study. Since the line transmits 6000MW power by two double circuit lines, only a single circuit is included under this study as they are identical, AC lighting source of amplitude 10kA in parallel with resistance of 350ohm to represent lightning as the lightning source is current in parallel with surge impedance

The effect of direct and indirect stroke

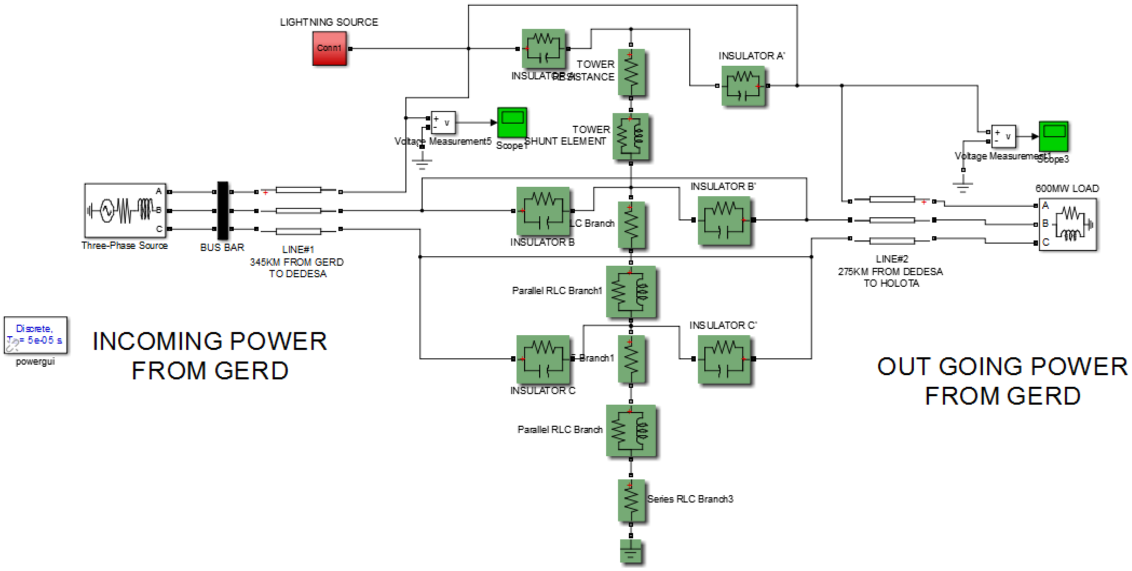


Figure 4-1 HV Tower model in MATLAB for direct stroke

Now let consider the direct stroke case (stroke to phase conductor). In this case the stroke (shown at the top edge the tower entitled as lightning source) is assumed to strike phase conductor.

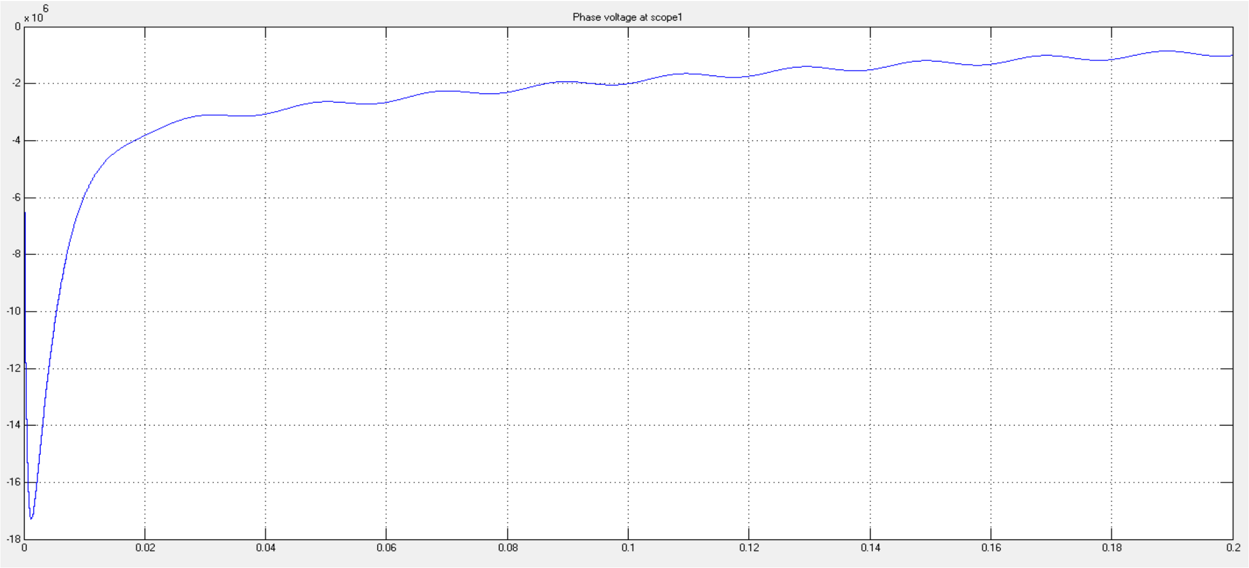


Figure 4-2 plot of phase voltage at scope 1 under direct stroke

From this result it is easy to see that when lightning strikes phase conductor voltage will go far beyond operating voltage for very short duration of time and then it quickly disappears. In this study lightning source is modeled by using current source of amplitude 20kA in parallel with series RLC branch of 400ohm to represent surge impedance of the tower. When direct stroke occurred the voltage in increased to 17MV and then decayed to about 1MV.

Indirect stroke

This will happen if the lightning strike shield wire or tower structure.

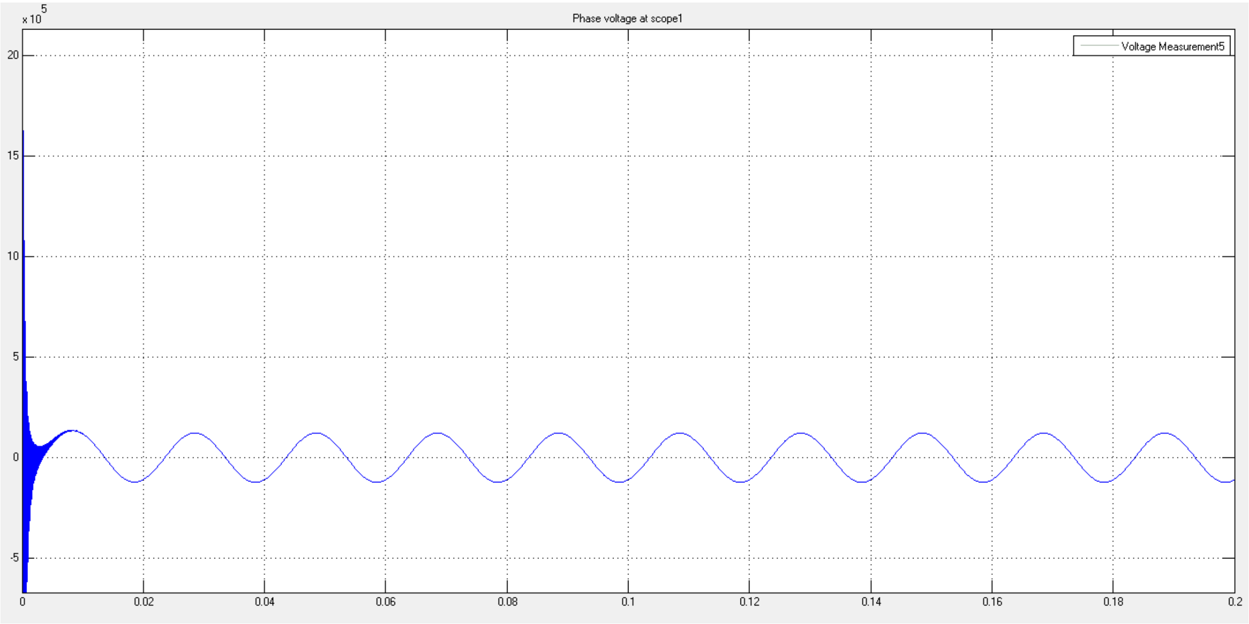


Figure 4-3 plot of phase voltage at scope 1 under indirect stroke

From this it can be concluded that when lightning stroke happens to shield wire or tower body, operating voltage or phase voltage will be decreased as insulator voltage goes beyond operating voltage there by reducing phase voltage to very small value.

4.2 Transient Simulation of GERD-Dedesa-Holeta TL

The model described in this section illustrates the protection system of series compensated transmission system that represents GERD-Diddesa-Holeta transmission line which is protected by MOV. The model represents a three-phase, 50 Hz, 500 kV power system transmitting power from a power plant consisting of sixteen 375 MVA generators to an equivalent system through a 620 km transmission line. The transmission line is split into two 345km and 275km lines connected between buses B1, B2, and B3.

To increase the transmission capacity, each line is series compensated by capacitors representing 50% of the line reactance. The line is also shunt compensated by a 330 MVAr shunt reactance. Each series compensation bank is protected by metal-oxide varistors (MOV). The two circuit breakers of line 1 are shown as CB1 and CB2.

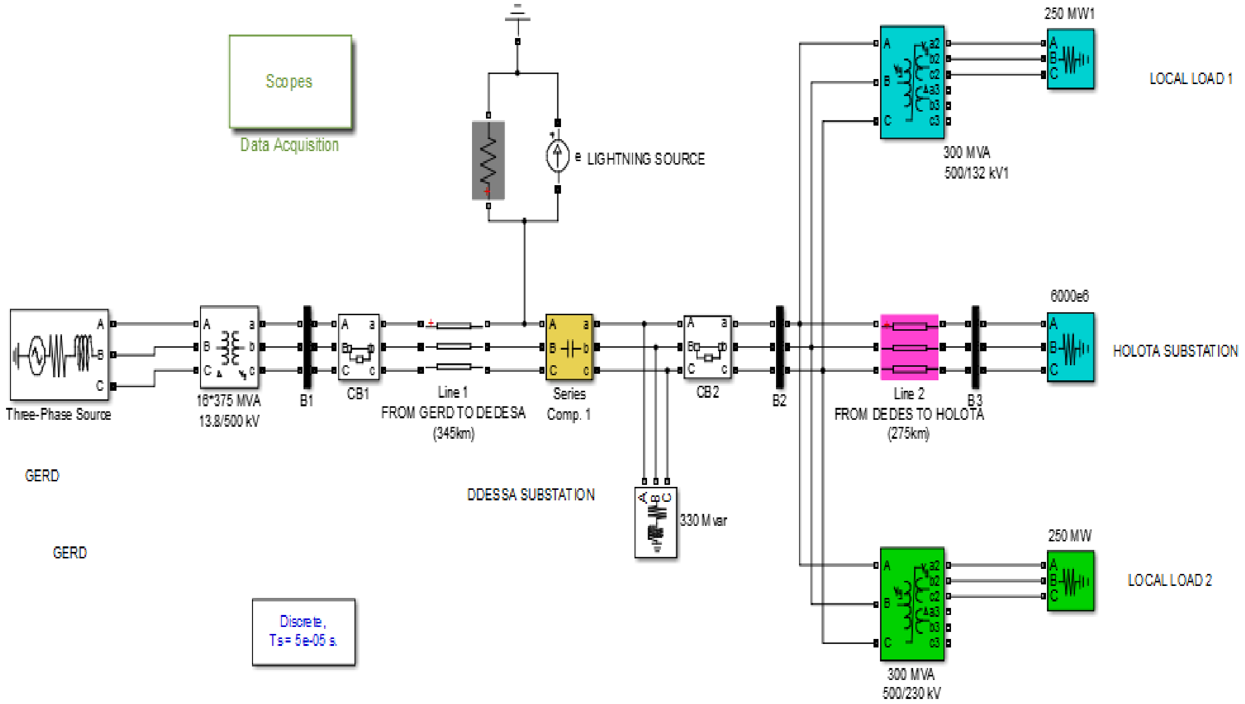
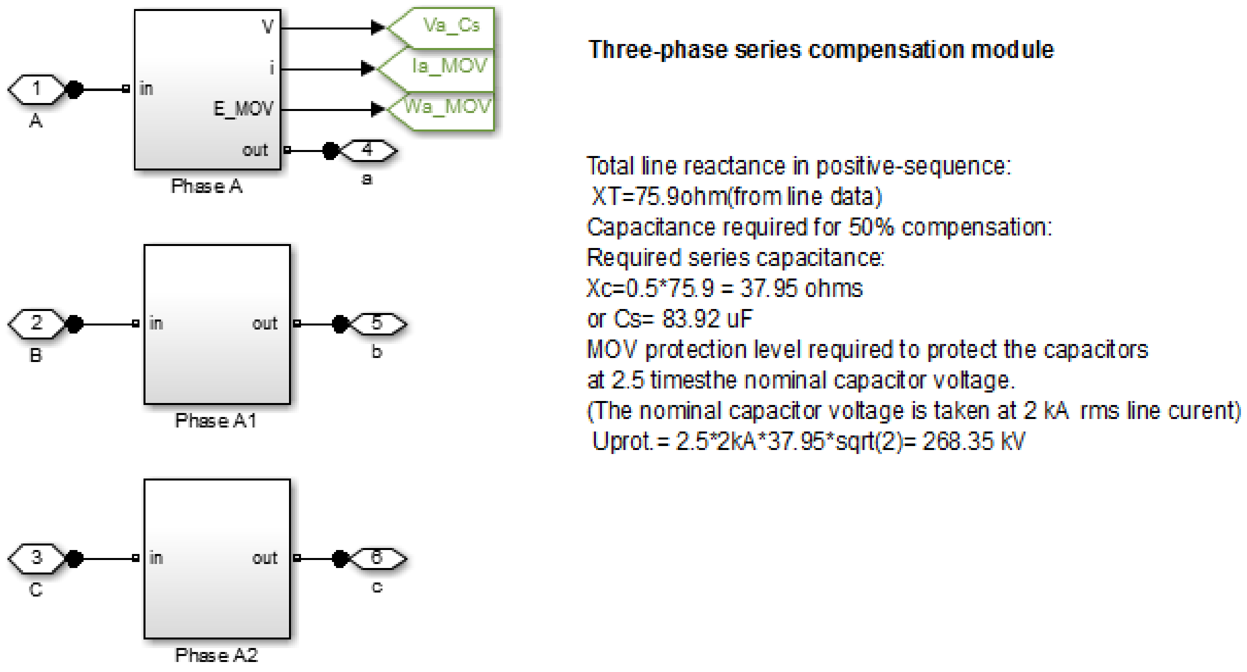


Figure 4-4 MATLAB model for transient analysis

Series Compensation Subsystem

The three-phase Series Compensation module consists of three identical subsystems, one for each phase. A note indicates how the capacitance value and the MOV protection level are calculated. The transmission line is 50% series compensated by 83.92 µF capacitor. The capacitor is protected by the MOV block of 60 columns and that its protection level (specified at a reference current of 500 A/column or 30 kA total) is set at 268.35kV. This voltage corresponds to 2.5 times the nominal capacitor voltage obtained at a nominal current of 2 kA RMS.



Three-phase series compensation module

Total line reactance in positive-sequence:
XT=75.9ohm(from line data)
Capacitance required for 50% compensation:
Required series capacitance:
Xc=0.5*75.9 = 37.95 ohms
or Cs= 83.92 uF
MOV protection level required to protect the capacitors
at 2.5 timesthe nominal capacitor voltage.
(The nominal capacitor voltage is taken at 2 kA rms line curent)
Uprot.= 2.5*2kA*37.95*sqrt(2)= 268.35 kV

Figure 4-5 three phase series compensation module

Again if we further open the modules we will see how MOV is modeled.

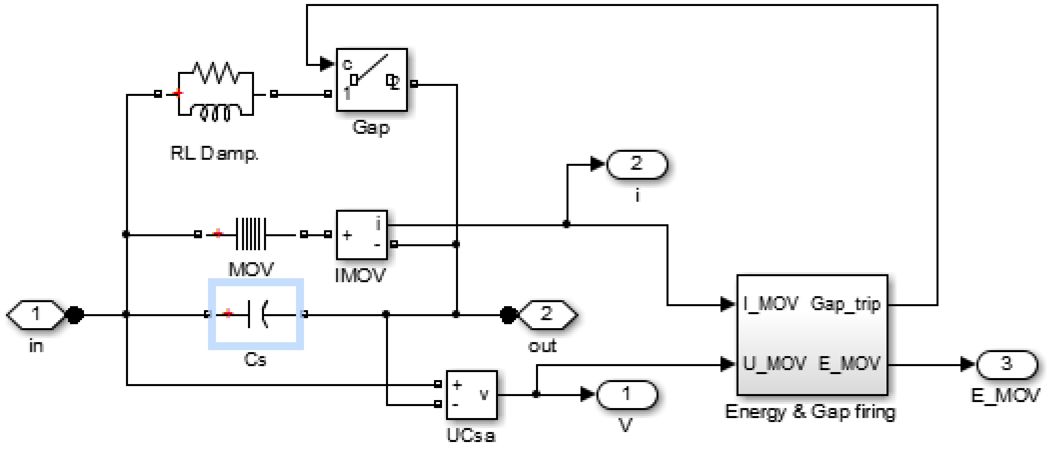


Figure 4-6 component of three phase series compensation module

Lightning transient simulation

Under this circumstance, MOV voltage, current and energy become.

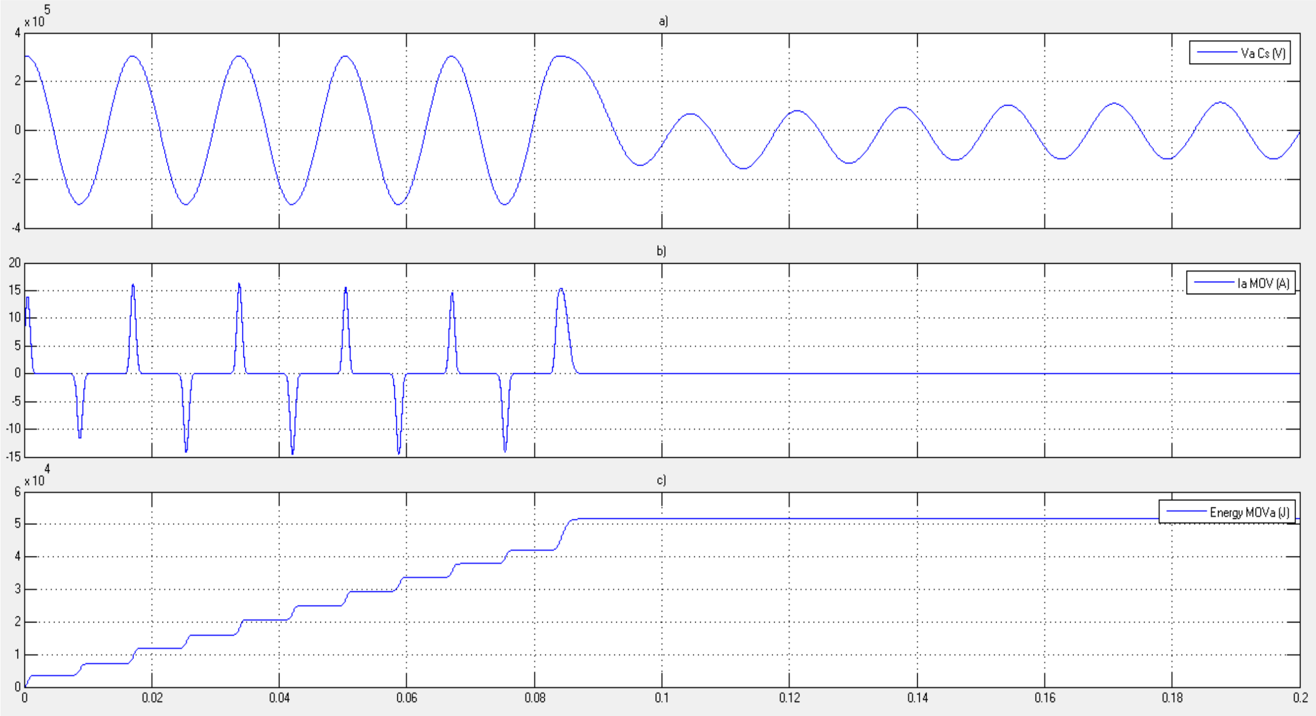


Figure 4-7 lightning transient simulation result

a. Series capacitor voltage,

b. MOV current

c. MOV energy for lightning study

The simulation starts in steady state. At the t = 1 cycle, lightning stroke is applied and the fault current reaches 10 kA. During the fault, the MOV conducts at every half cycle and the energy dissipated in the MOV builds up to 5MJ. At t = 5 cycles the line protection relays open breakers CB1 and CB2 and the energy stays constant. At the breaker opening time, the fault current drops to a small value and the line and series capacitance start to discharge through the fault and the shunt reactance. The fault current extinguishes at the first zero crossing after the opening order given to the fault breaker (t = 6 cycles). Then the series capacitor stops discharging and its voltage oscillate

4.3 Simulation of Transmission line protected from sending and receiving end by MOV

Below figure shows a 500 kV transmission system with two transmission line arrester placed at the sending end and the receiving end of the line. Over the system a lightning surge of 20 kA was induced and the resulting simulation was carried out by using MATLAB software

A 500 kV transmission system feeds a load (2000MW) through a 620 km transmission line. The result of the simulation shows the temporary increase in current at MOV which is done by the lightning when 20 kA lightning current is applied. On the other hand, the temporary increase in voltage in each arrester.

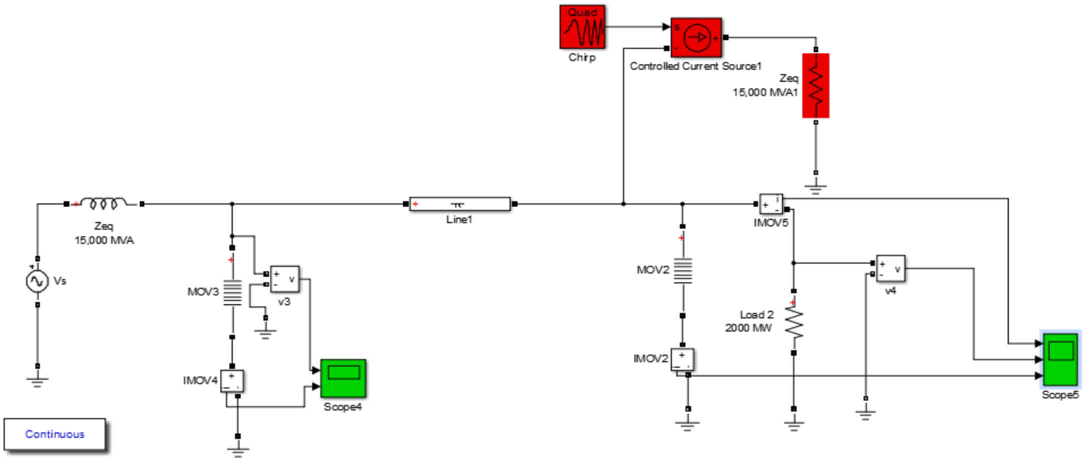


Figure 4-8 Figure 4-8: Model to simulate TL protected by MOV

Here the generation and load are both protected by metal oxide varistors (MOV). The MOV consists of 30 columns protecting the components at 2.5 times its rated voltage

Hence protection voltage is

$$2.5 * 500\text{kV} = 1250\text{kV}$$

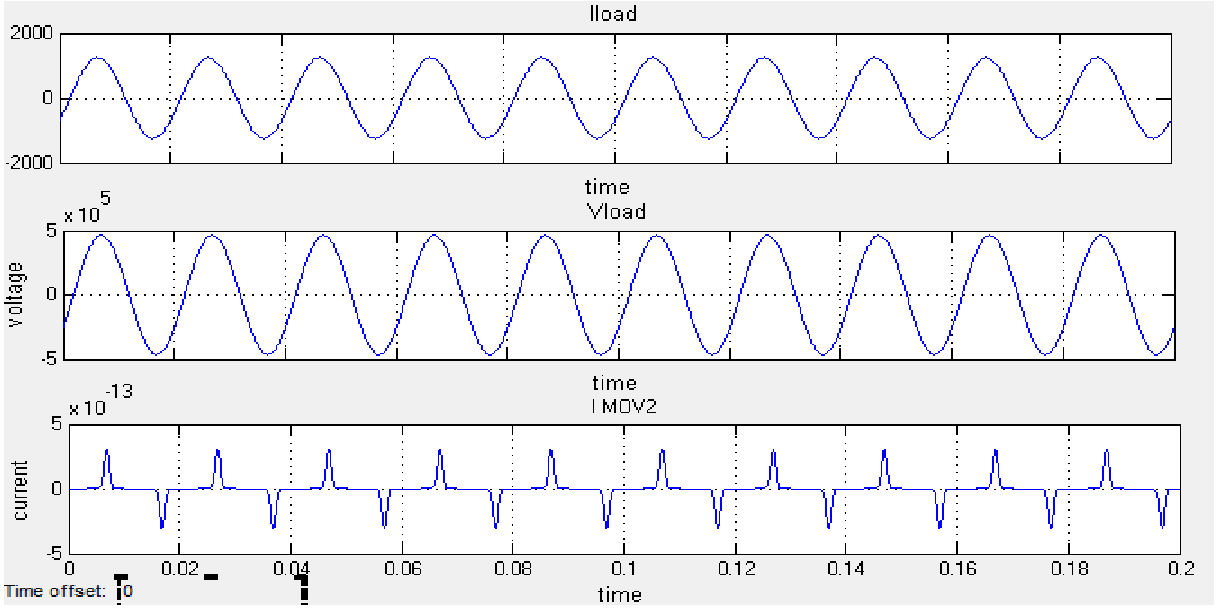


Figure 4-9 Load current, load voltage, and MOV current under normal condition

If stroke happens at receiving end of TL, the resulting current and voltage wave form (without employing MOV Surge arrester) are represented by Fig 4.10. Initially, the current will raises up to 10kA and the voltage will raises up to 4MV.

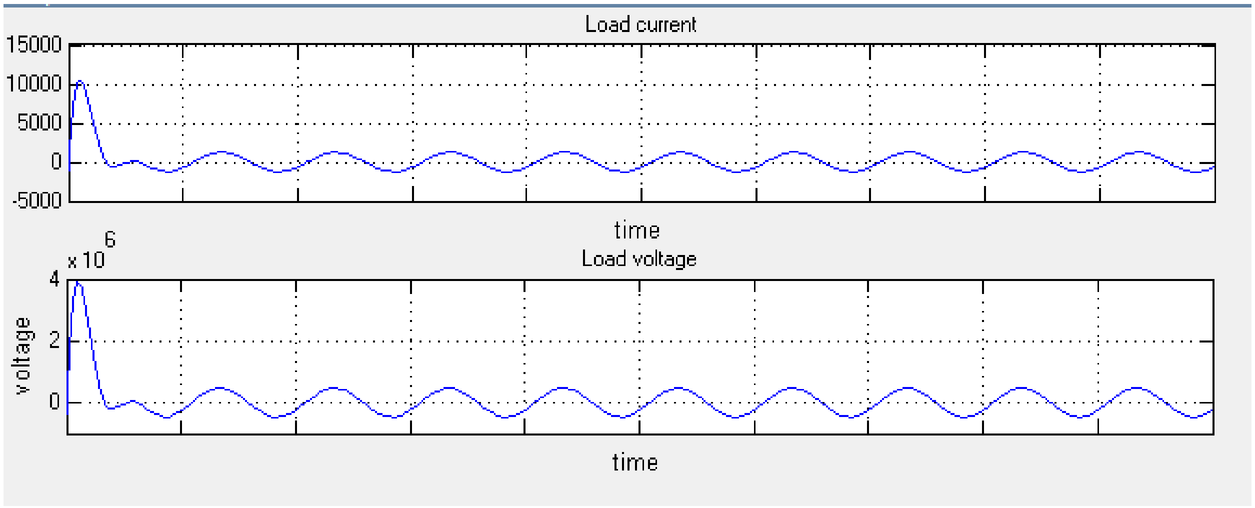


Figure 4-10 Load current, load voltage, and MOV current when lightning strike the line

If MOV Surge arrester is employed to the system at sending and receiving ends, the current and voltage wave forms look like the following. Initially when the current and voltage wave go to high value, the MOV will conduct until the value drops to tolerable value.

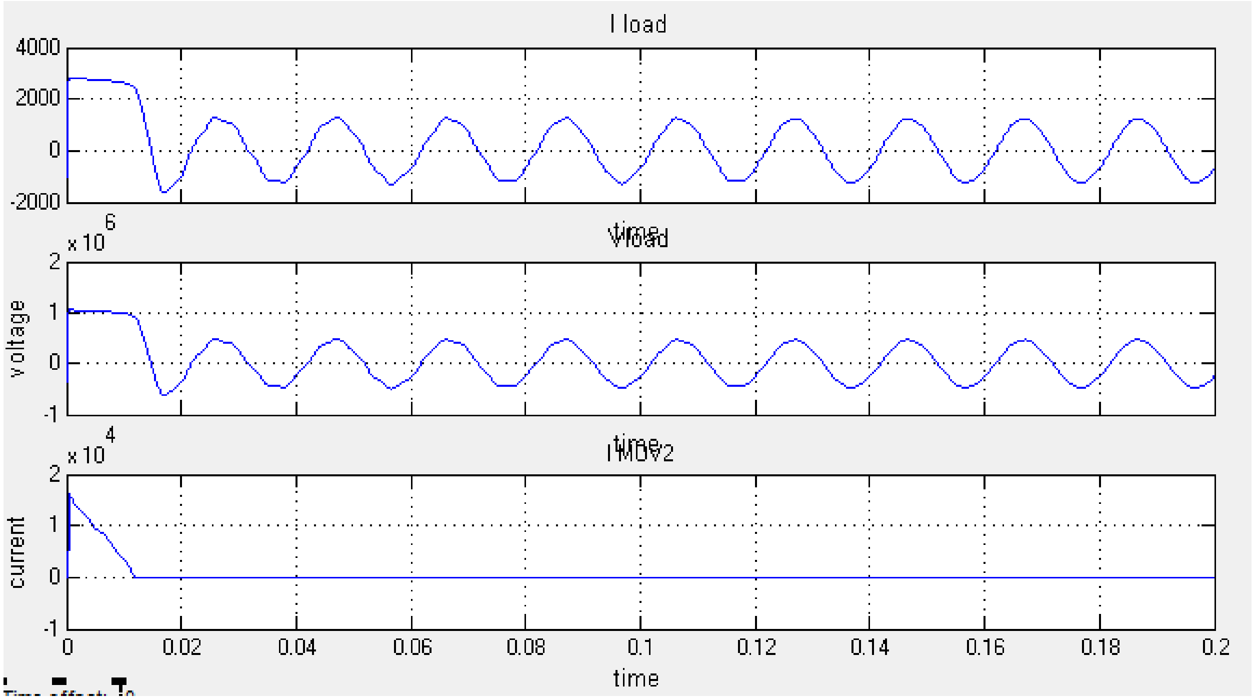


Figure 4-11 Load current, load voltage, and MOV current after employing Surge arrester

Had there were no arrester at the point of stroke, the voltage and current at load would be plotted as in Figure 4.10 voltage temporarily grows up to 4MV and then drops to about 200kV. Again the current suddenly grows up to about 10kA and then decayed to nearly 0.

But when surge arrester is employed to the system the current and voltage wave will be plotted as in figure 4.11. Load current temporarily grows up to 2.5kA when MOV conducts and drops to less than 2kA when lightning is removed. Again load voltage goes to 1MV when surge arrester conducts and drops to about 500kV when lightning is removed

Chapter 5 Conclusion, Recommendation and Future Work

5.1 Conclusion

An assurance of reliability of work of electric power systems needs detailed analysis of exploitation risks of all devices. Overhead high voltage transmission lines have special meaning in such systems. Among exploitation risks lightning overvoltages have the most important influence on insulation coordination and optimization of electric withstand of insulation systems of electric power lines. Especially lightning over voltage, which can be generated in overhead lines, need detailed analysis; because of the risks they pose on the system. They might create danger for insulation systems of transmission lines and electric power substations. This research covers the range of risk problems which concern lightning overvoltages in electric power lines, protected by shielding wires and metal oxide surge arresters. Progress in insulation coordination specially follows from the development of possibility of computer simulation of overvoltages risks of insulation systems. Therefore, the mathematical Modelling of devices and phenomena which have influence on courses and maximal values of lightning overvoltages has special meaning.

The results of computer simulations of lightning overvoltages in overhead lines are significantly depend on mathematical models of towers and earthing systems. The current strokes with large values during lightning strokes to shielding wires flow to the earth through tower with different construction and dimensions.

The results of analysis of protection effectiveness of overhead lines by shielding wires based on the electrogeometric power line model confirms, that phase conductors of overhead lines protected by shielding wires can be risked by directly lightning strokes with small currents. The analysis of lightning overvoltages in overhead lines should take into account both overvoltages generated during strokes to shielding wires as well as to phase conductors with maximal lightning currents which can be determined on the basis of the line construction analysis.

The results of computer simulations of lightning overvoltages in overhead lines show that overvoltages which create risk to the earth insulations systems of lines and transformers generated during lightning strokes to shielding wires do not exceed residual voltages of surge arresters. In this conditions the surge arresters work on the beginning and practically linear parts of the current-voltage characteristics and practically have no influence on over voltage courses and their maximal values. The analysis shows that overvoltages generated in the phase conductors during lightning strokes to the shielding wires are limited to values which are safe for insulation systems.

The analysis also shows that the shielding wires, which are installed in overhead lines in the lightning protection engineering of electric power devices, do not assure the full protection of line phase conductors against direct lightning strokes. Lightning strokes with small currents can stroke to phase conductor in spite of shielding wires. The overvoltages generated in this condition which exposures insulation systems of lines and devices in power substations can increase the values of overvoltages which are generated during lightning strokes to shielding wires. Overvoltages generated during lightning strokes with small values to phase conductor are limited by use of metal oxide surge arresters which are installed on the end of the overhead lines and installed in power substations. The computer simulation of lightning over voltage reveals that shielding wires and surge arresters create the complex overvoltage protection of insulation systems of overhead transmission lines.

The maximum value of lightning over voltages to which insulation systems of lines and electric power substations exposed to depends on the construction of overhead lines and parameters and localization of surge arresters. Therefore, the improvement of overvoltage protection systems of overhead transmission lines and power substations is possible.

5.2 Recommendations

Overvoltages which are generated during lightning discharges to overhead lines can cause flashover in air insulation systems and can overload equipment connected to it. Flashovers have a significant influence on the courses and maximum values of lightning overvoltages. Therefore based on finding of this research the researcher recommends to divide transmission line in to grades per 100km and employ surge arrester so that the effect of lightning stroke that could arise at far distant from substation cannot cause problem to substation equipment.

5.3 Future Works

Based on the simulation study done in this research to study the lightning performance of 500kV transmission line, it is very important if computer soft wares like Electromagnetic Transient Propagation (EMTP) and Power System Computer Aided Design (PSCAD) are used in future study. These soft wares provide an alternative way to bring the precise result in study of lightning protection level of high voltage transmission line.

Again in this research as the line is not energized and as it is new, there is no recorded data about its lightning stroke history. Therefore all analysis are made by using scientific assumption used by collecting international standards used in lightning protection systems by referring to contractor manual. For future if somebody wants to do research on this transmission line it is important to consider this actual datum.

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Chapter 6 Appendix: A Type and Characteristic of OPGW used in GERD-Dedesa-Holeta TL

The OPGW type of GERD-DEDESA-HOLETA 500kV transmission project is OPGW-24B4-110, the main characteristic of OPGW-24B4-110 is listed in Table 1, and the structure of composition is listed in Table 1。 As shown in Fig.1 is the sketch map of OPGW.

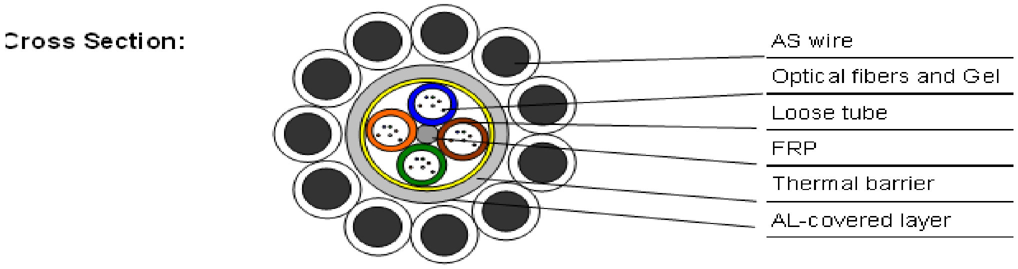
Table 1 main characteristics of OPGW-24B4-110

NO.	ITEM		UNIT	CHARACTERISTIC
1	Type			OPGW-24B4-110
2	Structure	Aluminum clad steel	number/diameter	11/3.1
		Aluminum allow	number/diameter	
		optical unit	Type/number/diameter	Loose tube type /1/8.0
3	calculated sectional area	Al tube	mm^2	27.36
		Aluminum clad steel	mm^2	83.02
		Supporting cross area	mm^2	110.4
4	Outer filament type			Aluminum clad steel
5	Outer filament diameter		Mm	3.1
6	Fiber type			G. 655D
7	Number of fiber		No.	24
8	two-way average attenuation coefficient of single fiber ,single coil after cable （1550nm）		dB/km	≤0.2
9	Cable Diameter		Mm	14.20
10	Cable Weight		kg/km	570
11	Ultimate Tensile Strength(UTS)		kN	75.3

NO.	ITEM		UNIT	CHARACTERISTIC
12	DC Resistance at 20℃		Ω/km	0.417
13	Short Time Current Capacity		$\mathrm{kA^2 \cdot s}$	100
14	Maximum temperature permissible	Instant	℃	200
		Continued	℃	80
15	Anti-lightning energy		C	100C
16	Modulus of Elasticity(E-Modulus)		$\mathrm{kN/mm^2}$	113.2
17	Thermal Elongation Coefficient		10-6/℃	14.9
17	Permissible Maximum Working Stress		%UTS	40
19	Maximum Coil length of OPGW		M	6000
According to IEC 60794-4, IEEE-1138 standards Stranding direction of outer layer is right hang(Z-Stranding)				

Table 2 OPGW-24B4-110 structure design

STRUCTURE	TYPE	CONDUCTIVITY（%）	DIAMETER（mm)	No.
Center	AL tube	---	8.00(Outer-Dia) 5.40(Inner-Dia)	1
Layer 1	AS	30%	3.10	11



Appendix: B Data for Lightning Arresters

Data for 33kV Lightning Arrestor

Description		Required	Offered
Type			ZnO, gapless
Installation		Outdoor	Outdoor
Nominal system voltage (kV)		33	33
Rated voltage of Arrester (kV), Ur		36	36
TOV capability	for 1seccond kV rms		41.4
	for 10seccond kV rms		39.6
Maximum permissible line to ground voltage			
Power frequency withstand voltage 1min, kV		70	70
Impulse voltage (1.2/50 micro second) (kV)		170	170
Residual voltage at 8/50 micro second and at 10kA kV)		95.8	95.8
Rated discharge current (kA)		10	10
Maximum discharge current (kA)		≥40	≥40
Creepage distance (mm)			1080
Overall weight (kg)			14
Energy capability	a. line discharge class (IEC)		
	b. 2 impulse as IEC 99-4, kJ/kV, Ur		5
	c. pressure relief withstand		20kA

Standard applied IEC-600994

Data for 500kV and 400kV Lightning Arrestor

Description		Required		Offered	
		500kV	400kV	500kV	400kV
Model/Type				ZnO, gapless	ZnO, gapless
Installation		Outdoor	Outdoor	Outdoor	Outdoor
Nominal system voltage (kV)		500	400	500	400
System continuous maximum voltage (kV)		550	420	550	420
Rated voltage of Arrester (kV), Ur		420	342	420	342
TOV capability	for 1seccond kV rms			504	411
	for 10seccond kV rms			483	394
Power frequency withstand voltage 1min, kV		680	630	680	630
Impulse voltage (1.2/50 micro second) (kV)		1550	1425	1550	1425
Residual voltage at 8/50 micro second and at 10kA (kV)		1065	852	1065	852
Rated discharge current (kA)		20	20	20	20
Maximum discharge current (kA)		≥40	≥40	≥40	≥40
Creepage distance (mm)				15125	
Overall dimensions(mm), height				5760	4110

Overall weight (kg)				1450	1450
Maximum residual voltage with current wave of (30/70 micro second) at 1kA (kV)		≥40	≥40		
Energy capability	a. line discharge class (IEC)	4	4	4	4
	b. 2 impulse as IEC 99-4, kJ/kV, Ur			23.04	23.04
	c. pressure relief withstand			63kA	63kA
Standard applied IEC-600994					

Appendix: C GERD-Dedesa-Holota Transmission Line tower Configuration

The tower of GERD-DEDESA-HOLETA 500kV transmission line has the following type of configuration