# Surge Arrester Placement for Long Transmission Line and Substation

by

Qianxue Xia

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Graduate Supervisory Committee:

George Karady, Chair
Raja Ayyanar
Qin Lei

ARIZONA STATE UNIVERSITY

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ABSTRACT

Prior work in literature has illustrated the benefits of using surge arrester as a way to improve the lighting performance of the substation and transmission line. Installing surge arresters would enhance the system reliability but it comes with an extra capital expenditure. This thesis provides simulation analysis to examine substation-specific applications of surge arrester as a way of determining the optimal, cost-effective placement of surge arresters. Four different surge arrester installation configurations are examined for the 500/230 kV Rudd substation which belongs to the utility, Salt River Project (SRP). The most efficient configuration is identified in this thesis. A new method "voltage-distance curve" is proposed in this work to evaluate different surge arrester installation configurations. Simulation results show that surge arresters only need to be equipped on certain location of the substation and can still ensure sufficient lightning protection.

With lower tower footing resistance, the lightning performance of the transmission line can typically be improved. However, when surge arresters are installed in the system, the footing resistance may have either negative or positive effect on the lightning performance. Different situations for both effects are studied in this thesis.

This thesis proposes a surge arrester installation strategy for the overhead transmission line lightning protection. In order to determine the most efficient surge arrester configuration of transmission line, the entire transmission line is divided into several line sections according to the footing resistance of its towers. A line section consists of the towers which have similar footing resistance. Two different designs are considered for transmission line lightning protection, they include: equip different number of surge arrester on selected phase of every tower, equip surge arresters on all phases of selected towers. By varying the number of the towers or the number of phases needs to be equipped with surge arresters, the threshold voltage for line insulator flashover is used to evaluate different surge arrester installation configurations. The way to determine the optimal surge arresters configuration for each line section is then introduced in this thesis.

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NOMENCLATURE

| | |
|---|---|
| $b$ | Distance between the two shielded wires. |
| $C_{hg}$ | Distributed capacitance of the high-voltage windings. |
| $C_{hl}$ | Distributed capacitance between the high-voltage winding and low-voltage winding. |
| $C_{lg}$ | Distributed capacitance of the low-voltage winding. |
| $E_0$ | Soil ionization gradient. |
| $E_a$ | Surge arrester discharge voltage. |
| $F_{in}$ | Control signal. |
| $h$ | Mean shield wires at the tower. |
| $h_1$ | Height from base to mid-section. |
| $h_2$ | Height from mid-section to the top; |
| $h_g$ | The height of the shield wire at the tower. |
| $h_{gw}$ | Shield wire midspan clearance to the ground. |
| $H_t$ | Height. |
| $I$ | Peak current amplitude. |
| $K$ | Constant. |
| $K_1$ | Constant. |
| $K_2$ | Constant. |
| $L$ | Insulator length. |
| $I$ | Stroke current through the resistance. |

$I_g$ Limiting current to initiate sufficient soil ionization.

$N$ Number of flashes to earth per square kilometer per year.

$N_L$ Number of flashes to the transmission line per 100 kilometers per year.

$N_s$ Total number of flashes causing shielding failure per 100 kilometers per year.

$r_1$ Tower top radius.

$r_2$ Tower mid-section radius.

$r_3$ Tower base radius.

$R_0$ Footing resistance at low current and low frequency.

$R_T$ Tower footing resistance.

$T$ Keraunic level in thunder days per year in the area.

$t$ Elapsed time after lightning stroke.

$\tau_1$ Time constant.

$\tau_2$ Time constant.

$U$ Maximum discharge voltage.

$V_{ins}^{'}$ Voltage across the adjacent tower insulator.

$V_{line}$ Voltage between the phase conductor and the ground.

$V_{pk}$ Crest value of the wave voltage.

$V_{string}$ Voltage across the insulator.

$V_{v-t}$ Flashover voltage.

$Z_g$ Neutral conductor surge impedance.

| | |
|---|---|
| $Z_m$ | Mutual surge impedance between phase and neutral conductors. |
| $Z_{Tsurge}$ | Tower surge impedance. |
| $\rho$ | Soil resistivity. |
| A | Tower located at the top of the ridge. |
| AEP | American Electric Power Service Corporation. |
| APS | Arizona Public Service Electric. |
| B | Tower located at the top of the ridge. |
| Bott | Bottom insulator of the tower. |
| BIL | Basic insulation level. |
| C | Tower at the bottom. |
| C1 | No installed surge arrester on the substation |
| C2 | Two surge arresters are installed at the entrance of the substation and the terminal of the transformer respectively. |
| C3 | One surge arrester is mounted at the entrance of the substation. |
| C4 | One surge arrester is installed on the terminal of the transformer. |
| CFO | Critical flashover Voltage. |
| D | Tower at the bottom. |
| L | Lower phase conductor. |
| LFCs | Lightning flashover charts. |
| M | Middle phase conductor. |
| MOSA | Metal oxide surge arrester. |

| | |
|---|---|
| MOV | Metal oxide varistor. |
| Mid | Middle insulator of the tower. |
| P | Node. |
| SRP | Salt River Project. |
| T | Top phase conductor. |
| TLSA | Transmission line surge arrester. |
| Top | Top insulator of the tower. |
| X | Lightning stroke point. |
| Y | Terminal of the transformer. |
| Z | Entrance of the substation. |

# 1. INTRODUCTION

## 1.1 Background

### 1.1.1 Lightning

The lightning is an electrical discharge between the atmospheres. The discharge can occur within the clouds, between the clouds, or between the clouds and the ground. The three types of discharges are referred to as in-cloud lightning, cloud-to-cloud lightning, and cloud-to-ground lightning. Among all lightning events happened on earth, cloud-to-ground lightning accounts for about 25% of all lighting events worldwide. This category of lightning flash is most likely to be relevant to our life.

If the lightning flash involves an object on the ground, it is then called the lightning strike. The most common type of strike is cloud to ground strike, while another type of strike is called ground to cloud strike. The ground to cloud strike originates from a tall object on the ground, propagate upwards and finally reach into the clouds. Most of the lightning flash delivers negative current; however, it may also deliver positive current in rare circumstance, which usually has higher magnitude and is more severe than the negative current. Thus, for surge protection, the positive current needs to be taken into consideration.

There are 16 million thunderstorms each year around the world, which is on average approximately 1,800 thunderstorms occurring per hour [1]. In the United States, the number of lightning strokes that hits the ground is between 8-0.5 strokes per square kilometer per year [2] and it is illustrated in Fig. 1.1. On average, 30% of all power outages annually are lightning-related, and the associated total cost is close to one billion dollars [3].

The keraunic level in a specified locality is roughly proportional to the number of lightning events to earth in that locality. It is suggested by [2] that:

$$N = 0.12T \tag{1.1}$$

where $N$ denotes the number of flashes to earth per square kilometer per year, and $T$ is the keraunic level in thunder days per year in the area.

When lightning flash terminates within a specific area around the transmission line, the transmission line will flashover. The approximation of the width of the area was given in [2] for a line with two shield wires.

$$W = b + 4h^{1.09} \tag{1.2}$$

$$h = h_g - 2/3(h_g - h_{gw}) \tag{1.3}$$

where $h$ denotes the mean shield wires at the tower, $h_g$ is the height of the shield wire at the tower, $h_{gw}$ is the shield wire midspan clearance to ground and $b$ represents the distance between the two shielded wires.

The number of flashes to the line can then be calculated:

$$N_L = 0.012T(b + 4h^{1.09}) \tag{1.4}$$

where $N_L$ is the number of flashes to the transmission line per 100 kilometers per year.

All the equations above are developed assuming that there are equal probabilities of lightning striking anywhere along the line, including the midspan. However, Wagner and Hileman [4]-[5] examine that the lightning flash which terminates at the midspan traveling to the nearby towers are likely to cause overvoltages below the flashover voltage of the tower. Thus, reference [6] shows that midspan lightning flashovers are quite uncommon. Reference [6] then takes 60% of the total number of the lightning strike on the line into account. The flashover frequency becomes:

$$N_T = 0.6(N_L - N_s) \tag{1.5}$$

where $N_s$ is the total number of flashes causing shielding failure per 100 kilometers per year.

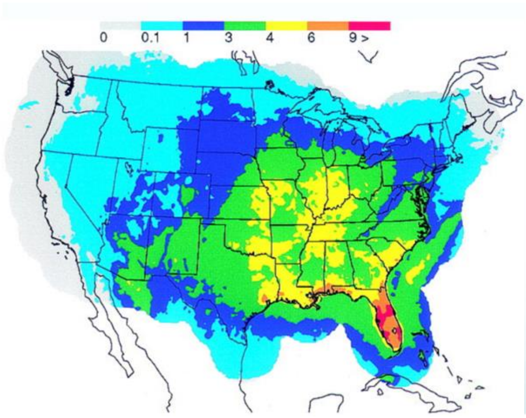



Fig. 1.1 Number of Cloud-to-ground Lightning Strikes per Square Kilometer per Year in the 10-year Period of 1989-1998 in the U.S [1].

### 1.1.2 Overvoltages

IEEE and CIGRE guides and standards divide the overvoltages in power system into three categories: lightning overvoltages, switching overvoltages and temporary overvoltages. The characteristics of overvoltages regarding the voltage magnitude and duration are illustrated in Fig. 1.2 [12].

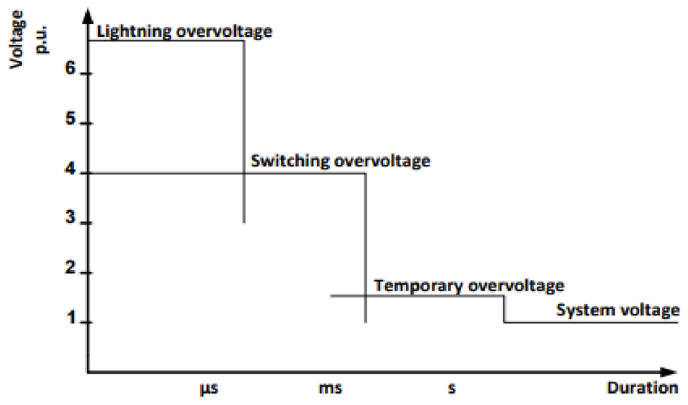



Fig. 1.2 Voltage of Different Type of Overvoltages as a Function of Time[12].

### Lighting Overvoltage

Lightning overvoltages are caused by the external event: lightning. In practice, there are three different types of lighting events that may cause outages in the power system:

Lightning flash terminating on the phase conductor of the transmission line is more likely to happen in an unshielded line. The phenomenon of lightning hits on the conductor of a shielded line is usually denoted as shielding failure.

Back flashover is the result of a direct lightning stroke to the tower structure and shielded wires. Lightning surges travel in both directions and down the tower into the ground, developing a voltage on the crossarm and stress the insulation. Flashover occurs when the voltage exceeds the threshold of the insulator string. The flashover of insulator then causes a line to ground fault and will be interrupted by the breakers. The backflash usually occurs during a lightning striking to the overhead shield wire where the ground impedance is high. Fig. 1.3 [42] illustrates the process of backflash.

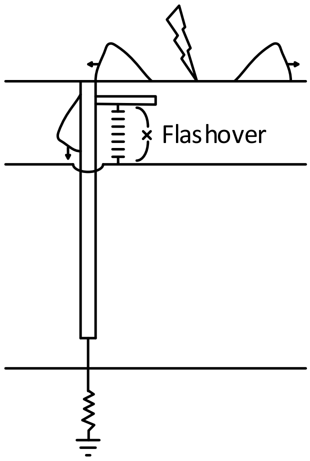



Fig. 1.3 The Back Flashover.

Previous researchers have shown that the back flashover is more prominent in the lightning protection of overhead transmission line rather than shielding failure [8]-[11].

**Switching overvoltages**

Switching overvoltages usually results from the breaker operation including fault occurrence, line energization, reclosing, capacitor switching. For the 115kV and above system [12], the switching surge should be taken into consideration.

**Temporary overvoltages**

Temporary overvoltages usually last a period of hundreds of milliseconds or longer while the switching overvoltages usually last hundreds of microseconds. This is a major difference between the switching overvoltages and the temporary overvoltages. The temporary overvoltages have a frequency that is close to the normal power frequency. The leading causes of the temporary overvoltages include single line-to-ground faults, ferroresonance, load rejection, loss of ground, long unloaded transmission lines (Ferranti rise), coupled-line resonance, and transformer-line inrush [12]. This type of overvoltage is crucial to determining surge arrester selection and installation.

### 1.1.3 Surge Arrester Protection

Metal oxide surge arresters (MOSA) are the most wildly used protective device nowadays. There are three main categories of MOSA, including gapless arresters, shunt-gapped arresters, and series-gapped arresters.

The surge arrester is expected to limit the lighting overvoltages and switching overvoltages. However, the surge arrester itself is designed to withstand the temporary overvoltages. In addition, it should be able to withstand the continuous system operating voltage.

All types of surge arresters share similar principles. In the most common type of surge arresters, the component metal oxide varistor (MOV) is used for conducting the lighting surge to the ground. The MOV is a semiconductor, which is highly sensitive to voltage and current. For power system normal operation voltage, the MOV has high impedance and acts as an insulator. However, if lighting or switching overvoltage occurs, the MOV impedance drops down and diverts the current to the ground. Thus, the voltage at the terminal of the arrester remains low, which protects the vicinity device from the overvoltages.

There are several methods to reduce the lighting related outages on transmission lines. Installing ground wires are the most common methods for reducing the number of the direct stroke on transmission lines. The optimal shielding design was presented in [13], while Mladen S.Banjanin [14] proposed a new method of using external ground wires to improve lightning protection of transmission lines. However, after the transmission lines are built, it is costly and time-consuming to add overhead shield wires or change the configuration of the ground wire. Surge arresters have the advantages that it flexible and can deal with nearly all types of surges. They are used in both lighting protection and switching surge control. It can help reduce the cost of line voltage uprating projects and compact line construction while other methods cannot.

The surge arresters installed on the transmission line towers operate differently than any other arrester application. When lightning hits the tower or the shield wire of a transmission line, the surge will be conducted onto the phase conductor by the surge arrester instead of going to ground.

When no arresters are in service and the shield wire experiences a direct stroke, the lightning surge will travel along the shield wire and down to the ground from nearest pole. If the voltage across the insulator increases and exceeds the withstand level of the line insulator, the insulator flashover occurs, leading to a line to ground fault.

If an arrester is installed on the tower, the surge current will directly transfer into the phase conductor as shown in Fig. 1.4. Thus, no flashover would occur across the insulators in this scenario.

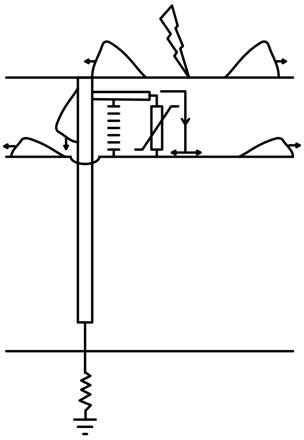


Fig. 1.4. Tower with Surge Arresters.

For shielded lines without line arresters, it is generally true that lower ground resistance at the towers and poles will improve the backflash performance. When line arresters are applied, however, a lower ground resistance may worsen the lightning performance of the overhead transmission line in some cases.

Except for the direct stroke and back flashover, the lightning may strike on the nearby ground and induce surges into the phase conductor. In this case, the overvoltage is usually not large enough to cause flashovers.

## 1.2 Motivation

A significant number of faults are caused by lightning every year. Installing surge arrester is an efficient way to improve the lightning performance of power systems. Most utilities install surge arresters at both the entrance of the substation and the terminal of the transformer. Due to the high installation cost of surge arresters, however, some utilities like Salt River Project (SRP) only install the surge arrester at the transformer side. The surge arresters at the entrance of the substation can prevent the penetration of lighting or switching generated traveling waves, which endangers equipment in the substation. How will the system operate without the surge arrester at the entrance need to be analyzed in order to examine the reliability of the SRP transmission line system. Since the lightning surge has the behavior of reflection and refraction, it is also useful to know whether there is a maximum recommended length of the line before an arrester needs to be applied.

Utilities in Japan significantly reduced the number of lightning stroke caused outages by installing surge arresters along the line. This method is expensive but produces significant improvements. Well-rounded protection can be achieved by installing the surge arrester across every insulator of each circuit. However, this method is a large expenditure, and it is unnecessary as the footing resistance is not uniform along the transmission line. The lightning performance of a transmission line depends on the line configuration, transmission line tower surge impedance, footing resistance, lightning surge rise time and amplitude. A utility must consider all the issues for the installation of line arresters. Thus, the effect of the footing resistance, lighting stroke front time and magnitude need to be thoroughly studied. This thesis aims at finding the design which can satisfy the reliability of the line service with the minimum number of surge arresters. A surge arrester installation strategy which can be applied to different transmission line system is proposed and developed in this work.

### 1.3 Summary of Contents

The rest of this thesis is structured as follows. In Section 2, detailed modeling guidelines are developed for the digital simulations involving fast front waveforms. In this section, modeling of the lightning surge is first presented, followed by the data of the transmission lines used in the simulation and the geometry of the towers. All the data are provided by the utility SRP. Then the models of the transformer and surge arrester are discussed, as well as the model of the transmission line tower. The detailed insulator model, calculation of tower surge impedance, and the model of the tower footing resistance are also presented.

Section 3 focuses on the lightning protection of the substation. A thorough literature review of substation lightning protection is presented. An evaluation of lightning protection design for a 500/230 kV substation with surge arresters is illustrated in this section. The substation and several spans of transmission line connected to the substation are included in the lightning study model. Then, four different surge arrester placement configurations are investigated. The voltage at the substation entrance and the voltage of transformer terminal are measured, along with the arrester energy duty and current. The voltage-distance curve is proposed to analyze the lightning performance of the four different configurations. Simulation results show that installing surge arresters only at the transformer location is adequate for the substation lightning protection. Advantages and disadvantages of installing surge arresters at the entrance of the substation or the terminal of the transformer are discussed.

In Section 4, the surge arrester lightning protection of the long transmission line is studied. The lightning performance of a transmission line depends on multiple factors. The effects of different tower footing resistance, the lightning surge rise time, and lightning surge amplitude on lighting protection performance are examined. It is been discussed that lower tower footing resistance cannot always improve the reliability of the line service. If the tower with high footing resistance is protected by surge arrester, the adjacent tower with low footing resistance exposed to high overvoltage and is likely to experience backflash. The region where the tower footing resistance varies from tower to tower needs to have surge arrester installed on tower close to the boundary of different line sections. The various design aimed at improving the lightning performance of the transmission line using a minimum number of surge arrester is studied in this section. Different designs considered for transmission line lightning protection using line surge arresters are: the surge arresters are not installed in all tower phases or on all towers. Section 4.3.1 studies the effect of the number of surge arresters per tower and develops criteria for optimal selection of surge arrester installation location on the towers according to the line section tower footing resistance. Section 4.3.2 presents the effect of the distance of surge arrester locations. The simulation model and simulation procedures as well as the simulation results are presented are presented in both sections. In Section 4.3.1, the surge arrester installation strategy is proposed.

Section 5 concludes this thesis and potential future work is presented in Section 6

# 2. Modeling

The lightning stroke to the transmission line and substation is the primary cause of the fast front transient in power system. The fast front transient covers a frequency range from 10 kHz up to 1 MHz. This chapter aims to identify the models of specific power system components used in the digital simulation which involves fast front transient.

## 2.1 Lightning Surge

The standard waveform of a lightning surge is specified by the IEEE standard 4-2013 [15] and is described as a 1.2/50 μs voltage impulse, which means the voltage wave reaches the crest in 1.2 μs and diminishes to half the crest value in 50 μs. Fig. 2.1 depicts the standard waveform of the lightning surge. In this thesis, the lightning impulse is modeled as a voltage source with external source control, which uses a surge generator to provide the surge waveform. IEEE standard 4-2013 [15] introduced a double exponential waveshape described as:

$$V = V_{pk} * K(e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}}) \tag{2.1}$$

$V_{pk}$ is the crest value of the wave voltage.

For a $1.2 \times 50\mu s$ wave, K=1.037, $\tau_1 = 68.5\mu s$, $\tau_2 = 0.404\mu s$

The crest value is recommended to be the basic lightning impulse insulation levels (BIL) of the equipment [16]. According to IEEE Std C62.82 [17], the BIL for 230 kV systems is 900 kV while it is 1800kV for 500kV systems.

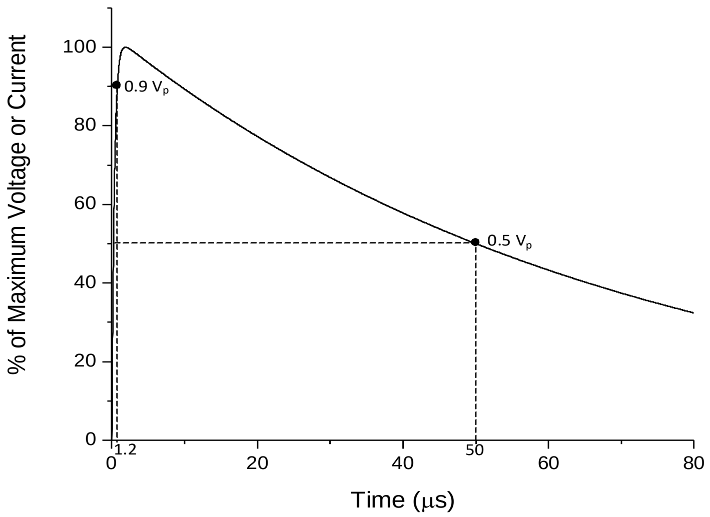



Fig. 2.1. Lightning Standard Waveform.

## 2.2 Transmission Line

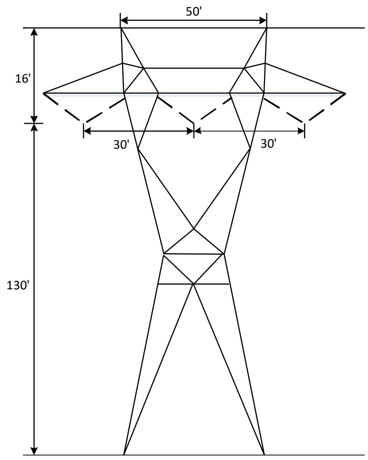
Transmission lines are modeled with the Frequency Dependent (Phase) Model in PSCAD since it is one of the most advanced time domain models. It can distribute the line resistance across the entire transmission line rather than lumped at the end of the line [18].

The data for the 230kV transmission line and the 500kV transmission line are provided by Arizona Public Service Electric (APS) and Salt-river project (SRP) respectively. Table 2.1 shows the parameters of those two transmission lines.

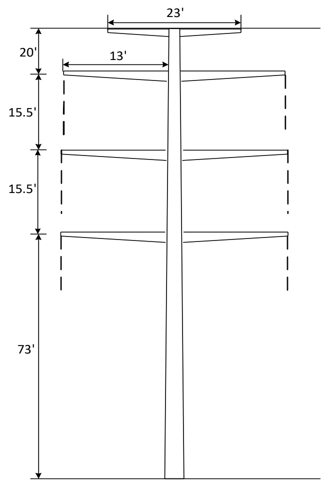
Table 2.1. Data for 230kV Transmission Line and 500kV Transmission Line.

| Parameters | 230kV | 500kV |
|---|---|---|
| Conductor | Cardinal | Chukar |
| Type | 954 KCM, ACSS | 1780 KCM, ACSR |
| Stranding | 54/7 | 84/19 |
| Average Span, ft. | 1000 | 1000 |
| No./phase; spacing, in. | 3, 18 | 2, 12 |
| Suspension Strings | | |
| Configuration | I | V |
| Insulator size, in. | $5^3/_4 \times 10$ | $11^1/_2 \times 7$ |
| No. strings/ phase | 2 | 2 |
| Lightning Protection | | |
| No. shield wires | 2 | 2 |
| Material | Alumoweld | Alumoweld |
| Diameter, in. | 0.385; 7 #8 | 0.385; 7 #8 |

Fig. 2.2 shows the geometrical features including the location of ground wires and phase conductors. Dotted lines represent the suspension insulators. The 230kV transmission line comprises a three-phase double circuit (see Fig. 2.2 (a)) while the 500kV transmission line is a three phase single circuit (see Fig. 2.2 (b)).




(a) 230kV Transmission Line Tower Design and Conductor Arrangement.




(b) 500kV Transmission Line Tower Design and Conductor Arrangement.

Fig. 2.2 500kV Transmission Line Tower Design and Conductor Arrangement.

The traveling wave on the transmission line is influenced and modified by the towers. Thus, to determine the overvoltage accurately, a sufficient number of towers should be modeled at both sides of the struck tower. Generally, when the traveling time for the lightning surge between the struck tower and the farthest tower to the substation is more than one-half of the lightning surge front time, the number of line spans will be considered as sufficient. If the effect for the tail of the lightning surge is taken into consideration, the number of spans need to be modeled should increase.

The line extended beyond the last tower, which is expected to avoid reflections that could affect the overvoltages, is represented by a long enough transmission line section. The line terminal representation results in no reflection from the line termination.

## 2.3 Transformer

The auto transformer used in this simulation is connected in star-star and has a rating of 533kVA as per the data provided by SRP. A high-frequency transformer model, as shown in Fig. 2.3, must be used in the study of the fast front transient. There are several detailed models which may include each winding turn and turn-to-turn inductance and capacitance. However, the model corresponding to each specific turn is not efficient for most applications due to computational complexity. A much simpler model can be obtained by using lumped capacitor and inductor.

In Fig. 2.3, $C_{hg}$ denotes the distributed capacitance of the high-voltage windings; $C_{lg}$ denotes the distributed capacitance of the low-voltage winding; and $C_{hl}$ denotes the distributed capacitance between the high-voltage winding and low-voltage winding [19].

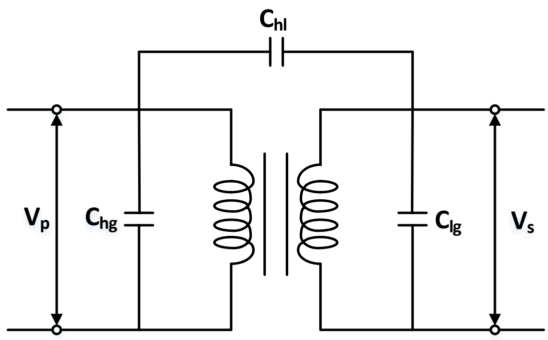



Fig. 2.3. High Frequency Model for the Transformer.

## 2.4 Surge Arrester

The characteristics of the 500kV and 230kV surge arresters used in this paper are given in Table 2.2 and Table 4.3 respectively. The V-I characteristic curve of the surge arresters is given in Fig. 2.4 and Fig. 2.5. The surge arrester type used in this system is SIEMENS 3EL2. In the tables, U denotes the maximum discharge voltage. I denotes the peak current amplitude.

Table 2.2. Technical Data for SIEMENS 3EL2 230kV Surge Arrester.

| 3EL2 | 1/2 $\mu s$ | 8/20 $\mu s$ | | | | 45/90 $\mu s$ | | |
|---|---|---|---|---|---|---|---|---|
| I(kA) | 10 | 5 | 10 | 20 | 40 | 0.5 | 1 | 2 |
| U(kA) | 458 | 406 | 432 | 480 | 544 | 346 | 354 | 372 |

Table 2.3. Technical Data for SIEMENS 3EL2 500kV Surge Arrester.

| 3EL2 | 8/20 $\mu s$ | | | | 45/90 $\mu s$ | | |
|---|---|---|---|---|---|---|---|
| I(kA) | 5 | 10 | 20 | 40 | 0.5 | 1 | 2 |
| U(kA) | 930 | 989 | 1088 | 1187 | 801 | 821 | 860 |

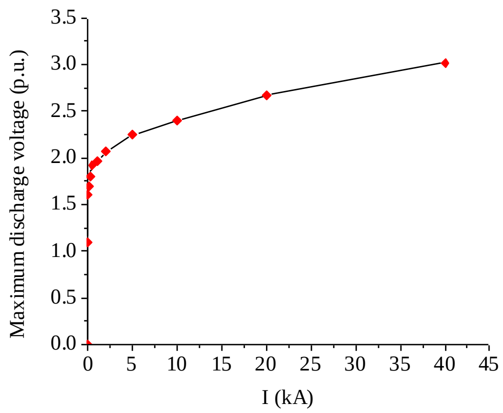



Fig. 2.4. Siemens 3EL2 230kV Surge Arrester.

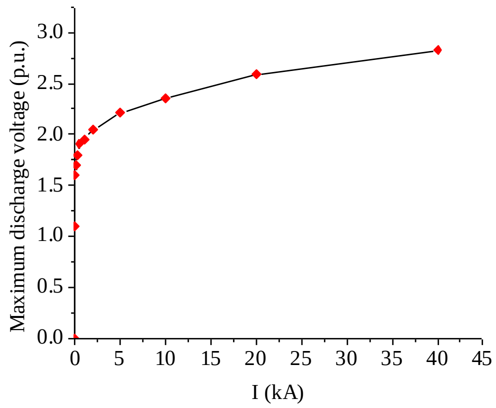



Fig. 2.5. Siemens 3EL2 500kV Surge Arrester.

## 2.5 Transmission Line Tower

Fast front transient tower models include the effect of tower geometry and tower grounding resistance. The tower body and tower arm can be represented using the transmission line Bergeron model in PSCAD since only the surge impedance and the surge travel velocity of the tower are needed to be concerned. The insulators are modeled with their flashover characteristics.

A simplified fast front transient tower model is depicted in Fig. 2.6. Where cylinders represent the phase conductor and the shield wires, the insulators are denoted by the switches and capacitors. The surge impedance and the footing resistance are used to represent the towers.

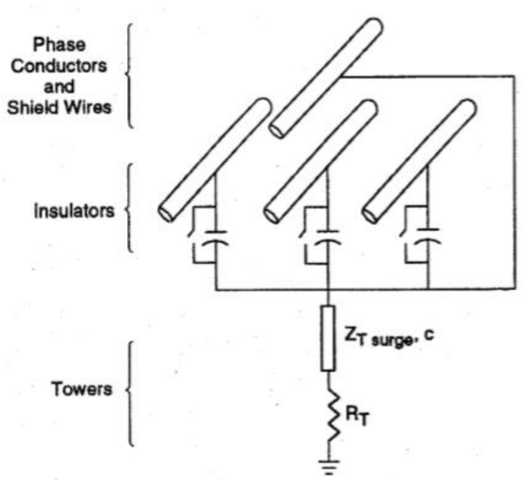



Fig. 2.6. The Overhead Transmission Line, Tower and Insulator Representation [22].

### 2.5.1 Insulators

As illustrated in Fig. 2.6, the insulators are represented by switches in parallel with capacitors connected between the respective phases and the tower. The switch, which is voltage-dependent, is open when the insulator is under normal operation condition and close when the insulator flashover occurs. The capacitors can represent the coupling effect of conductors to the tower structure.

The backlashover mechanism of the insulators can be modeled by volt-time method [2]. The volt-time characteristic of insulators is represented as a function of insulator length. The equation (2.2) can be used to calculate the insulator flashover voltage.

If the voltage across the insulator exceeds $V_{v-t}$, back flashover occurs.

$$V_{v-t} = K_1 + \frac{K_2}{t^{0.75}} \tag{2.2}$$

where

$V_{v-t}$: Flashover voltage, kV

$K_1$: $400 \times L$

$K_2$: $710 \times L$

$L$: Insulator length, m

*t*: Elapsed time after lightning stroke, $\mu s$

Fig. 2.7 is an illustration of the volt-time curve of the insulation for $L = 1.65\ m$.

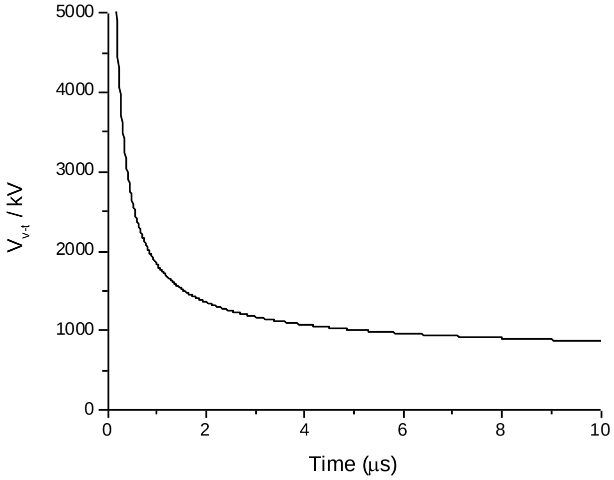



Fig. 2.7. The Plot of the Flashover Voltage vs. the Elapsed Time after Lightning Stroke.

A snapshot of the model of the insulator in PSCAD is illustrated in Fig. 2.8.

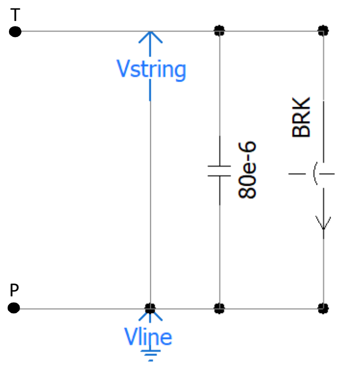



Fig. 2.8. Insulator Model in PSCAD.

The node T in Fig. 2.8 is connected to the tower of the insulator while node P is connected to the phase conductor. Thus, $V_{string}$ represents the voltage across the insulator and $V_{line}$ is the voltage between the phase conductor and the ground.

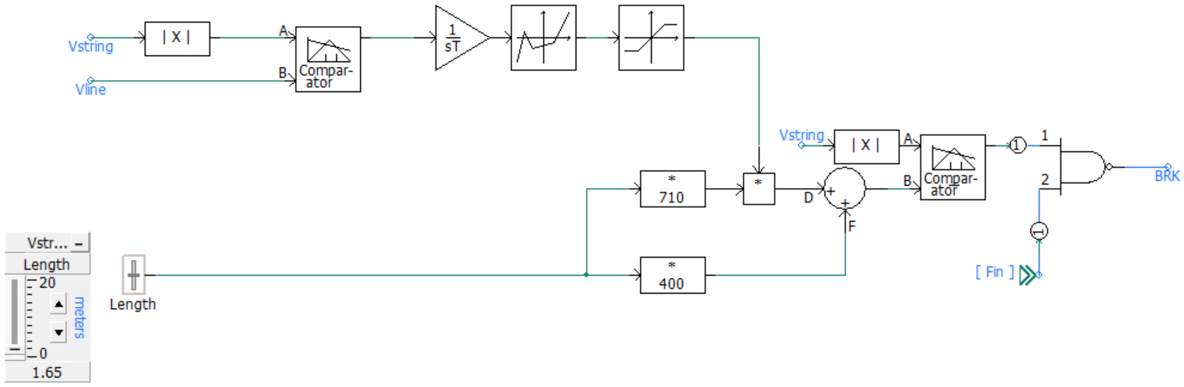



Fig. 2.9. Switch Control Signal Generator Model.

The signal BRK controls the switch which represents the insulator. When BRK is 1, the switch is open. When BRK is 0, the switch is closed.

Fig. 2.9 is the control of the insulator modeled in PSCAD. The input of the control is the $V_{string}$, $V_{line}$, and $F_{in}$. $F_{in}$ is used to enable the flashover behavior of the insulator. The output is the signal BRK. When $F_{in}$ is set to be 0, the switch will keep open.

The Non-Linear Transfer Characteristic Component in PSCAD is used to obtain the $V_{v-t}$ according to the time. This component model a non-linear transfer characteristic by using straight-line-segment approximation. Totally ten sets of points are used in this component, which is the time and the corresponding result of $t^{0.75}$. The output corresponding to a specific time is determined by straight-line interpolation between the points.

One thing should be noted is that the negative flashover voltage of cap and pin insulators with non-uniform solid layer could be 10%-15% lower than the positive switching flashover voltage [2]. To make it simple, we assumed that for either positive or negative voltage across the insulator, they have the same flashover voltage.

### 2.5.2 Tower Surge Impedance

The tower surge impedance can be defined as the voltage developed across an insulator string at the tower top per unit of lightning current entering the tower [2].

Wagner and Hileman [20] proposed the expression below to calculate the surge impedance of a cone:

$$Z_{av} = 60 * \ln[\cot(0.5 * \tan^{-1}(r_{avg}/H_t))] \tag{2.3}$$

$$r_{avg} = \frac{r_1 h_2 + r_2(h1+h2) + r_3 h_1}{h1+h2} \tag{2.4}$$

Where:

$r_1$ is the tower top radius;

$r_2$ is the tower mid-section radius;

$r_3$ is the tower base radius;

$h_1$ is the height from base to mid-section;

$h_2$ is the height from mid-section to the top;

$H_t = h_1 + h_2$.

As Chisholm [21] stated that the cylindrical model fails when used to analyses horizontal-current response. Thus, the model used in the report to calculate the surge impedance of the transmission line towers are chosen to be calculated based on conical antenna tower model which can provide better results.

Corona effect is not considered since it is a conservative approximation to neglect it. The propagation velocity of traveling wave in towers is approximate 80% of the speed of light.

In PSCAD simulation, the body of the towers is represented as Bergeron model transmission lines with the surge impedance and surge travel velocity.

### 2.5.3 Tower Footing Resistance

The tower model needs to include the tower grounding resistance with special emphasis on its lightning current magnitude dependent characteristics due to soil ionization.

The footing impedance is represented as a current dependent non-linear resistance as follows [23].

$$R_T = \frac{R_0}{\sqrt{1+\frac{I}{I_g}}} \tag{2.5}$$

$$I_g = \frac{1}{2\pi} \cdot \frac{E_0 \rho}{R_0^2} \tag{2.6}$$

where $R_T$ is the footing resistance, $R_0$ is the footing resistance at low current and low frequency, $I$ is the stroke current through the resistance, and $I_g$ is the limiting current to initiate sufficient soil ionization, being ρ the soil resistivity (Ω.m) and $E_0$ the soil ionization gradient (300 kV/m).

# 3. LIGHTNING PROTECTION OF SUBSTATION

## 3.1 Literature Review

Most studies about the surge arrester placement focus on the transmission line [24]-[28] while very few papers discuss the effect of the placement of surge arresters in a substation. Past research effort has proposed a method which has a significant effect on the improvement of shielding devices. Such shielding devices are expected to protect the substation equipment adequately [29]. In addition, the backflashover study of the substation is performed in [25], [30]. The direct stroke on the transmission line feeding into the substation has not been fully discussed. Thus, this chapter focuses on the direct lightning stroke which can cause very severe damage to the equipment in the substation. The effectiveness of surge arresters' function regarding limiting the arising overvoltage is identified in [31]. The correlation between overvoltage and the rise time of the lightning stroke current was investigated in [32], and the effect of tower footing resistance variation is studied in [25]. In this section, only the placement of the surge arresters on the substation is of concern. Most of the literatures use the EMTP-type programs to evaluate the lightning performance of surge arrester [27], [33]. However, the EMTDC program can provide better transmission models. Thus, the PSCAD/EMTDC program is used to perform simulations in this work.

The reason for the overvoltage caused by lightning in a substation is either the station shielding failure or the lightning stroke to a transmission line feeding to the substation [12]. In a well-designed substation, the majority of strokes are to the lines, creating surges that travel along the line and enter into the substation. The lightning surge that originates in the transmission line can be divided into three categories: a lightning flash terminating on a phase conductor, on an overhead shield wire, or on the nearby ground which induces a surge into the conductors [12]. The lightning that strikes on a phase conductor is the focus of this section since the overvoltage it causes to the substation is expected to be the most severe. The lightning striking on the line sets up traveling waves moving along the line. When the traveling wave reaches the entrance of the station, it is modified by the terminating impedance of the substation. The crest voltage doubles when the traveling wave encounters an open circuit breaker and reflects back to the transmission line, which corresponds to the worst case. When the lightning striking on a transmission line causes a phase to ground fault, the faults may provide a path for current to flow into the ground and the impedance at that point will change significantly. In this case, the traveling wave will reflect back and forth between the lightning striking point and the entrance of the substation. Lattice diagram, shown in Fig. 3.1 (a), is used to illustrate the situation. Note that, in Fig. 3.1, X denotes the lightning stroke point; Y denotes the terminal of the transformer; and the line entrance of the substation is marked as Z.

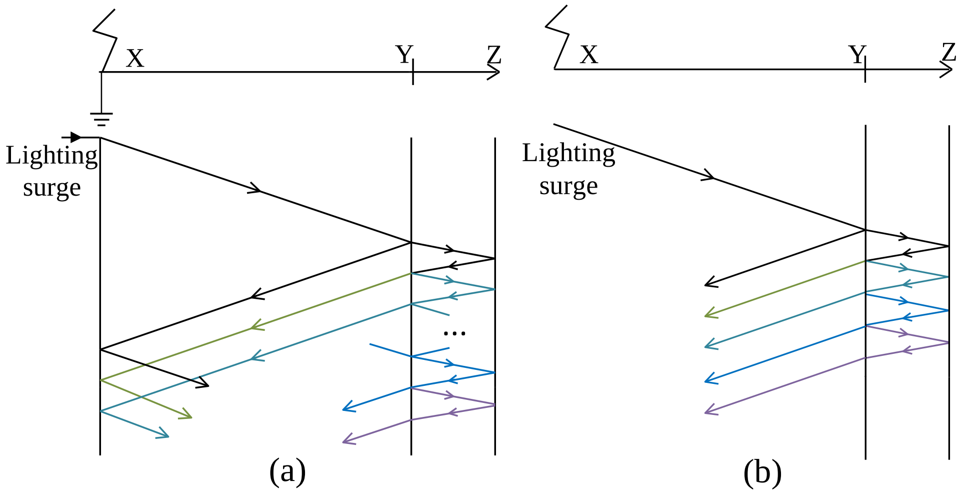



Fig. 3.1. Lattice Diagram of the Traveling Wave.

The voltage of a specific point at a transmission line is the sum of the instantaneous values overall individual traveling waves at that point. Thus, it is very likely that the highest overvoltage at the substation entrance will occur when lightning strikes a critical point. A critical point is defined as a specific location where if lightning hits, the maximum peak voltage amplitude will occur at the terminal of the transformer. The critical point is one of the major concerns of this chapter and is discussed in the model development section. Another factor considered in this chapter is that no impedance change occurs along the transmission line when the lightning does not cause any ground fault. With the assumption that there is no attenuation of the lightning surge along the transmission line due to the line resistance, the distance of lightning stroke to the substation is independent of the voltage at the entrance, which is illustrated in Fig. 3.1 (b).

According to IEEE Standard C62.22-2009 [12], surge arresters can be installed at the line entrance of the substation to protect apparatus in the substation such as the circuit breakers, disconnect switches, and instrument transformers. However, due to the high cost of surge arresters, this standard is not enforced by all utilities. Thus, four different configurations are evaluated in this section and they are listed as follows:

1) No surge arrester in the substation;

2) Surge arrester installed at the entrance of the substation;

3) Surge arresters installed at the terminals of the transformer;

4) Surge arresters installed at both the substation line entrance and the terminals of the transformer.

Then, the protection scheme that provides the optimal protection with the least cost will be determined.

## 3.2 Model Development

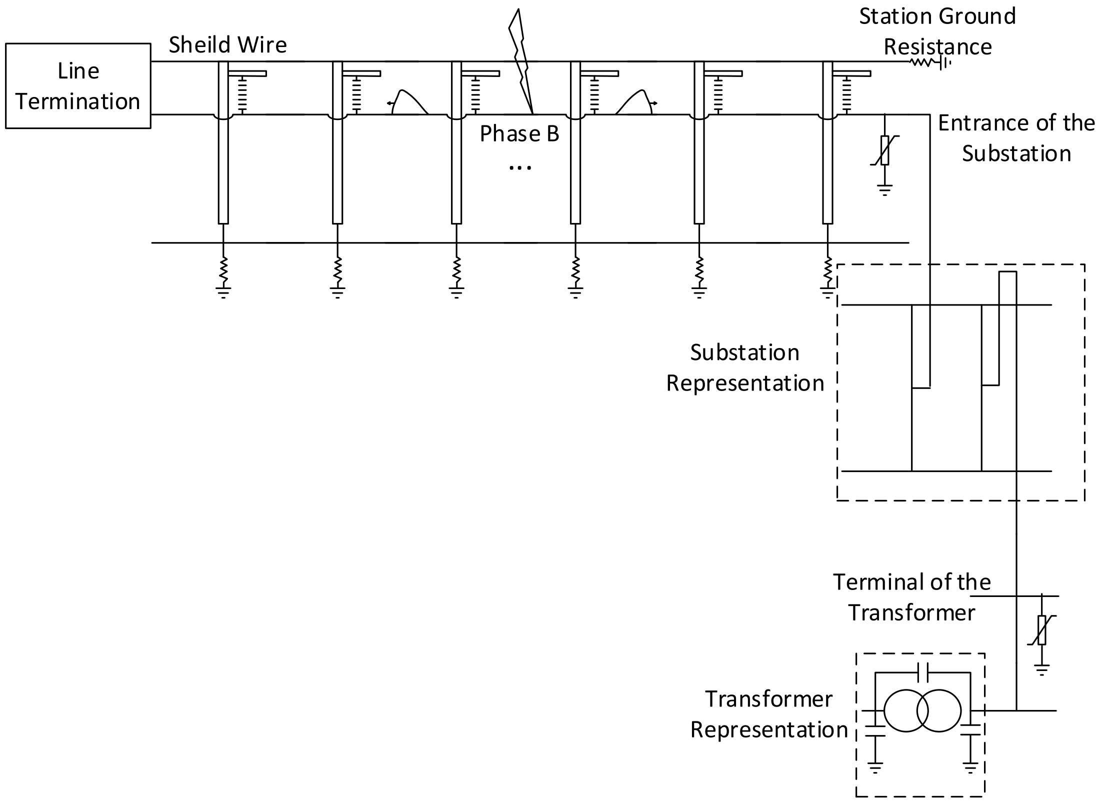



Fig. 3.2. Simulation Model Representation.

In Fig. 3.2, only one shield wire and phase B conductor are depicted. By varying the lightning struck location, the critical point which has the maximum overvoltage on the terminal of the transformer can be determined. The lightning stroke is terminating on the phase B. Travelling waves are generated on both side of the lightning struck location. In this chapter, surge arresters are not installed on the transmission line towers. They are installed at the entrance of the substation, or the terminal of the transformer, or both.

Four different surge arrester configurations are developed and investigated for studying the surge arrester placement on substations. These four configurations are:

C1: No installed surge arrester on the substation

C2: Two surge arresters are installed at the entrance of the substation and the terminal of the transformer respectively.

C3: One surge arrester is mounted at the entrance of the substation;

C4: One surge arrester is installed on the terminal of the transformer.

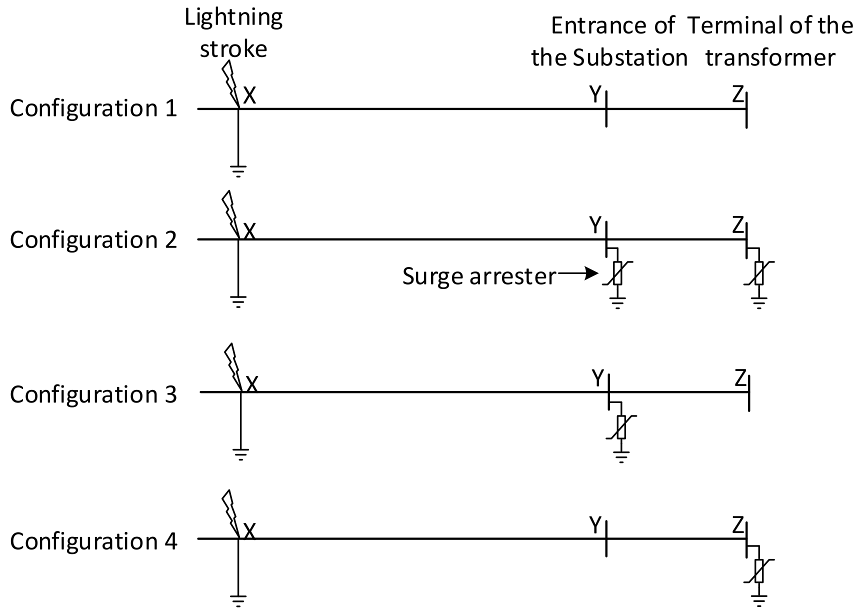



Fig. 3.3. One Line Diagram of the Four Configurations.

A one-line diagram that illustrates the four different configurations is shown in Fig. 3.3.

The procedure used to analyze the effect of different surge arrester configurations on the substation is listed below:

(1) Designing the line section which comprises ten spans of the 230kV transmission line and the connected substation in PSCAD using the field data. No surge arrester is installed in this configuration at step (1). It is assumed that the lightning hits on Phase B of the transmission line.

(2) Gradually changing the distance from the lightning stroke location to the entrance of the substation. For each lightning stroke, the crest voltages at the entrance of the substation and the transformer terminal are recorded.

(3) The improvement of the system lightning performance for the rest of the three configurations, which use surge arresters, are analyzed by repeating step (2). In addition, the performance of the surge arresters is recorded.

Step (2) describes how the voltage-distance curves are drawn. The voltage-distance curve can identify the critical point which is used to determine the maximum recommended length of the line before an arrester needs to be applied. Moreover, the voltage-distance curves can help determine the optimal configuration which can satisfy the specific lightning performance.

## 3.3 Simulation Results

It is explained in the literature review section that the worst case would occur when lightning hits the transmission line and causes the line to ground fault, which is the focus of the simulations performed with PSCAD in this section.

Fig. 3.4 illustrates a simplified model for the transmission line and the substation. For simplicity, only phase B is depicted in Fig. 3.4. The point of the lightning stroke on the transmission line is denoted as Point X. Point Y is the 230kV line entrance of the substation. Point Z represents the 230kV terminal of the transformer, which connected to the substation.

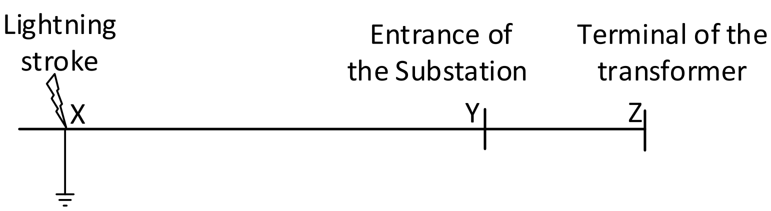



Fig. 3.4. A Simplified Model for the Transmission Lines and the Substation.

For a specific stroke location, for instance, the distance from lightning stroke to the entrance of the substation is 200m. Simulation results are given regarding plots of waveforms for the important variables such as arrester voltage, current, and energy duties. The voltages over time at Point Y and Point Z for configuration C1 are shown in Fig. 3.5.

The oscillation voltage in Fig. 3.5 may result from the transformer capacitors and inductors. Since there is no surge arrester in this system, the maximum voltage is over 1600kV which is much higher than the BIL value (900kV). The equipment in the substation including circuit breakers, instrument transformers, and the transformers, are in danger.

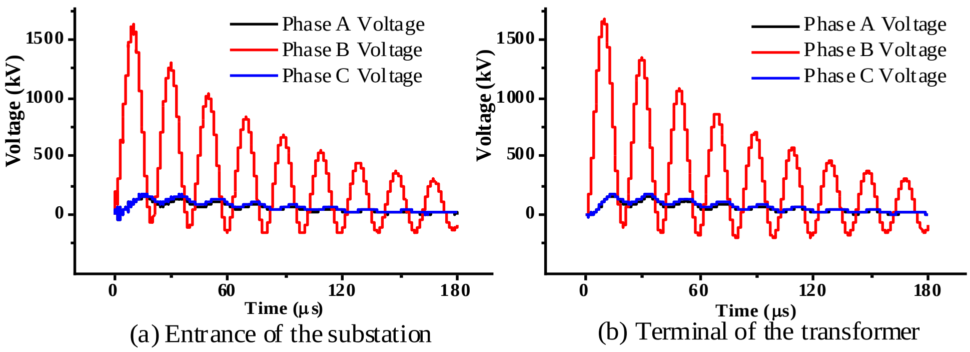



Fig. 3.5. The Voltage at Point Y and Z for C1.

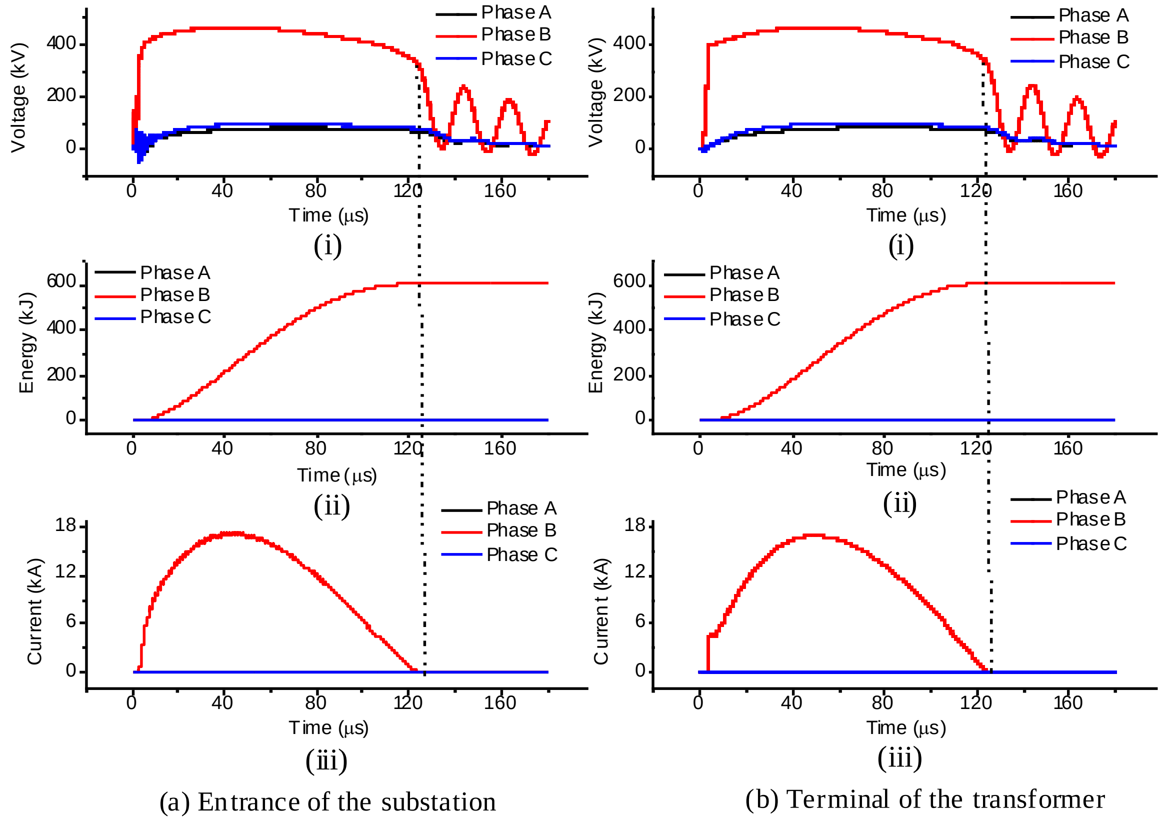



Fig. 3.6. Voltage and the Surge Arrester Energy as well as the Current at Point Y and Z for C2.

Fig. 3.6 (a).(i) and Fig. 3.6 (b).(i) illustrate the voltages at Points Y and Point Z for C2 respectively. The energies absorbed by the surge arresters at Point Y and Point Z are shown in Fig. 3.6 (a).(ii) and Fig. 3.6 (b).(ii) respectively. The currents flowing through the surge arrester are present in Fig. 3.6 (a).(iii) and Fig. 3.6 (b).(iii) respectively. In Fig. 3.6 (a).(i) and Fig. 3.6 (b).(i), from 0-120 $\mu s$, the voltage is held to be the surge arrester discharge voltage. When the currents in the surge arresters drop down to zero (see the dash line in Fig. 3.6), the arrester returns in normal operation condition. In other words, the surge arrester's impedance returns to infinity. After 120 $\mu s$, the voltage becomes oscillating, which is caused by the transformer inductance and capacitance. Since phase A and phase C do not have surge arrester functioned, the energy and the current of the surge arresters installed on these two phases are all zero. Therefore, the energy and current curves of phase A and phase C are overlapped in Fig. 3.6. The analysis described above also applies to C3 and C4. It is worth noting that the energies absorbed in C3 and C4 are close to C2, but they are a bit lower than the sum of the energy absorbed by the two surge arresters in C2. Meanwhile, the average voltage of C3 and C4 are higher than the average model of C2.

The effect of the surge arrester configurations concerning the point which injected the lightning stroke on a 230 kV transmission line and the substation is studied using the voltage-distance curve in Fig. 3.7.

Fig. 3.7 illustrates that the trend of the peak voltage amplitude curves of all four configurations decreases as the distance between the lightning stroke location and the substation increases. However, for C1, the crest voltage at the entrance of the substation reaches the peak when the lightning stroke is 160m away from the substation. Therefore, the critical point is 160m. Also, for C4, the curve of the crest voltage is oscillating and thus, it has several maxima.

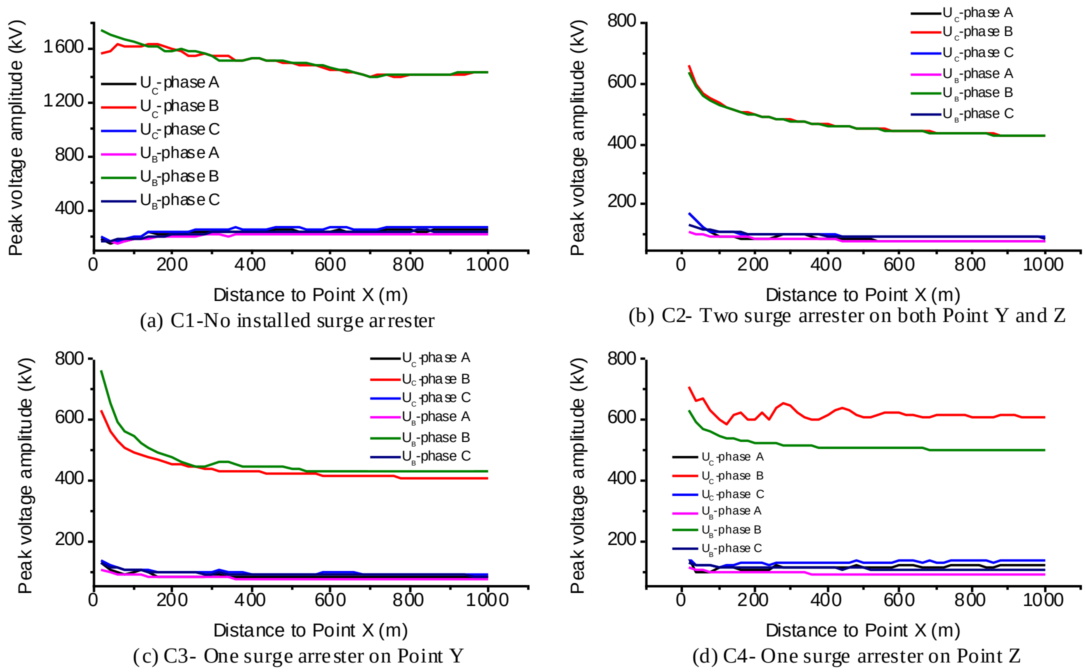



Fig. 3.7. The Voltage-distance Curve for All Three Phase of the Point Y and Z.

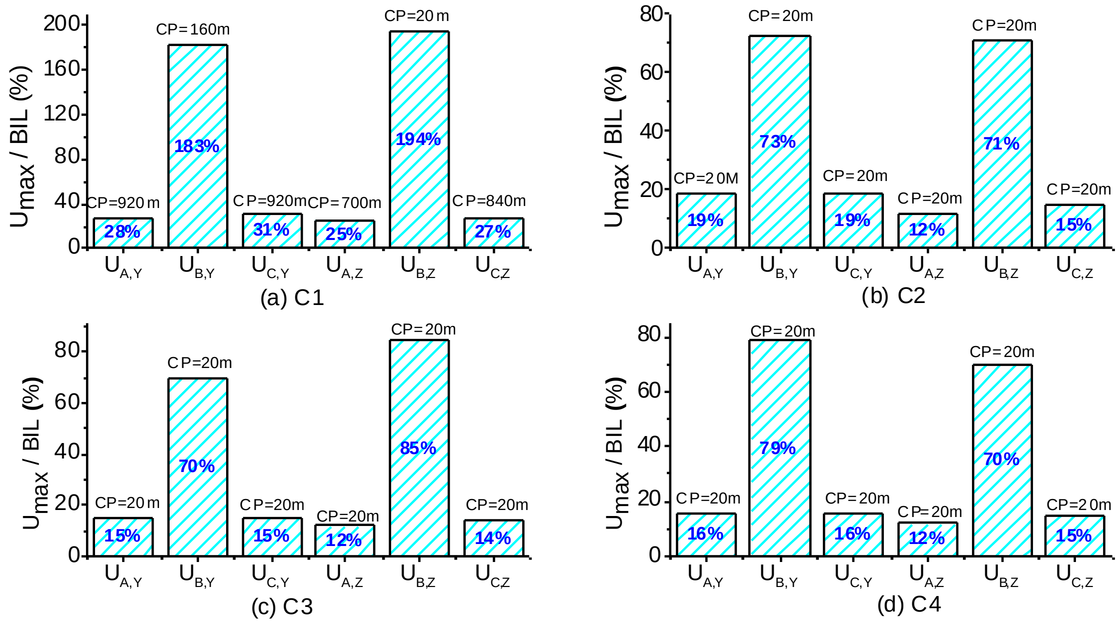
Fig. 3.7 (a) shows the simulation results with C1. This is one of the cases that have critical point which is not the closest point to the substation in the simulation. Fig. 3.7 (a) shows the difference of the maximum voltage of each phase on Point Y and Point Z with BIL value. The phase B voltage at the entrance of the substation and the terminal of the transformer exceed the BIL value, and the system is in danger.

Fig. 3.7 (b) shows that the crest values of the phase B voltage on Point Y and Point Z are almost overlapped. The voltages drop down sharply from lightning strokes located at 0m to 400m and then stabilize for the locations that are over 800m away from the entrance of the substation. From Fig. 3.7 (b), the maximum voltages at Point Y and Point Z are 73% and 71% of the BIL value respectively. C2 has the best lightning protection performance as the average of the maximum voltage at Point Y and Point Z are the lowest among the four configurations.

Except for the voltage of C1, the maximum voltage at Point Z of C3 is the highest. The voltage at the terminal of the transformer (Point Z) is 85% of the BIL value. Since a transformer is a very vulnerable and expensive equipment in the power networks, a failure of a transformer can result in high cost of repair or replacement and outage losses. Therefore, it is better to leave some margin for the peak voltage amplitude at the transformer terminal. Regarding the protection of the transformer, C4 has a better lightning protection performance than C3. In addition, the maximum voltage for the two points is 85% in C3 and 79% in C4, which shows another advantage of C4 over C3. Due to the mutual coupling effect, phase A and phase C have the peak voltage amplitude around 100kV. The voltages on phase A and phase C are far less than the voltage on phase B. In Fig. 3.8, it is clear that phase A and phase C voltages can only reach up to 31% of the BIL value. Therefore, the voltages of phase A and phase C are not shown in Fig. 3.9.

For C4 in Fig. 3.9, the peak voltage amplitude at Point Y is higher than the peak voltage amplitude at Point Z. However, the situation is the opposite for C3. Therefore, the location which has surge arrester installed would have lower overvoltage than the locations. Point $P_1$ is the intersection of the two curves $U_Y$-C4 and $U_Z$-C3. The difference between the peak voltage amplitude at Point Z in C3 and Point Y in C4 is large at the beginning and gradually reduces to zero at the intersection Point $P_1$. Then the peak voltage amplitude at Point Y in C4 surpasses the voltage at Point Z in C3. Thus, the highest voltage is under C3 first and soon becomes the voltage under C4. After Point

$P_2$, the curve of $U_Z$-C3 becomes even lower than the $U_Z$-C4. Which means that after point P2, the voltage of the transformer under configuration 3 is lower than the voltage under configuration 4. The probability for lightning stroke on a transmission line within 100m to the entrance of the substation is very low. Therefore, C3 may provide a better protection for the equipment in the substation since the voltage at the entrance of the substation is always high in C4. C3 also performs better than C4 with respect to transformer lightning protection.




CP - critical point

Fig. 3.8. The Ratio between the Maximum Voltage and the BIL Value Under Different Configurations.

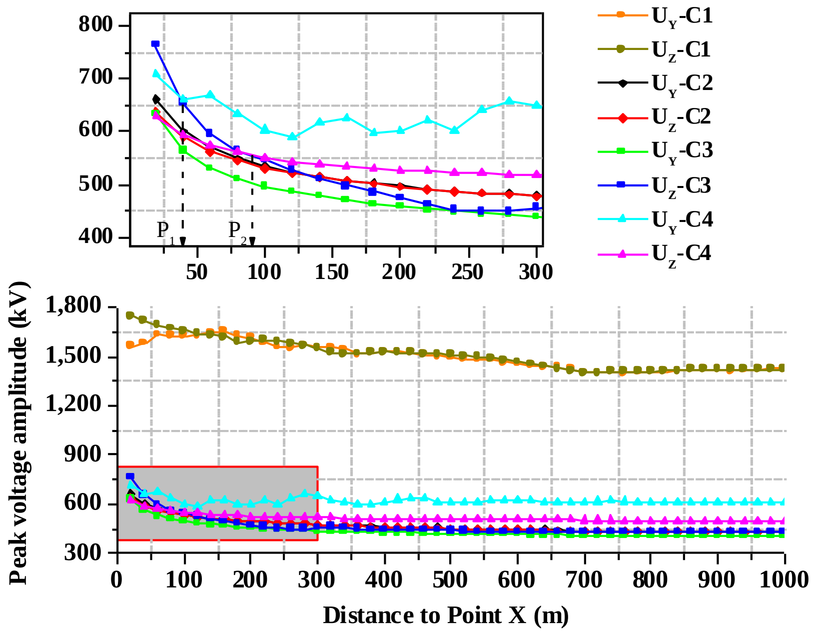
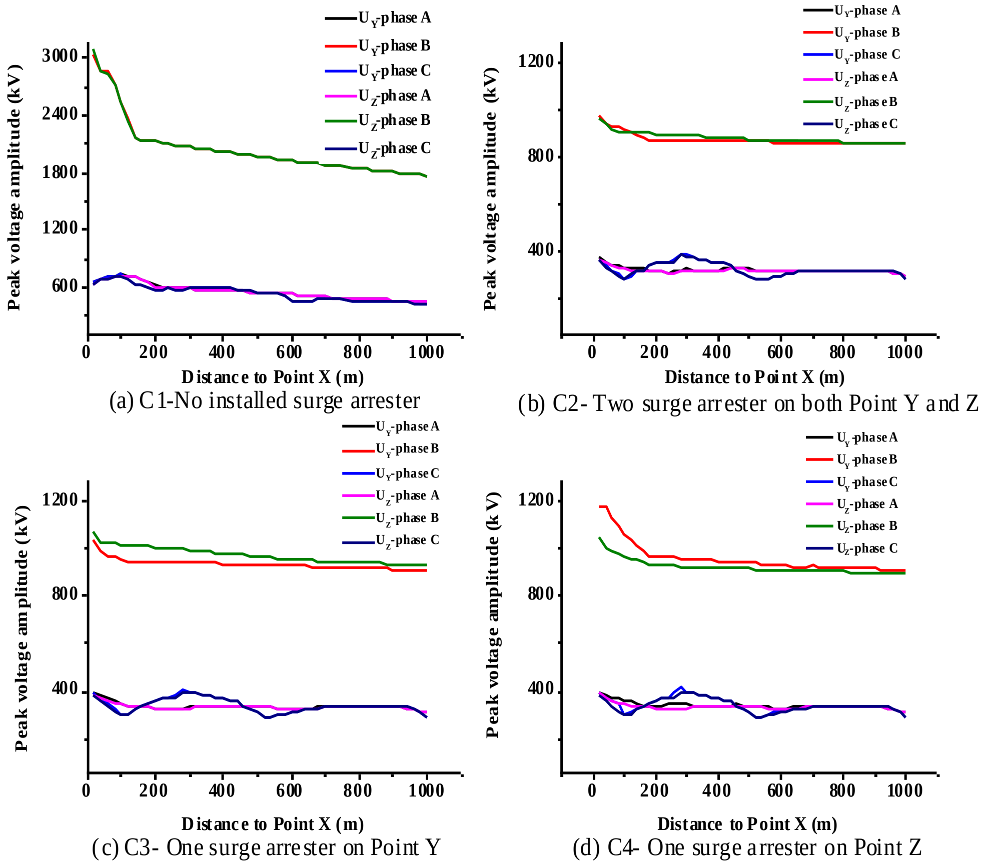



Fig. 3.9. Voltage-distance Curve for Phase B at Point Y and Z.

The simulation for the 500kV substation is also performed. The procedures for obtaining the voltage-distance curve are the same as the 230kV substation. Moreover, Fig. 3.10 is similar to Fig. 3.7, which shows that the characteristic of lightning performance for different surge arrester configurations under different voltage levels is almost the same.




(a) C1-No installed surge arrester

(b) C2- Two surge arrester on both Point Y and Z

(c) C3- One surge arrester on Point Y

(d) C4- One surge arrester on Point Z

Fig. 3.10. The Voltage-distance Curve for All Three Phases of the Point Y and Z of 500kV Substation

## 3.4 Conclusions

The primary objective of this section is to examine whether only installing arrester at the terminal of the transformer can efficiently protect the 500/230kV substation.

By analyzing the performance of four different configurations regarding the location of surge arresters, appropriate parts of a 230kV transmission line, as well as the 500/230kV substation, are modeled using PSCAD. The model built using the real line data is utilized to simulate the effect of lightning stroke hitting at a different location on the transmission line.

The voltage-distance curve is proposed to evaluate the effectiveness of the lightning protection of the four different surge arrester configurations when a lighting stroke hits on the transmission line feeding to the substation. A good visual depiction of the simulation results is offered by implementing the voltage distance curve.

Though installing the surge arresters at both the entrance of the substation and the terminal of the transformer has the best performance among the four configurations, the high installation cost of the surge arrester makes it less competitive. Moreover, the other two configurations which have surge arrester installed either at the entrance of the substation or the terminal of the transformer are sufficient for lighting protection. In the configuration of installing the surge arrester at the entrance of the substation, it is possible that the transformer may suffer the voltage up to 85% of the BIL value. However, this happens only when the lighting stroke hits on a small area that is very close to the substation. It is rare that the lighting would hit on that area. The voltage at the entrance of the substation when the surge arrester is installed at the terminal of the transformer is always high, which may require the equipment at the entrance of the substation to have a better lightning voltage withstanding capability. Regarding the economic impact, the failure of the transformer can result in high cost due to repair or replacement costs and outage losses. To guarantee that the transformer is well-protected, the configuration which only has surge arrester installed at the terminal of the transformer can be implemented. Therefore, installing surge arrester at the terminal of the transformer in the Rudd 500/230kV substation by SRP is proved to be adequate and efficient concerning both the lightning performance and the economic cost.

# 4. LIGHTNING PROTECTION OF TRANSMISSION LINE

## 4.1 Literature Review

Equipping the towers with transmission line surge arresters (TLSA) has been a very effective way to improve the reliability of transmission lines. After monitoring the three circuits where TLSA are installed on all phases of 13-kV distribution lines with a spacing of 40 meters (every pole), 200 meters, or 400 meters for one year, Reference [34] concluded that the distribution lines with surge arresters does not have a much better lightning performance than the circuit without surge arresters. Moreover, the flashover rates for both scenarios are low. They also presented that the circuit with arresters installed on every pole still had several lightning faults during the monitoring period. However, several practical factors are not considered in reference [34]. For instance, distribution line major flashovers are not caused by lightning. Distribution lines are rarely exposed to lightning since they are mainly located in urban areas where many lightning pods are built. This explains why the flashover rate is low for circuits with and without surge arrester in [34]. In addition, for the 13kV low voltage level distribution line, the basic insulation level (BIL) is around 95kV. Thus, the associated breakdown voltage for the arresters is 95kV. However, the probability of lightning overvoltage exceeding the BIL value of the line system is high. Therefore, it is reasonable that flashovers may still occur on the transmission line even when arresters are installed on every pole of the circuit.

The surge arrester may not provide significant improvements in reliability for the distribution system. However, surge arresters can substantially improve the lightning performance on high voltage transmission lines. This is demonstrated by the field experiments on the application of surge arresters on transmission lines [35]-[38].

References [40]-[41] have studied the parameters that can affect the lightning overvoltage across the insulator in a transmission system. [40]-[41] concluded that low footing resistance could improve the lightning performance of the system. However, back to 1980s, American Electric Power Service Corporation (AEP) believed that under a specific situation, grounding may adversely affect the lightning performance [42]. It can occur in the rocky regions where the earth resistivity is high as stated in [42]. The traditional method to avoid lightning flashover of transmission lines on the rocky region is to reduce the footing resistance. However, it is not very effective to reduce the grounding impedance of the tower at the top of the ridge where the tower footing resistance is generally the highest. In addition, towers are more likely to be built on the top of the ridge in order to make the construction easier. Thus, it is very likely that the footing resistances of towers that are located in the rocky regions are very different with the footing resistances of its adjacent towers. Fig. 4.1 illustrates a one phase and one shield wire diagram of a three-phase system. Tower A and tower B that are located at the top of the ridge have the highest footing resistances while tower C and tower D are located at the bottom of the ridge and have comparatively low footing resistance.

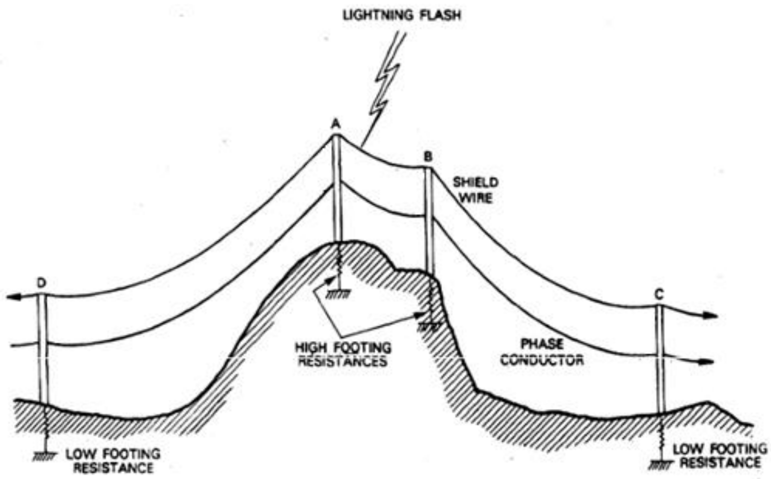



Fig. 4.1.Towers at the Top of a Ridge and Towers at the Bottom of a Ridge [42].

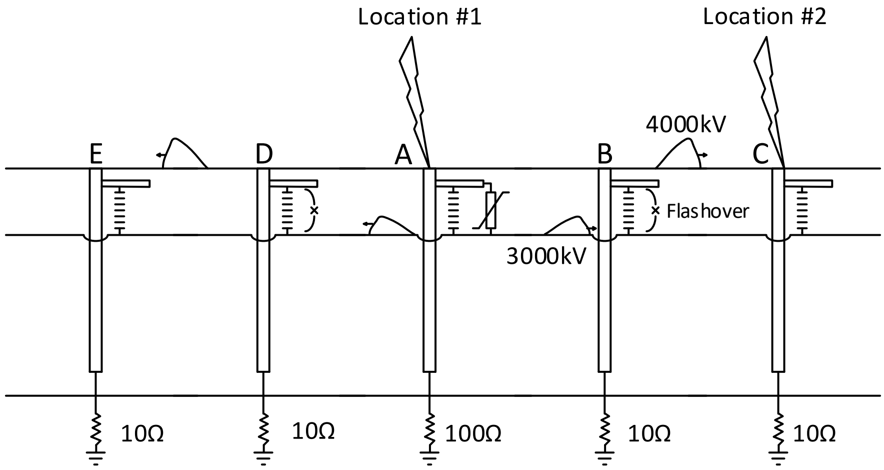



Fig. 4.2. Lightning Striking a Protected Tower Causing the Adjacent Towers Flashover.

Fig. 4.2 presents an example that illustrates a special case when the lightning performance is adversely affected by lowering the tower footing resistance. In Fig. 4.2, tower A has a 100Ω footing resistance, since it is on the ridge of the mountain, the tower footing resistance is relatively high. Tower B and tower D, adjacent towers of tower A, are located at the bottom of the ridge; and both towers have 10Ω footing resistance.

Tower C and tower E have the same footing resistance as tower B and tower D. Only tower A is equipped with surge arresters.

When lightning strikes location #1 shown in Fig. 4.2. Assuming 4000 kV lightning surge is generated at the top of the tower. With 1000kV voltage drop on the surge arrester, the 3000kV lightning surge is injected into the phase conductor through the surge arrester and travels in both directions into the adjacent towers. If the footing resistance of adjacent tower is infinity, which is an ideal situation for high grounding resistance, the voltage across the insulator of the adjacent tower will be equal to the voltage on the lightning struck tower when the phase conductor and the shield wire are lossless lines. The voltage across the insulator of the stricken tower is arrester discharge voltage and is below the critical flashover voltage (CFO). After changing the footing resistance of tower A to 10Ω, the 4000kV traveling wave on the shield wire will pull down by the low footing resistance of the adjacent towers. Since the voltage at the phase conductor does not change significantly, the voltage across the insulator would exceed the CFO. Back flashover will occur on both adjacent towers.

When lightning strikes the location #2 and the surge arrester is only installed at tower C, the low footing resistance of the lightning struck tower can reduce the voltage across the insulator to a value below the CFO value.

Fig. 4.2 is not a suitable surge arrester application. The configuration in Fig. 4.3 is more preferred.

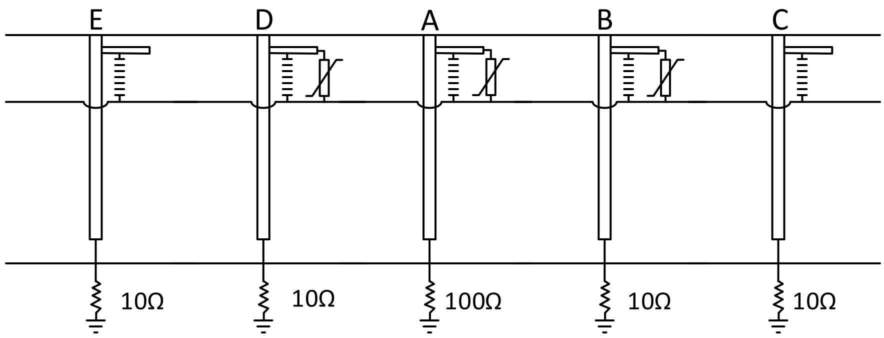



Fig. 4.3. The Installation of Surge Arresters on the Adjacent Towers.

If line arresters are applied only on a number of line sections with poor grounding, arresters also need to be installed on at least one or two towers that are adjacent to the poor grounding resistance section. For example, in Fig. 4.4, the towers in line section 1 are equipped with surge arrester since they have high grounding resistance. The towers in line section 2 have lower grounding resistance and no surge arrester is installed in line section 2. However, the tower A and tower B which are on the boundary of line sections need to be equipped with surge arresters. The "line section" is several spans of transmission line where the variation of its tower footing resistance can be ignored.

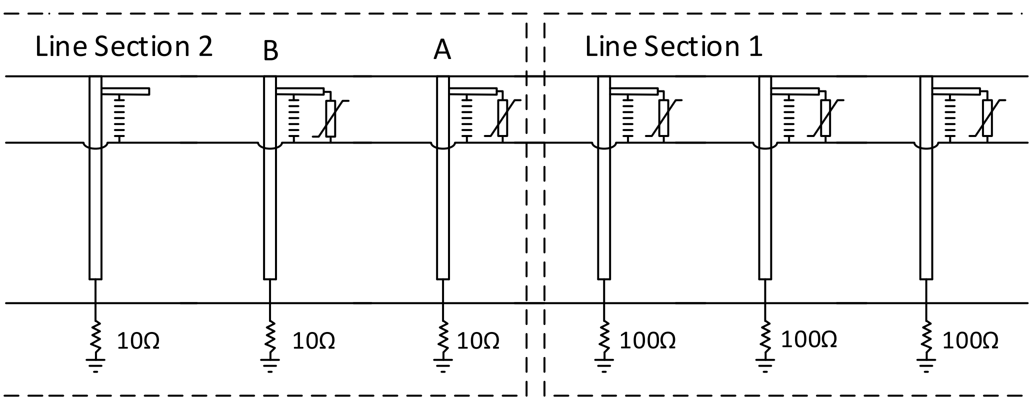



Fig. 4.4. The Installation of Surge Arresters on the Boundary of Line Sections.

Under the discussion section of paper [34], T. E. McDermott proposed equation (4.1), which is used to estimate the voltage across the insulator of the adjacent tower when the tower with surge arrester is subjected to the lightning stroke.

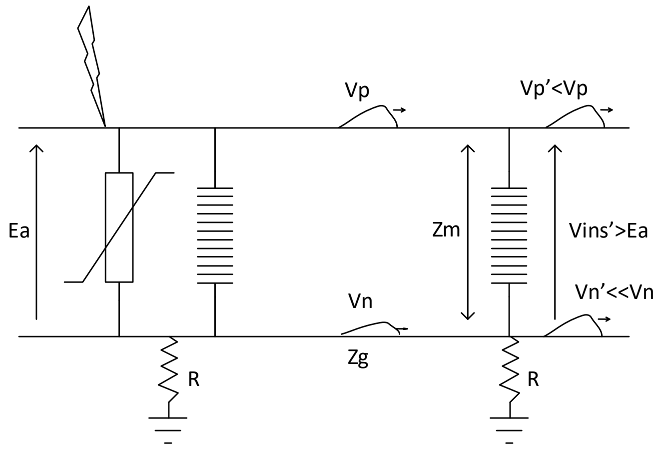



Fig. 4.5. Stroke to a Phase Conductor with no Adjacent Line Arresters

$$V'_{ins} = E_a + V_n \left[1 - \frac{2R+Z_m}{2R+Z_g}\right] \quad (4.1)$$

Where, $V'_{ins}$ denotes the voltage across the adjacent tower insulator, $E_a$ is the surge arrester discharge voltage. $Z_g$ represents the neutral conductor surge impedance and $Z_m$ is the mutual surge impedance between phase and neutral conductors.

The resistance of the ground wire and the phase conductor is ignored in the equation. However, difference of the resistance between the conductor and the shield wire can enlarge the overvoltage across the insulator. The results obtained from the equation (4.1) will be greatly different from the simulation results.

In recent years, many researchers focus on the surge arrester placement for the transmission line. Multiple ways are used to assess the lighting performance of different surge arresters spacing and user of a different number of surge arrester per tower. Paper

[25] uses the “Lightning flashover charts” (LFCs) as a graphic representation of the flashover situation on each pole concerning different lightning stroke locations. The LFCs can give an overall impression of the lightning performance of different surge arrester placement strategies. However, it is a simple illustration and is not able to provide all the information. Paper [36] focuses on the effect of a different number of surge arresters per tower. The threshold current for insulator flashover was used in [36] to help evaluate the lightning performance of transmission lines. Reference [39] further improve the accuracy of evaluating the lightning performance of the overhead lines by using the statistical approach to obtain the flashover rate for each surge arrester placement strategies. The flashover rates were calculated by implementing Monte Carlo method. Reference [25], [36], [39], however, did not provide any detailed criterion for choosing the suitable strategies for specific line sections.

## 4.2 Effect of Footing Resistance

There are two different scenarios that can be used to study the effect of the footing resistance. The first scenario is that the tower footing resistances of the transmission line vary in a rocky region. While in the urban area. The tower footing resistance may be alike, which is the second scenario studied in this work.

### 4.2.1 The Effect of Footing Resistance for Towers Near the Boundary of the Line Sections.

**Model Development**

A model, which has twelve transmission line spans with line matching elements, was developed according to the 230kV transmission line parameters given by SRP. Fig. 4.7 (a) illustrates the transmission line section used in the simulation. The eleven towers included in the protection section are called Tower 1, Tower 2, …, and Tower 11 respectively. Tower 6 is the lighting struck tower and is the only tower which has surge arrester in the protection section. The footing resistances of the Tower 1 through Tower 5 and Tower 7 through Tower 11 change from 10Ω to 100 Ω while the footing resistance of Tower 6 remains to be 100 Ω. The purpose of this simulation is to support the conclusion that if line arresters are installed only on a section of line with high footing resistance, arresters need to be installed on one or two towers near the boundary of different line sections.

The Vstring in Fig. 4.7 (a) represents the voltage across the insulator of Tower 7. It is defined as the voltage at the phase conductor (Vline) minus the voltage of the tower.

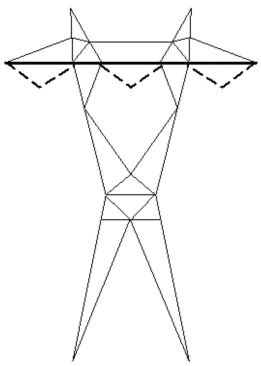
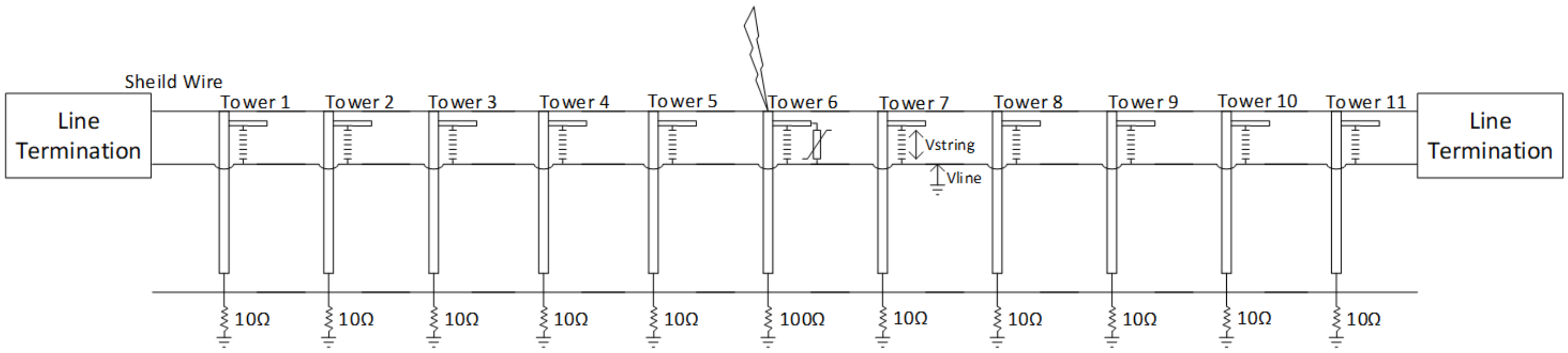
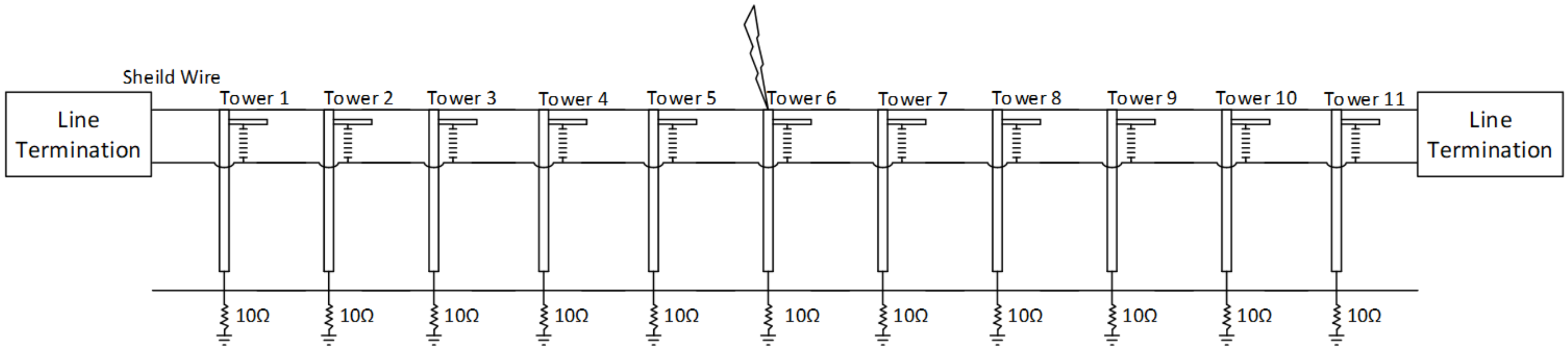


Fig. 4.6. Tower Configuration used in the Simulation




(a)

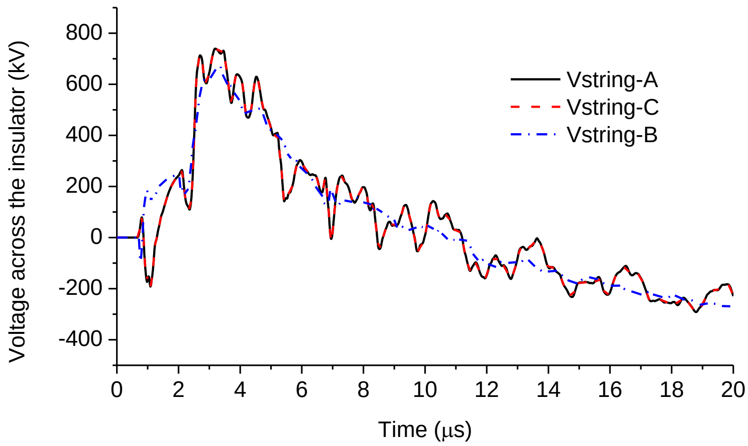



(b)

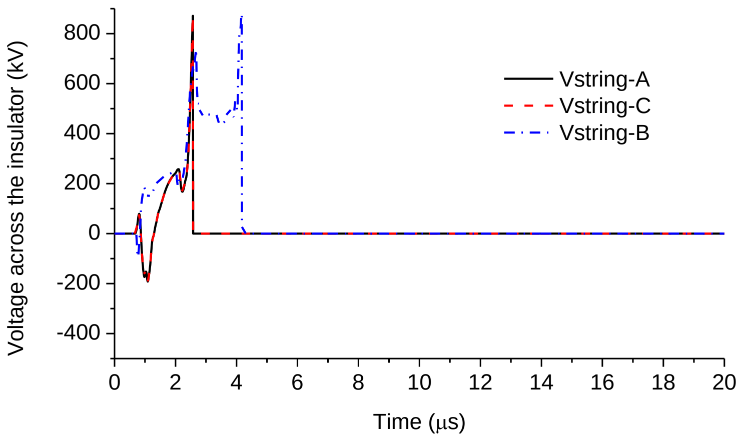
Fig. 4.7. The Model Used for Simulation: 12 Spans with Line Termination Module.

**Simulation Results**

As illustrated in Fig. 4.8 (b), when the footing resistance is 10Ω, the voltage across the insulator connecting to phase A and phase C suddenly becomes zero at around 2.5 s, which indicates the insulator flashover. However, no flashover occurs when the adjacent tower footing resistance is 100 Ω as shown in Fig. 4.8 (a). The lightning performance of the line section becomes worse when the footing resistance of the tower decreases.




(a) Voltage Across the Insulator of Tower 7 When the Footing Resistance of the Tower 1 Through Tower 5, Tower 7 Through Tower 11 is 100 Ω.




(b) The Voltage Across the Insulator of Tower 7 When the Footing Resistance of Tower 1 Through Tower 5, Tower 7 Through Tower 11 is 10 Ω.

Fig. 4.8. The Voltage Across the Insulator as a Function of Time.

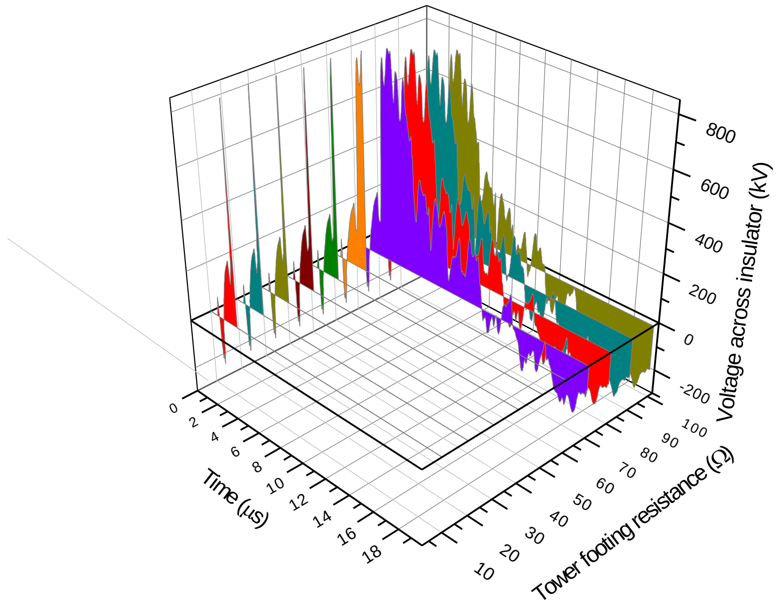



Fig. 4.9. The Voltage Across the Insulator of Phase A as a Function of the Time and the Footing Resistance.

As shown in Fig. 4.9, the line section does not have any back flashovers when the footing resistance of the adjacent tower is above 70 Ω. The peak voltage magnitude increases with the tower footing resistance decreases.

Since Tower 6 is equipped with surge arresters, no flashover occurs on Tower 6. In addition, the voltage across the insulator of Tower 6 remains around the arrester discharge voltage for a long time. The results demonstrate that when lightning hits the tower with high footing resistance, the surge arresters will deliver the lightning surge to the adjacent tower. When the adjacent tower has relatively low footing resistance, flashover is likely to occur.

### 4.2.2 The Effect of Footing Resistance for Towers in the Same Line Section.

The effect of footing resistance in a line section where the variation of its tower footing resistance can be neglected is studied in this section. Meanwhile, The effect of the front time of lightning stroke as well as the magnitude of lightning stroke is also examined.

**Model Development**

The model used in this work is illustrated in Fig. 4.7 (b). No surge arrester is installed in the line section. In order to obtain the maximum overvoltage, the insulator flashover is disabled in the simulation. Fig. 4.10 depicts the tower configuration used in the simulation. In order to study the effect of insulator location, the tower structure used in this section is different from Section 4.2.1. the difference is that the tower structure in Fig. 4.10 has different distances from the tower top to the insulators of different phase conductor.

In the simulation, apart from the footing resistance, sensitivities of the magnitude and the wave shape of the lightning stroke are also investigated.

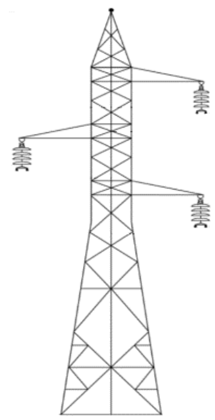


Fig. 4.10. Tower Configuration Used in the Simulation.

**Simulation Results**

A. Front time of lightning stroke

Fig. 4.11 compares overvoltage at insulator with a different front time of lightning strokes with a magnitude of 1200kV between 1.2/50μs, 2/77.5 μs, and 3/75 μs.

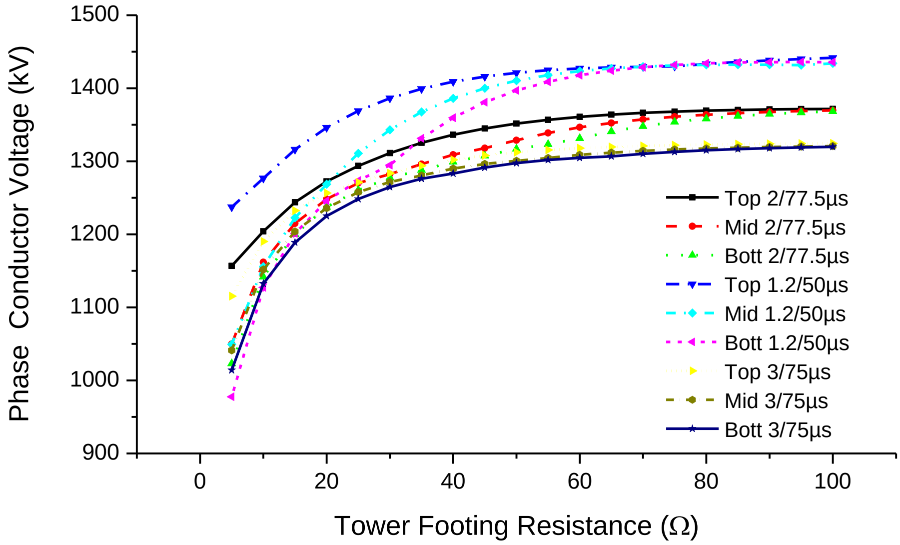



Fig. 4.11. Overvoltage at Insulator as a Function of Different Front Time of the Lightning Stroke.

In Fig. 4.11, "Top" indicates the top insulator of the tower, "Mid" and "Bott" represent the middle insulator and the bottom insulator of the tower respectively.

Fig. 4.11 illustrates that shorter front time will increase the overvoltage. In addition, higher tower footing resistance and magnitude of lightning stroke may result in an increase of the overvoltage. When the footing resistance is less than 50 Ohms, the difference of the overvoltage caused by different front time of the lightning surge is negligible. While the influence of the lightning surge waveshape becomes significant when tower footing resistance is above 50 Ohms.

Fig. 4.11 shows that the top insulator suffers the highest overvoltage. Since the top insulator is closest to the tower top and has the smallest IR drop for the lightning surge, which is why the overvoltage on the top phase conductor is the highest.

Table 4.1 compares the flashover performance of all the insulators with different front time between 1.2/50µs, 2/77.5 µs, and 3/75 µs.

Table 4.1. Overvoltage with Varying Front Time of Lightning Stroke

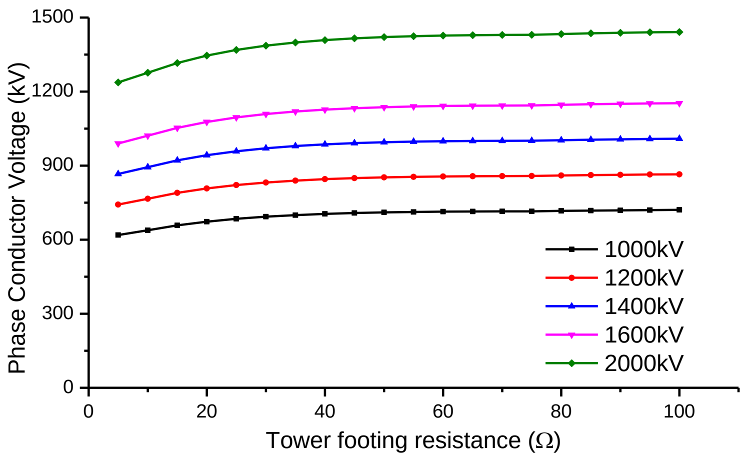
| Tower footing resistance (Ohm) | Wavefront 1.2/50µs | | | Wavefront 2/77.5µs | | | Wavefront 3/75µs | | |
|---|---|---|---|---|---|---|---|---|---|
| | Top | Mid | Bott | Top | Mid | Bott | Top | Mid | Bott |
| 3.00 | N | N | N | N | N | N | N | N | N |
| 5.00 | N | N | N | N | N | N | N | N | N |
| 8.00 | N | N | N | N | N | N | N | N | N |
| 10.00 | F | F | N | N | N | N | N | N | N |
| 20.00 | F | F | N | F | F | N | N | N | N |
| 30.00 | F | F | F | F | F | N | F | N | F |
| 40.00 | F | N | F | F | N | F | F | F | N |
| 50.00 | F | F | N | F | F | N | F | F | N |
| 60.00 | F | F | N | F | F | N | F | F | N |
| 70.00 | F | N | F | F | F | N | F | N | F |
| 80.00 | F | N | F | F | F | N | F | N | F |
| 90.00 | F | N | F | F | F | N | F | N | F |
| 100.00 | F | N | F | F | F | N | F | F | N |

F-Flashover N-No flashover

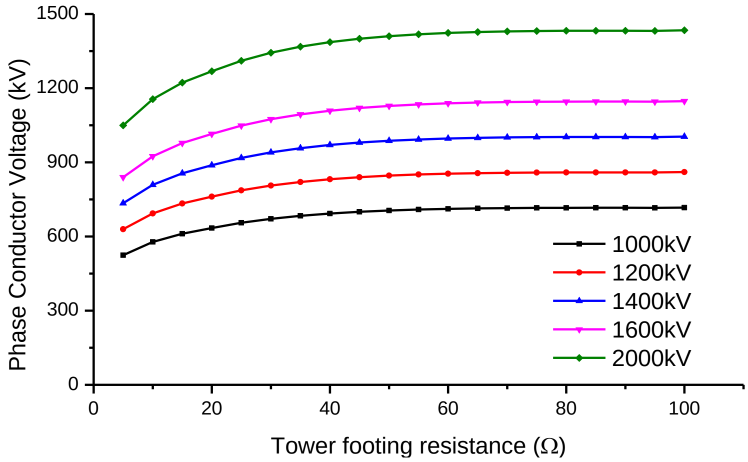
It can be observed from the Table 4.1 that the top phase insulator has the highest flashover rate among the three-phase insulators. Moreover, Table 4.1 shows that the flashover rate also increases as the front time of the lightning surge increases.

B. The magnitude of the lightning surge

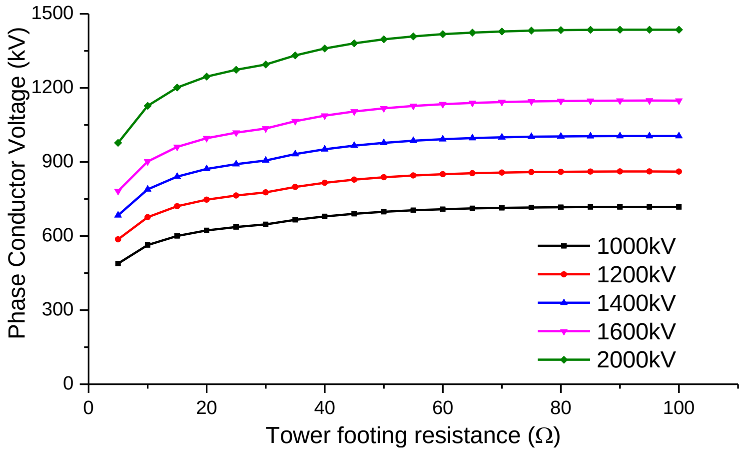
Fig. 4.12 compares overvoltage at insulator with different magnitude of lightning strokes between 1000kV to 2000kV with front time 1.2/50 µs. It can be observed from Fig. 4.12 that when the lighting surge peak magnitude is higher, higher overvoltage will occur in the system.




(a) Top phase insulator




(b) Middle phase insulator




(c) Bottom phase insulator

Fig. 4.12. Overvoltage at Insulator with Different Magnitude of Stroke.

Table 4.2 compares the flashover performance of all the insulators with different voltage magnitude between 1000kV, 1200kV and 1400kV. For the case of 1400kV, the flashover occurs at both the top and the middle phase of the insulator. While for the case of 1600kV, the flashover occurs at all three phase of the insulator. When the magnitude of a lightning stroke is more than 1400kV, the back flashover always occurs as shown in Table 4.2.

Table 4.2. Overvoltage with Varying Front Time of Lightning Stroke.

| Tower footing resistance (Ohm) | Insulator Flashover | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Magnitude 1000kV | | | Magnitude 1200kV | | | Magnitude 1400kV | | | Magnitude 1600kV | | |
| | Top | Mid | Bott | Top | Mid | Bott | Top | Mid | Bott | Top | Mid | Bott |
| 3.00 | N | N | N | N | N | N | F | F | N | F | F | F |
| 5.00 | N | N | N | N | N | N | F | F | F | F | F | F |
| 8.00 | N | N | N | F | F | N | F | F | N | F | F | N |
| 10.00 | N | N | N | F | F | N | F | F | N | F | F | N |
| 20.00 | N | N | N | F | F | N | F | F | N | F | F | N |
| 30.00 | N | N | N | F | F | F | F | F | N | F | F | F |
| 40.00 | N | N | N | F | N | F | F | F | F | F | F | F |
| 50.00 | N | N | N | F | F | N | F | F | N | F | F | F |
| 60.00 | N | N | N | F | F | N | F | F | F | F | F | F |
| 70.00 | N | N | N | F | N | F | F | F | F | F | F | F |
| 80.00 | N | N | N | F | N | F | F | F | F | F | F | F |
| 90.00 | N | N | N | F | N | F | F | F | F | F | F | F |
| 100.00 | N | N | N | F | N | F | F | F | F | F | F | F |

F-Flashover N-No flashover

### 4.2.3 The Effect of Tower Footing Resistance for Different Phases Located at Different Height.

**Model Development**

The model used in the simulation is illustrated in Fig. 4.7 (b). The tower configuration. The tower structure in Fig. 4.13 has two three-phase circuits and two shield wires.

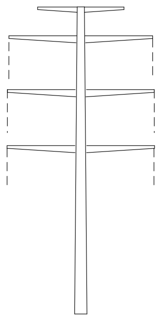
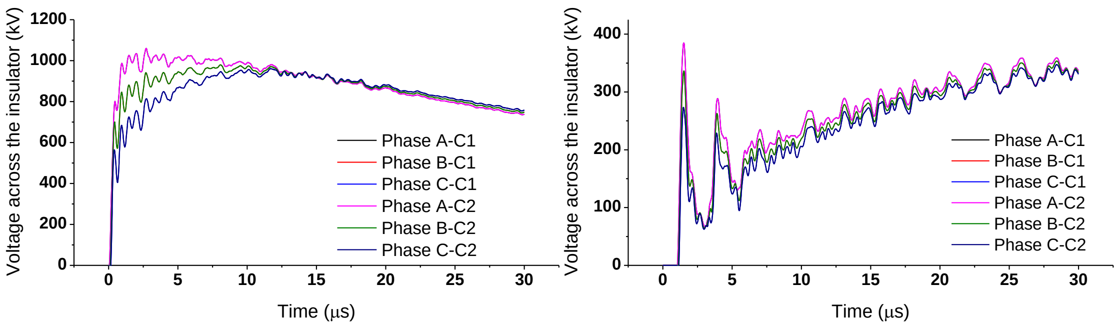


Fig. 4.13. Tower Configurations Used in the Simulation.

**Simulation Results**

The voltages across the insulators of phases A, B, C are different since they are in different locations. According to Fig. 4.14, the peak voltage magnitude of phase A is higher than those of phase B and phase C. Note that phase A is the top phase of the tower, phase B is the middle phase, and phase C is the phase located at the bottom of the tower. It can be concluded that the probability of the flashover occurring on the upper phase is higher than the middle or lower phase. Since the lengths of the tower's arms are the same, the voltage of phase A of circuit one equals the voltage of phase A of circuit two. Similar conclusions can be drawn to phase B and phase C.




(a) Stricken tower (b) Adjacent tower

Fig. 4.14. The Voltage Across the Insulator of the Stricken Tower and the Adjacent Tower when Lightning Strikes the Top of Tower 6.

In Fig. 4.14, both footing resistance of the stricken tower and the adjacent tower are 10 Ohms. The lightning voltage is 1600kA with linear ramp waveform (1.2/50µs). Note that C1 denotes circuit one of the 230kV transmission line and C2 denotes circuit two of the 230 kV transmission line.

When lightning strikes the top of a tower, the voltage across the insulator may largely depend on the footing resistance of the stricken tower. However, the footing resistance of the adjacent tower may not have a significant influence on the voltage across the insulator of the stricken tower. In both Fig. 4.15 and Fig. 4.16, the footing resistance of the stricken tower is 10 Ohms. The lightning current is 1600kA with a linear ramp waveform of 1.2/50µs. Fig. 4.15 shows that the peak voltage magnitude of the voltage across the insulator of the adjacent tower increases as the footing resistance of the adjacent tower increases. Fig. 4.16 illustrates the dependency of overvoltage across the insulator of the adjacent tower on the footing resistance of stricken tower. The increase of footing resistance of stricken tower results in a moderate increase on the overvoltage of the adjacent tower. This suggests that the footing resistance of a tower can only affect the overvoltage of itself. The footing resistance of the adjacent tower changes will not have a significant impact on the overvoltage of the stricken tower.

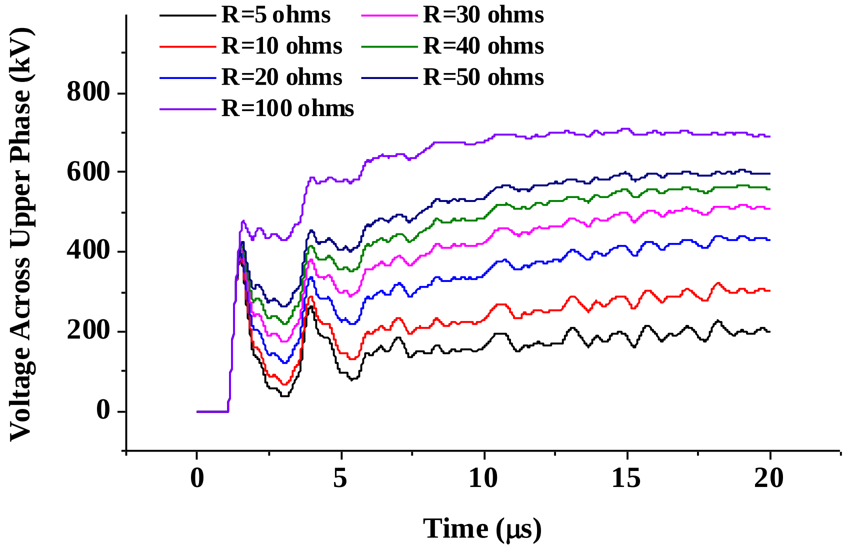



Fig. 4.15. The Voltage Across the Insulator of the Adjacent Tower when Lightning Strikes the Top of Tower 6 with Various Adjacent Tower Footing Resistance.

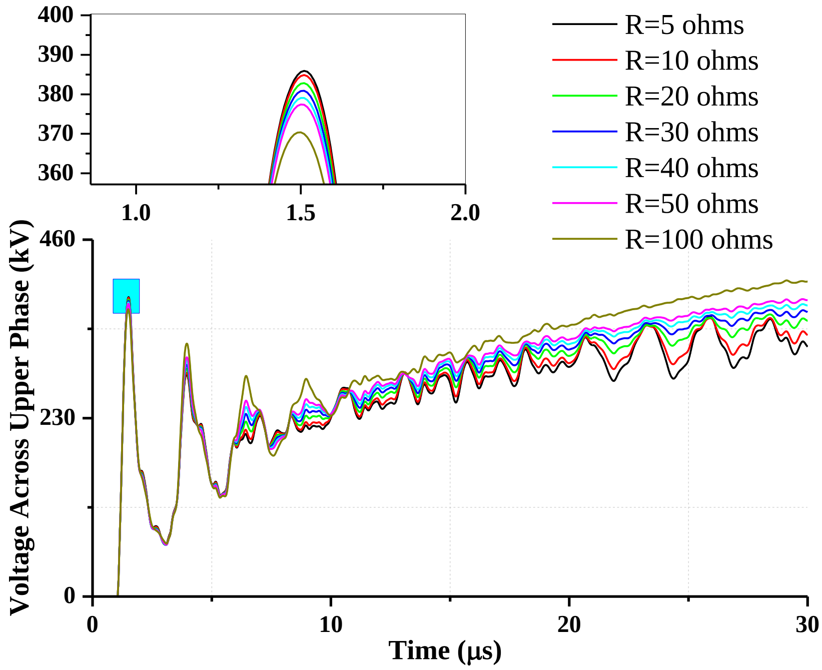



Fig. 4.16. The Voltage Across the Insulator of the Adjacent Tower when Lightning Strikes the Top of Tower 6 for Various Stricken Tower Footing Resistance.

## 4.3 The Design of Surge Arrester Placement for Overhead Transmission Line

Within a protected line section, where the footing resistance of towers is similar to each other, two major surge arrester protection design can be used to improve the lighting performance. One of the design is to equip all the towers in the line section with surge arresters on selected phases. The second design is to installed surge arrester on all the phases of selected towers in the line section. Fig. 4.17 illustrates all the practical configurations of surge arrester installation under the two designs. For the first design, four different configurations are examined in Section 4.3.1. As shown in Fig. 4.17, the six squares connected to each other are used to represent the six phases of the double circuit transmission line used in this section. When the square is black, it indicates that there are surge arresters installed on this phase for all the towers in the line section. For design two, each square represents a tower. The black square represents the tower which is equipped with surge arresters. The three configurations under design two are studied in Section 4.3.2.

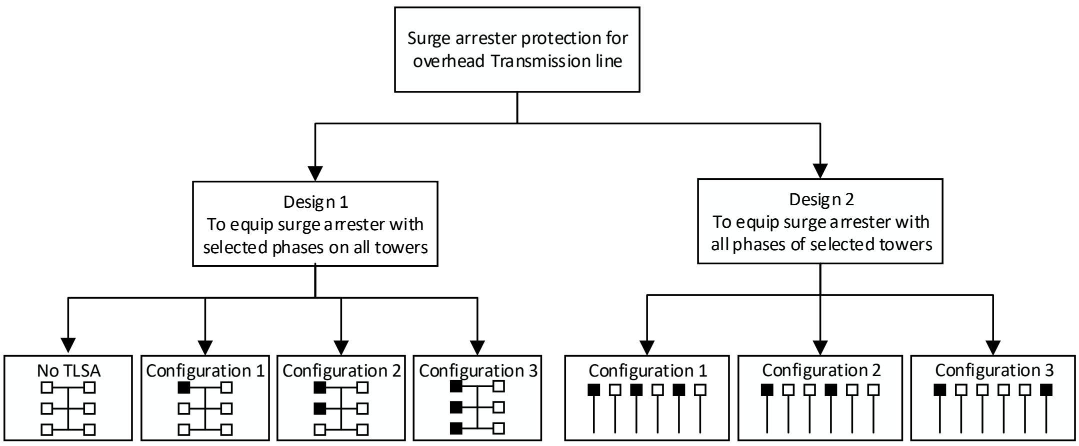



Fig. 4.17. Illustration of Different Designs and Configurations analyzed in this Thesis.

### 4.3.1 Design 1: Equipped Surge Arrester with Selected Phases on All Towers

The double circuit 230kV transmission line has 6 phase conductors and two shield wires. The protected line section includes twelve spans of transmission line, each line section is 300 meters long and consists of 11 towers. The two circuits on the transmission line are denoted as circuit one and circuit two.

The four different configurations under design two are:

- No surge arrester installed in the line section.
- Surge arresters are installed on the top phase of circuit one for all the towers in the line section.
- Surge arresters are installed on both the top phase and the middle phase of circuit one for all the towers in the line section.
- Surge arresters are installed on all three phases of circuit one for all the towers in the line section.

**Model Development**

Surge arresters are installed on every tower of the line section, as shown in Fig. 4.19. The effect of the number of surge arresters per tower is analyzed in this section. Fig. 4.18 represents the model used for configuration 1 where surge arresters are installed on the top phases of all towers in the line section.

Since the line section is symmetric and the lightning stroke is assumed to be terminated on tower 6, only the results of tower 6 through 11 are presented. Fig. 4.18 provides a detailed model representing tower 6 through tower 11.

The footing resistances of the towers in a single line section are assumed to be equal. To study the effect of the footing resistance in this section, all the tower footing resistance are changed simultaneously. The sequence of the insulator flashover is recorded and the threshold lightning voltage for the insulator flashover are obtained.

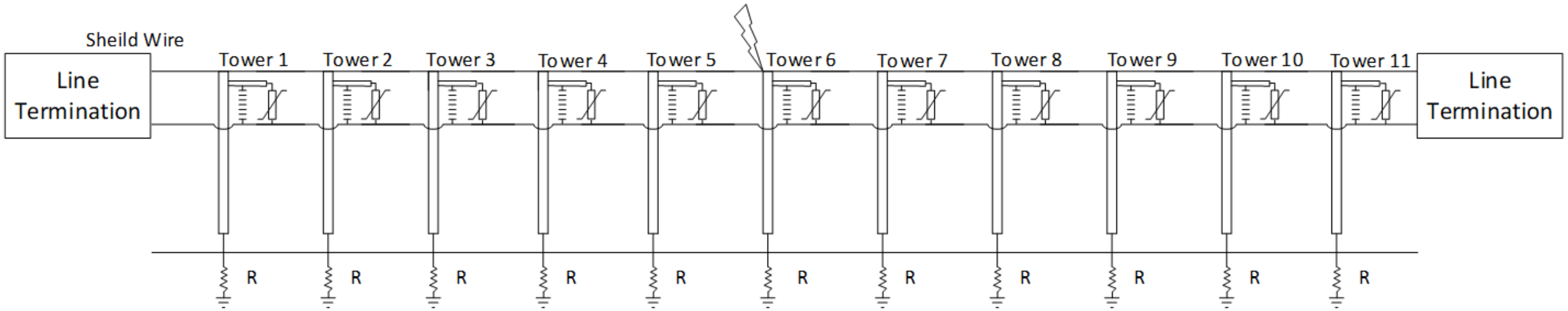



Fig. 4.19. The Model used for Simulation: 12 Spans with Line Termination Module.

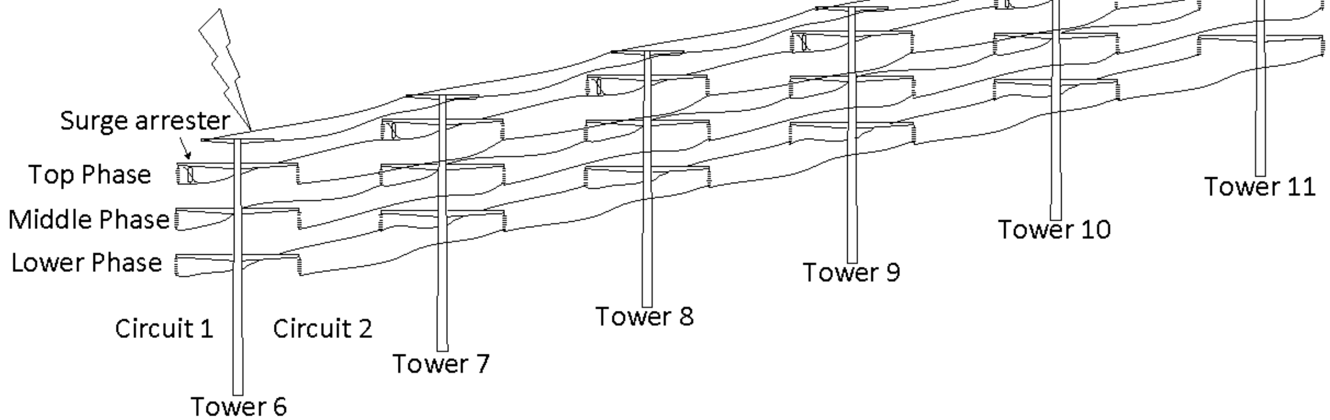



Fig. 4.18. Configuration 1: Surge Arrester Installed on the Top Phase of Circuit One.

**Simulation Results**

A. Simulations without surge arrester

To study the impact of lightning striking the transmission line without the use of the surge arrester, PSCAD simulations are performed to simulate the lightning surge to the tower top ranging from 1200kV to 1800kV. The towers 1 through 5 and the towers 7 through 11 are symmetric in terms of the tower structure. Thus, only the results of the towers 1 through 6 are displayed.

Table 4.3 shows the towers and phases on which flashover occurs as a function of lighting peak voltage on the top of the tower. For lighting voltage peak magnitude over 1250kV, flashover occurs at the top and bottom phases in sequence. When the lighting voltage peak magnitude is above 1300kV, all three phases of the lightning stricken tower have flashovers. For a lightning surge level of 1350kV, flashovers occur on certain phases of all the towers. When lightning surge goes over 1600kV, flashover in all three phases occurs for more than one towers.

B. Simulations with the presence of the surge arresters

It is essential to install surge arresters on transmission lines to avoid insulator flashover due to a lightning surge greater than 1200kV.

Surge arresters are installed on all towers for the studies in this section. However, it is not necessary to installed surge arresters on all the phases. The effect of different numbers of surge arresters per tower on lightning protection performance is analyzed. In the test case, the surge arrester is only installed on the circuit one. The simulation includes three different configurations: 1) the surge arrester is installed on the top phase of circuit one; 2) surge arrester is installed on the top and middle phase of circuit one; and 3) surge arresters installed in all three phases of circuit one. As shown in Section 4.2, the maximum overvoltage occurs at the upper phase. This is the reasons to equipped surge arresters on the top phase of circuit one in all configurations.

Table 4.3 through Table 4.6 show the improvement of the lightning performance of the 230kV transmission line section with the increase of the installed surge arresters. Installing one surge arrester on the tower can improve the lighting performance significantly. For instance, the voltage for the line section to start having insulator flashovers increases from 1250kV to 1400kV. At 1450kV, flashover occurs on five towers out of six towers. Flashover occurs on all towers only when the lightning surge magnitude is above 1800kV.

Installing surge arresters on top and middle phases of circuit one do not show much improvement in the lightning performance of the 230kV transmission line over installing surge arresters on the top phase only. The critical flashover voltage increases from 1400kV to 1450kV. However, the total number of flashover decrease significantly. The insulator on tower 1 and tower 2 are operating in normal condition when the lightning surge is increasing from 1500kV to 1800kV.

Installing surge arresters on all three phases of circuit one does not eliminate the flashovers of the tower completely. For 1550kV lightning surge striking the line section, flashover occurs on the middle and lower phases of circuit 1 on tower 6 and tower

4. However, the total number of flashover in the line section has been further reduced. Tower 1, tower 2 and tower 3 are free from flashover when the peak magnitude of the lightning surge is below 1800kV. To protect the circuit against flashover for lighting voltage above 1550kV. More surge arresters are required to be installed on the protected line section. However, for the 230kV transmission lines used in our simulation, the probability of lightning peak voltage greater than 1550 kV is low.

Note that flashover occurs on the top phase of circuit two most frequently. Moreover, the top phase is most likely to be the first to have insulator flashover.

As mentioned above, the variation of the footing resistance will affect the lighting performance of the transmission line. Fig. 4.20 shows the lightning voltage threshold above which flashover occurs on at least one insulator concerning the footing resistance.

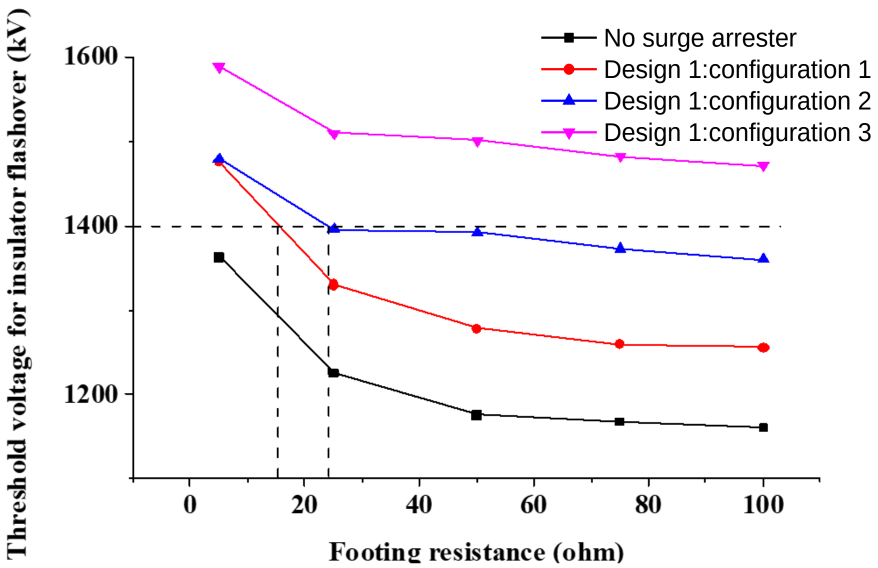



Fig. 4.20. Lighting Voltage Threshold Above Which Insulator Flashover Occurs as a Function of Footing Resistance, for Four Configurations.

To maximize the reliability of service on the transmission line using a minimal number of surge arresters, some surge arrester strategy is proposed.

For instance, the studied transmission lines section is required to be capable of accepting 1400kV lightning strokes. Fig. 4.20 shows that when the footing resistance of the line section is between 0 ohms and 15 ohms, installing surge arrester on the upper phase of circuit one is enough for the lightning protection. Where the footing resistance of tower is between 15 ohms to 25 ohms, configuration 2 may be justified. However, when the tower footing resistance is above 25 ohms, surge arresters should be installed in all three phases of one of the circuits of the towers in that line section.

The transmission line will be divided into several line sections according to its tower footing resistance. For each line section, one surge arrester installation configuration is applied.

Increasing the number of surge arresters installed on circuit one changes surge arrester duty slightly before the magnitude of the lightning increase to the number high enough for insulator flashovers happens. Fig. 4.21 shows the effect of the number of surge arresters on the maximum energy absorbed by the surge arrester for towers with 30 ohms footing resistance. The lightning stroke is terminating on the top of tower 6 for this test case.

The energy absorbed by the surge arrester on tower 5 and tower 7 is the highest among all eleven towers. In Fig. 4.21, it shows that when the lightning surge magnitude is not high enough to make insulator flashover occurs, the maximum surge arrester energy increases when the number of surge arrester installed on circuit one decreases. This can be explained that when there is no flashover occurs, the energy of the lighting will mostly be absorbed by the surge arresters. Once the number of surge arrester increases, the average energy need to be absorbed by each arrester will decrease. However, most of the energy can be absorbed by the ground if back flashover occurs in the line section. It can explain the dip in the curve of the energy absorbed by the surge arrester. In addition, the energy absorbed by the surge arrester decreases when the number of flashover increases. As mentioned above. The number of flashovers for configuration 3 is the smallest. When flashover occurs in the line section under this configuration, the maximum energy is the largest. Note that the surge arrester absorbed energy is always below the surge arrester energy capability in the test case.

The curve for the discharged current of the surge arrester has a similar characteristic with the curve of energy duty of surge arrester. The footing resistance for the towers in the line section is 30 Ohms and the lightning stroke is terminating on the top of tower 6 for this test case.

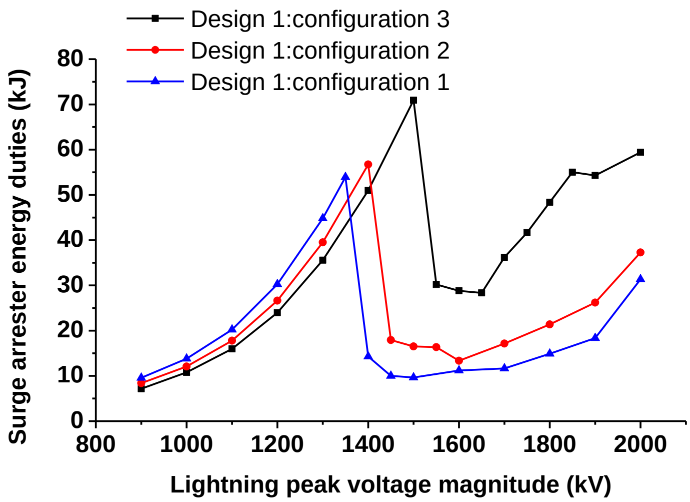



Fig. 4.21. Worst Case Energy Absorbed by a Surge Arrester Installed on Circuit One as a Function of Peak Lightning Voltage Magnitude for a Different Number of Surge Arresters on Circuit One.

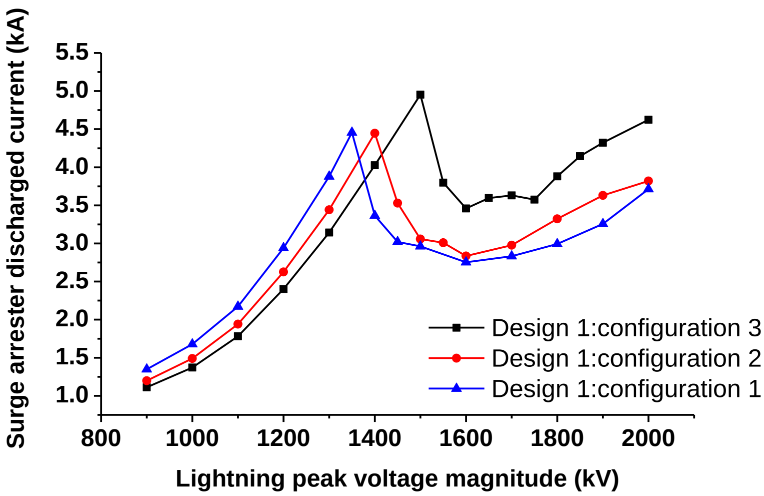



Fig. 4.22. Worst Case Surge Arrester Discharged Current as a Function of Peak Lightning Voltage Magnitude for a Different Number of Surge Arresters on Circuit One.

Table 4.3. The Sequence for Insulators Flashover as a Function of 1.2/50$\mu s$ Lightning Surge Amplitude for the Lighting Strikes on the Top of the Tower 6 with 20Ω Footing Resistance.

| V/kV | Tower 1 | | | | | | Tower 2 | | | | | | Tower 3 | | | | | | Tower 4 | | | | | | Tower 5 | | | | | | Tower 6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | |
| | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L |
| 1200 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1250 | | | | | | | 1 | | 2 | 1 | | 2 | 1 | | 2 | 1 | | 2 | 1 | | | 1 | | | | | | | | | 1 | | 2 | 1 | | 2 |
| 1300 | | | | | | | | 1 | | | 1 | | | | | | | | 1 | | | 1 | | | 1 | | | 1 | | | 1 | 3 | 2 | 1 | 2 | 3 |
| 1350 | | | 1 | | | 1 | | 1 | | | 1 | | | | 1 | | | 1 | 1 | | | 1 | | | 1 | | | 1 | | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1400 | | | | | | | | | | | | | | 1 | | | 1 | | 1 | | | 1 | | | 1 | 2 | | 1 | 2 | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1450 | | | | | | | | | | | | | | 1 | | | 1 | | 1 | | | 1 | | | 1 | 2 | | 1 | 2 | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1500 | | | | | | | | | | | | | | 1 | | | 1 | | 1 | | | 1 | | | 1 | 2 | | 1 | 2 | | 1 | 2 | | 1 | 2 | |
| 1550 | | | | | | | | 1 | | | 1 | | | 1 | | | 1 | | 1 | | | 1 | | | 1 | 2 | | 1 | 2 | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1600 | | | | | | | | | | | | | 2 | 1 | | 2 | 1 | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2,3 | | 1 | 2,3 | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1800 | | | | | | | | | | | | | | 1 | | | 1 | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | | | 1 | | | 1 | 2 | 3 | 1 | 2 | 3 |

T denotes the top phase conductor;

M denotes the middle phase conductor;

L denotes the lower phase conductor;

The number 1, 2, 3 … denote the sequence of the phase conductor flashover on each tower

Table 4.4. The Sequence for Insulators Flashover as a Function of 1.2/50$\mu s$ Lightning Surge Amplitude for the Lighting Strikes on the Top of the Tower 6 with 20Ω Footing Resistance. Surge Arrester is Installed on the Top Phase of Circuit 1.

| V/kV | Tower 1 | | | | | | Tower 2 | | | | | | Tower 3 | | | | | | Tower 4 | | | | | | Tower 5 | | | | | | Tower 6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | |
| | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L |
| 1200 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1250 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1300 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1350 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1400 | | | | | | | | | | | | | | | 1 | | | 1 | | | 2 | 1 | | 2 | | | | | | | | | 2 | 1 | | 2 |
| 1450 | | 1 | | | 1 | | | 1 | | | 1 | | | | | | | | | | 2 | 1 | | 2 | | | | 1 | | | | 3 | 2 | 1 | 3 | 2 |
| 1500 | | | | | | | | 2 | 1 | | 2 | 1 | | | 1,2 | | | 1,2 | | | 2 | 1 | | 2 | | | | 1 | | | | 3 | 2 | 1 | 3 | 2 |
| 1550 | | | | | | | | | | | | | | | 1 | | | 1 | | | | 1 | | | | | 2 | 1 | | 2 | | | 2 | 1 | | 2 |
| 1600 | | | | | | | | | | | | | | | 1 | | | 1 | | 3 | 2 | 1 | 3 | 2 | | | 2 | 1 | | 2 | | 3 | 2 | 1 | 3 | 2 |
| 1800 | | | 1 | | | 1 | | | 1 | | | 1 | | 1 | 2,3 | | 1 | 2,3 | | | 2,3 | 1 | | 2,3 | | 2 | 3,4 | 1 | 2 | 3,4 | | 2 | 3 | 1 | 2 | 3 |

T denotes the top phase conductor;

M denotes the middle phase conductor;

L denotes the lower phase conductor;

The numbers such as 1, 2, and 3 denote the sequence of the phase conductor flashover on each tower.

Table 4.5. The Sequence for Insulators Flashover as a Function of 1.2/50$\mu s$ Lightning Surge Amplitude for the Lighting Strikes on the Top of the Tower 6 with 20Ω Footing Resistance. Surge Arresters are Installed on the Top and Middle Phases of Circuit 1.

| V/kV | Tower 1 | | | | | | Tower 2 | | | | | | Tower 3 | | | | | | Tower 4 | | | | | | Tower 5 | | | | | | Tower 6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | |
| | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L |
| 1200 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1250 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1300 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1350 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1400 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1450 | | | | | | | | | | 1 | | | | | | 1 | | | | | 1 | 2 | | 1 | | | | 1 | | | | | 1 | 2 | | 1 |
| 1500 | | | | | | | | | | | | | | | 1 | | | 1 | | | 2 | 1 | | 2 | | | | | | | | | 2 | 1 | | 2 |
| 1550 | | | | | | | | | | | | | | | 1 | | | 1 | | | 2 | 1 | | 2 | | | | 1 | | | | | 2 | 1 | | 2 |
| 1600 | | | | | | | | | | | | | | | 1 | 2 | | 1 | | | 4 | 1,3 | 2 | 4 | | | | 1 | 2,3 | | | | 3 | 1 | 2 | 3 |
| 1800 | | | | | | | | | | | | | | | 1 | 3 | 2 | 1 | | | 4 | 1,3 | 2,5 | 4 | | | 3 | 1 | 2,4 | 3 | | | 3 | 1 | 2 | 3 |

T denotes the top phase conductor;

M denotes the middle phase conductor;

L denotes the lower phase conductor;

The numbers such as 1, 2, and 3 denote the sequence of the phase conductor flashover on each tower.

Table 4.6. The Sequence for Insulators Flashover as a Function of 1.2/50$\mu s$ Lightning Surge Amplitude for the Lighting Strikes on the Top of the Tower 6 with 20Ω Footing Resistance. Surge Arresters are Installed in All the Three Phases of Circuit 1.

| V/kV | Tower 1 | | | | | | Tower 2 | | | | | | Tower 3 | | | | | | Tower 4 | | | | | | Tower 5 | | | | | | Tower 6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | | Circuit 1 | | | Circuit 2 | | |
| | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L | T | M | L |
| 1200 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1250 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1300 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1350 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1400 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1450 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1500 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1550 | | | | | | | | | | | | | | | | | | | | | | | 2 | 1 | | | | | | | | | | | 2 | 1 |
| 1600 | | | | | | | | | | | | | | | | | | | | | | 1 | 2 | | | | | 1 | | | | | | 1 | 2 | |
| 1800 | | | | | | | | | | | | | | | | | | | | | | 1 | 2 | | | | | 1 | | | | | | 1 | 2 | |

T denotes the top phase conductor;

M denotes the middle phase conductor;

L denotes the lower phase conductor;

The numbers such as 1, 2, and 3 denote the sequence of the phase conductor flashover on each tower.

**Surge arrester installation strategy**

The simulation in this section provides a way of determining the optimal, cost-effective solution for surge arrester placement. With this approach, the customer only needs to equip particular phases with line surge arresters, and can still ensure sufficient lightning protection of the overhead line and reduce network failures.

The optimum protection strategy for selection of tower phases to be protected can be summarized below:

The procedure for selecting the optimal surge arrester configuration consists of six steps:

Step 1) Divide the transmission line into line sections according to the tower footing resistance.

Step 2) Install surge arresters on one or two towers near the boundary between the line sections.

Step 3) Build the transmission line model.

Step 4) Perform the same simulation in this section to obtain the plot of the threshold voltage vs the footing resistance.

Step 5) Select the surge arrester installation strategy according to the protection level and the footing resistance of the line section.

The first step requires that the variation of the tower footing resistance is negligible within single line section. The second step aims at protecting the towers which have footing resistance different from its adjacent tower. According to the protection level and protection margins, the desired threshold voltage can be determined. Therefore, the optimal surge arrester configuration for a line section can be chosen by the footing resistance and the desired threshold voltage of the line section.

### 4.3.2 Design 2: Equipped Surge Arrester with All Phases of Selected Towers

**Model Development**

The double circuit 230kV transmission line section has two three-phase circuits and two shield wires. It consists of 13 spans of transmission line, each span is 300m long. Since the probability of all the towers being stricken by lightning stroke would be the same. The simulation of lightning striking Tower 1 to Tower 12 in twelve different runs were implemented. Eight different lightning peak voltage magnitude was used in the simulation. under each specific lightning surge peak voltage magnitude, twelve different simulations of lightning terminating on tower 1 through tower 12 respectively are implemented.

This section presented the simulation procedure in details. The proposed procedure is used to analyze the effect of the surge arrester location distance for the line section lighting performance. The simulation consists of five steps as listed below.

Step 1) Under Configuration X (X=0 TLSA, configuration 1, configuration 2, and configuration 3). Lightning stroke is terminating on tower N (N=1, 2, 3, …, 12); the lightning stroke magnitude is M (M=1000, 1200, 1400, …, 1800) kV (standard waveshape). Run the simulation (Run #1).Record the number of flashover on phase A, B, and C. The sum of the number of flashover on phase A, B, C is the total number of flashover for the 1100kV lightning stroke under Run #N.

Step 2) Lightning stroke is terminating on tower N+1, lightning stroke magnitude and waveshape remain the same as in Step 1). Run the simulation (Run #N+1). Record the number of flashover on phase A, B, and C.

Step 3) Increase the crest value of the lightning stroke to M+200 kV. Repeat the Step 1) – Step 3).

Step 4) Change the configuration to X+1. Repeat Step 1) to Step 5).

As illustrated in Fig. 4.20, the surge arrester is installed on every two towers. Fig. 4.23 provides a detailed model of tower 6 to tower 11.

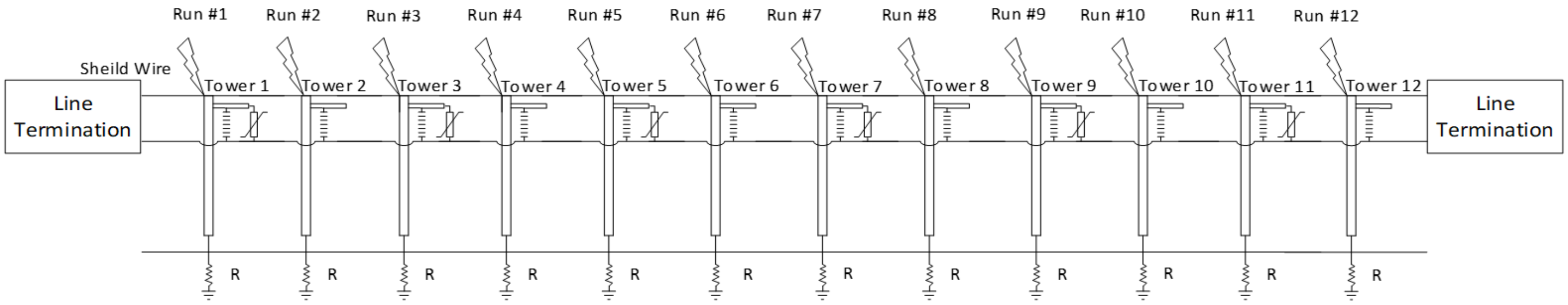



Fig. 4.24. The Model Used for Simulation: 13 Spans with Line Matching.

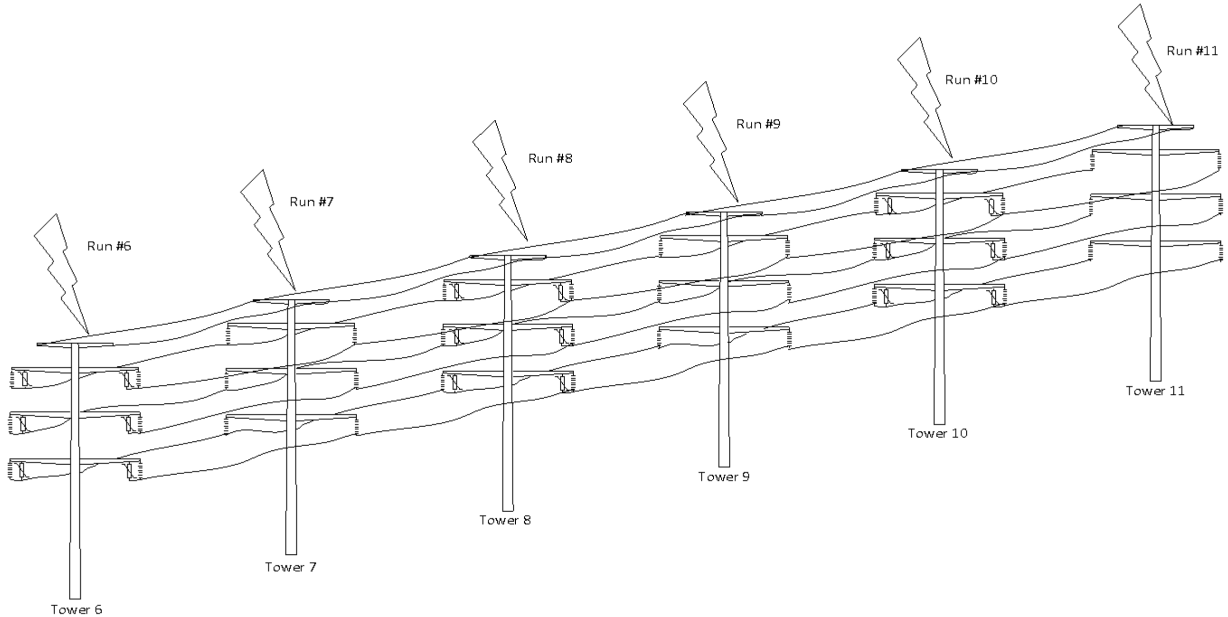



Fig. 4.23. Configuration 2: Surge Arrester Installed on Every Two Towers.

## Simulation Results

For each simulation, lighting strikes on different towers. The total number of all towers is shown in Fig. 4.25. For each set of 12 simulations under certain peak voltage magnitude, the simulation which has the most significant number of flashovers is recorded and plotted in Fig. 4.25. Noted that all the footing resistance was set to be 25 ohms.

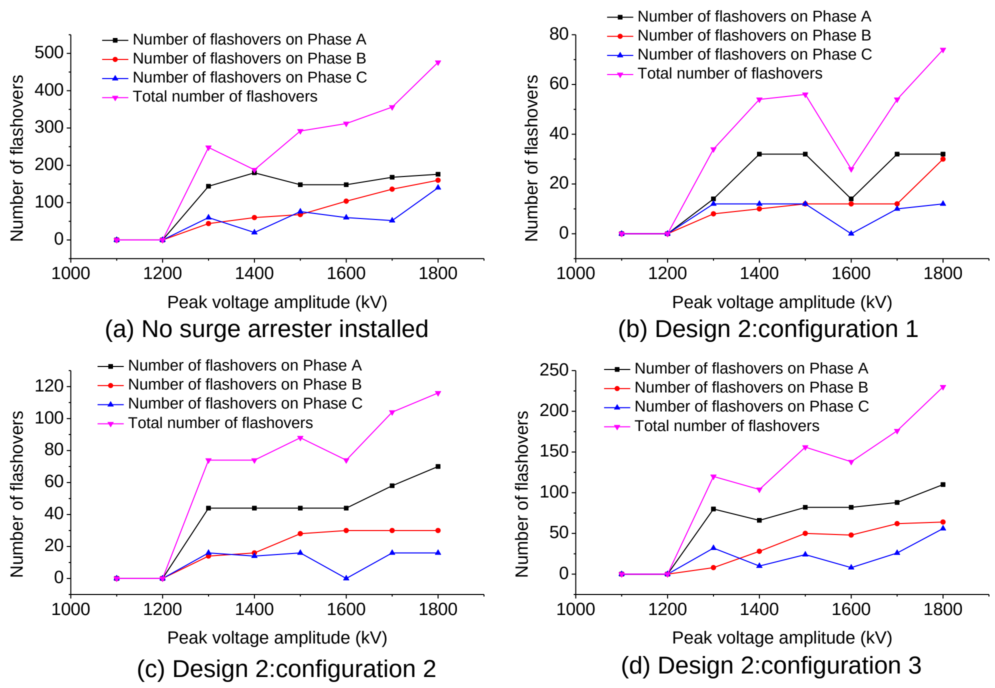



Fig. 4.25. Number of Insulators Flashovers for All the Towers and on All the Phase in the Protected Section as a Function of Lightning Current Amplitude for 12 Simulations.

Fig. 4.25 illustrate the number of flashovers occur on all 12 towers when lightning hit on different towers according to the lighting voltage peak magnitude. When increasing the peak voltage magnitude, the number of flashovers generally goes up. The number of flashovers on Phase A is the most significant of all the three phases. This is consistent with the simulation results in Section 4.2. The reason is that the insulators on phase A are on the top, higher than the insulators on the other phases. The top insulator locates close to the lightning stroke, thus has the fewer losses on the tower arms. Therefore, it has the largest number of flashover.

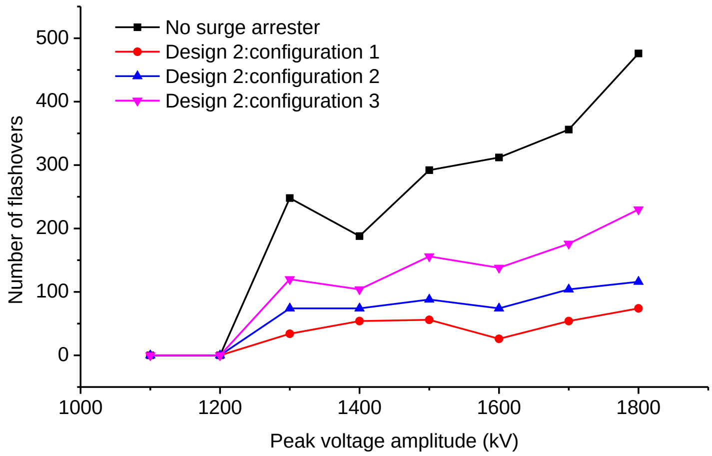



Fig. 4.26. The Number of Insulators Flashovers for all the Towers in the Protected Section as a Function of Lightning Current Amplitude for 12 Simulations.

To compare the number of flashovers with different surge arresters configurations, the number of flashovers on different phases are ignored in Fig. 4.26. Fig. 4.26 focuses on the total number of insulator flashovers. The number of flashovers increases with the decrease of the number of surge arresters installed. The effect of the number of surge arrester is more pronounced at high lightning voltage magnitude. For 1800kV lightning surge, the number of flashovers without surge arrester is around 500. However, when surge arresters are installed on every five towers, the number of flashovers decrease to around 250, half of the number without surge arrester. The difference for installed surge arrester three spans apart and two spans apart is comparatively small. The number of flashovers for configuration 2 when the peak voltage amplitude is

1800kV is around 100, while the number of flashover for installs the surge arresters two spans apart under the same lightning voltage is 80.

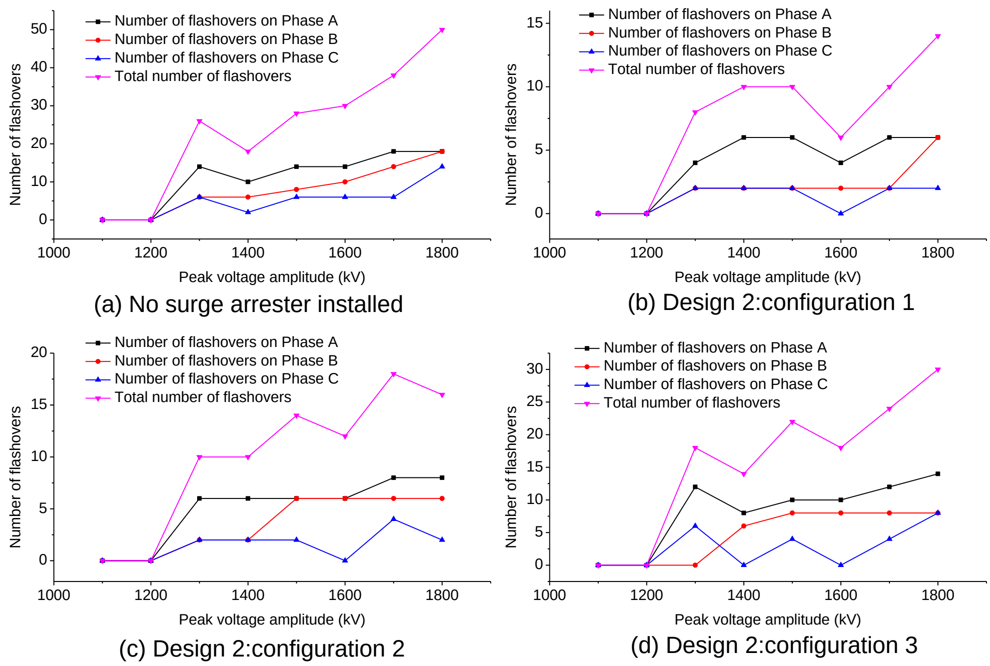



Fig. 4.27. Number of Insulators Flashovers for All the Towers and on All the Phase A, B, and C in the Protected Section as a Function of Lightning Current Amplitude for One Simulation Which Has the Maximum Number of Flashovers in Each Set of the 12 Simulations.

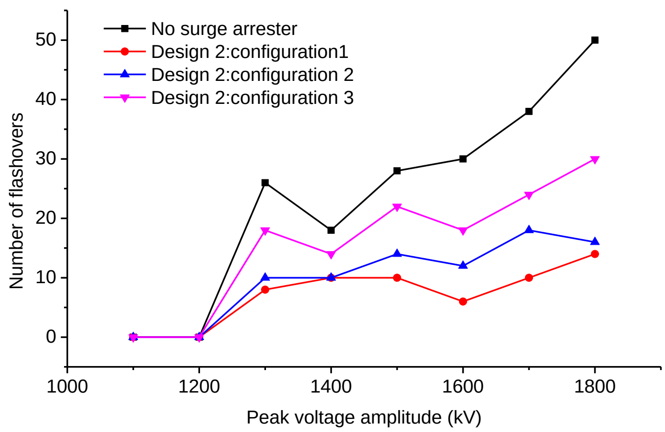



Fig. 4.28. The Number of Flashovers of Insulators for All the Towers in the Protected Section as a Function of Lightning Current Amplitude for One Simulation Which Has the Maximum Number of Flashovers in Each Set of the 12 Simulations.

In Fig. 4.27, the simulation which has the maximum number of flashovers on all the tower among 12 simulations under specific voltage peak magnitude is illustrated. It has the same characteristic as Fig. 4.26. The difference is that for Phase A and B, the number of flashovers does not change too much according to the number of surge arrester installed on the protection scheme.

Fig. 4.28 compare the total number of flashovers and ignore the number of flashovers on Phase A, B, and C. In Fig. 4.28 the intersection for configuration 1 and configuration 2 is around 1400kV. This shows that when the lightning peak magnitude is lower than 1400kV, installing surge arresters three spans apart has less flashover than installed surge arresters two spans apart.

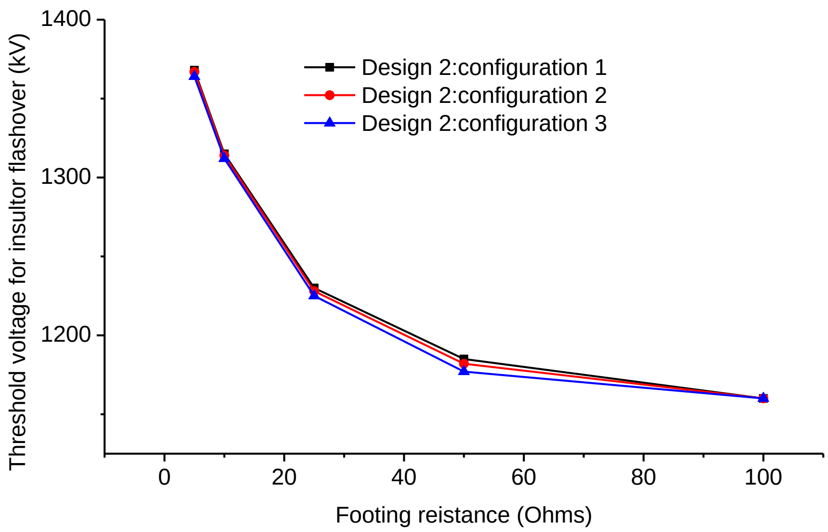



Fig. 4.29. Lighting Voltage Threshold Above Which Insulator Flashover Occurs as a Function of Footing Resistance.

Compare Fig. 4.29 with Fig. 4.12 in Section 4.3.1, the variation in threshold voltage for insulator flashover is negligible under different configurations for Fig. 4.29. The three curves representing different configurations are overlapped. In another word, the threshold insulator flashover voltage for different configurations do not have much difference. The reason is that all the configurations analyzed in Section 4.3.2 have towers which have no surge arrester installed. The insulators on the towers which do not have surge arrester installed will be the first to flashover. Thus, the threshold voltage just simply depends on the flashover voltage of the insulators on the tower without surge arrester. Therefore, for this kind of design, the best way is to analyze using the flashover rate of the transmission line.

### 4.4 Conclusions

In section 4.2, it is stated that the footing resistance can significantly affect the overvoltage across the insulators. Therefore, for the tower which has high footing resistance, it is recommended to install the surge arresters which have better energy discharge capability. When the footing resistance of the transmission line towers varies, the footing resistance may adversely affect the lightning performance of the system under certain condition. The simulations conducted in section 4.2 shows that the decrease of the footing resistance of the adjacent tower may increase the overvoltage across the insulator of the adjacent tower when surge arresters are installed on the stricken tower with high footing resistance. Thus, when the towers are located near the boundary of the protected section, it is recommended to examine whether the towers need to be equipped with surge arresters. After dividing the transmission line into several line section according to its footing resistance, different surge arrester configurations are utilized to improve the lightning performance of each line section. The first design is to install different numbers of surge arresters on selected phases of all towers. For the first design, the simulation results show that the insulators on the top phase are most likely to experience flashover. Thus, the insulator should installed on top phases. The three different configurations, which are used to determine the number of surge arresters that should be installed on the towers, are: 1) surge arresters are installed on the top phase of circuit one; 2) surge arresters are installed on the top and middle phases of circuit one; 3) surge arresters are installed in all the three phases of circuit one. The Lighting voltage threshold for the insulator flashover as a function of footing resistance for four configurations was studied. The results can be used to determine the optimal surge arresters configuration used in single line section. Considering the second design where the surge arresters are installed on selected towers, different configurations share the same threshold voltage. However, the number of surge arrester installed on the circuit one largely affects the total number of flashovers on all towers. For instance, the number of flashovers for installing surge arresters every five spans is half of the numbers when no surge arrester is installed on the transmission line. The threshold voltage cannot be used as the criteria for choosing the optimal surge arrester installation configuration.

# 5. CONCLUSIONS

The case studies presented in Section 3 proves that installing surge arrester only on the terminal of the transformer can provide adequate protection for the substation equipment and transformer for the SRP Rudd substation. The process used for examining the lightning performance of the substation and its incoming line can be applied to other substations. The modeling guideline is applicable for the scenarios that share the same frequency range of lightning surge. In addition, the location of the lightning stroke does not have a significant effect based on the reflection and refraction characteristic of the traveling wave. However, the location of the lightning can still affect the maximum overvoltage on the substation due to the changing distance of traveling wave to the substation. The longer traveling path for the lighting impulse to the substation will further reduce the lighting impulse magnitude. Since the resistance of a line section is proportional to its length.

The lightning performance of the transmission line depends on multiple factors. The factors of this study include front time of lightning stroke, the magnitude of lightning stroke, and tower footing resistance. As presented in Section 4.2, both the magnitude and the front time of the lightning surge would negatively affect the lightning performance of the transmission line system. Though the two factors related to the lightning stroke are not controllable, reducing the footing resistance of the tower is the major solution for improving the lighting reliability of the transmission line system. For shielded lines without line arresters, it is generally true that lower ground resistance at the towers and poles will improve the backflash performance. However, it does not hold when surge arrester applied to the transmission line. Low footing resistance may worsen the lightning performance of system. This mainly happens in the area where tower footing resistance varies. When the footing resistance of the line sections remains the same, it holds that lower ground resistance at the towers and poles will improve the lighting performance. As presented in Section 4.2, both the magnitude and the front time of the lightning surge would negatively affect the lightning performance of the transmission line system.

Even though installing surge arresters on every tower and every phase along the transmission line can ensure complete lighting protection, it can be very costly. Section 4.3.1 and Section 4.3.2 propose approaches to determine the optimal and cost-effective solution for improving the reliability of the lines. As illustrated in Section 4.3.1 and Section 4.3.2, utilities only need to equip particular phases or individual line segments with surge arresters that would still ensure sufficient lighting protection for the lines. The utilities will then only need to invest a reduced amount of money and thus save the total cost.

# 6. FUTURE WORK

The effects of footing resistance on lighting protection are examined by two different scenarios in this thesis. One of the scenarios has varied footing resistance between towers in the protected line section. While the towers' footing resistance are similar in the second scenario. The simulation under the second scenario assumes equal footing resistance in the line section. However, in practice, the footing resistance of the tower may not be exactly the same. Thus, a standard needs to be made to determine the range of the variation of different towers' footing resistance in a single line section. Within the line section, the small variation of the footing resistance can be ignored.

A new surge arrester installation strategy is proposed to determine the appropriate surge arrester configuration by installing a different number of surge arrester per tower. However, simulation results show that the proposed strategy is not applicable for determining the number of towers needs to be equipped with surge arresters. The threshold voltage for different configuration is almost the same under various tower footing resistance when surge arresters are not installed on all towers. Thus, the threshold flashover voltage is not the best way to determine the optimal configuration of surge arresters. A systematic mechanism needs to be developed to determine the most effective configuration.

Due to the random nature of lightning, the evaluation of the lighting performance should base on a statistical approach; the Monte Carlo method can be used to calculate the flashover rate. Comparing the flashover rate of different surge arrester configurations is a better way to evaluate the lighting performance.

Arrester failure also needs to be concerned. Surge arresters are exposed to switching overvoltage and lightning overvoltage. All these stresses, as well as the environmental pollution and manufacturing defects, may lead to arrester failures. The nearby direct lighting stroke is also a common cause of arrester failure [43]. Thus, the arrester failure is essential for studying the system lighting performance.

In addition, the two installation designs, including 1) installing a different number of surge arresters per tower and 2) installing surge arrester different spans apart, need to be compared. Moreover, they can be combined. Combining these two configurations requires full examination. The numerical simulation of installing surge arrester on certain towers and certain phases at the same time should be conducted.

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