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STUDY ON DIFFERENT TYPES OF SURGE ARRESTER FOR 132kV OVERHEAD TRANSMISSION LINE IN SHIELDING FAILURE ANALYSIS

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This report is submitted in partial fulfilment of requirement for the degree of Bachelor in Electrical Engineering (Industrial Power)

Faculty of Electrical Engineering

UNIVERSITi TEKNIKAL MALAYSIA MELAKA

2014

I declare that this report entitle "Study on Different Types of Surge Arrester for 132kV Overhead Transmission Line in Shielding Failure Analysis" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

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To my beloved family

ACKNOWLEDGEMENT

In the name of Allah, the most Gracious and most Merciful

Praise be to Allah, Lord of universe for His bounties bestowed upon us, Peace be to the Prophet Muhammad s.a.w the sole human inspiration worthy of imitation. Alhamdulillah all praise be to Allah S.W.T the Almighty for giving me the strength, guiding me in my final year project undertaken.

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ABSTRACT

Transients overvoltage caused by lightning is considered a major source of disturbances in high voltage transmission line systems. Lightning that consume an extreme high density of current, high capacity of voltage and transient electric discharge occurred on the transmission lines that travel towards the terminal or substation may lead to severe damages, particularly to the expensive electrical equipment. When the transient overvoltage due to lightning occurred at the phase conductor of the transmission line, the phenomena called shielding failure. Study on the shielding failure is crucial in order to evaluate the performance of transmission line as the lightning strokes terminate on the phase conductor of the transmission line. Metal Oxide Surge Arrester is used to limit the voltage across the equipment terminals in the presences of a surge on the system. In this project, the transmission line, lightning strike and surge arrester are modelled using PSCAD software. Three different types of surge arrester are modelled which are the IEEE model, Pincetti model and Fernandez Diaz model. It is found that the IEEE model is the best surge arrester model when injected more than 10KA current impulses of 8/20us since it have almost similar value of the residual voltage with the manufacture data tested result. The IEEE model was selected to apply to the 132kV transmission line in order to evaluate shielding failure phenomena. The result obtained show that the IEEE model succeeds to provide the optimum protection to the 132kV transmission line during lightning strike.

ABSTRAK

Transient voltan tinggi yang disebabkan oleh kilat dianggap sebagai sumber utama berlakunya gangguan di dalam sistem talian penghantaran voltan tinggi. Kilat yang terdiri arus berketumpatan tinggi dan voltan berkapasiti tinggi berlaku pada arah terminal atau pencawang boleh membawa kepada kerosakan yang teruk, terutamanya untuk peralatan elektrik. Apabila lebihan voltan disebabkan oleh kilat berlaku pada konduktor fasa talian penghantaran, fenomena ini dipanggil *shielding failure. K*ajian terhadap fenomena *shielding failure* adalah penting untuk menilai prestasi talian penghantaran di mana strok kilat akan tamat pada konduktor fasa di talian penghantaran. Fungsi penangkap kilat dengan mengehadkan voltan untuk merentasi terminal pada peralatan apabila berlakunya surge pada sistem. Projek ini menggunakan perisian PSCAD untuk memodelkan talian penghantaran, strok kilat, penangkap *surge*. Tiga jenis penangkap *surge* yg dimodelkan adalah model IEEE , model Pincetti dan model Fernandez Diaz. Kajian mendapati bahawa model IEEE adalah yang model penangkap *surge* terbaik apabila disuntik dengan 10kA arus impuls 8/20us. Ini kerana model IEEE mempunyai nilai voltan *residual* yang hampir sama dengan data pembuatan. Model IEEE telah dipilih untuk melindungi talian penghantaran 132kV semasa fenomena *shielding failure*. Keputusan yang diperolehi menunjukkan bahawa model IEEE berjaya untuk memberikan perlindungan yang optimum kepada talian penghantaran 132kV semasa strok kilat terhasil.

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LIST OF ABBREVIATION

TOV	-	Temporary Overvoltage
CFO	-	Critical Flashover Voltage
MSL	-	Multiple Stroke Lightning
SSL	-	Single Stroke Lightning
SA	-	Surge Arrester
MCOV	-	Maximum Continous Operating Voltage
IEEE	-	Institute of Electrical and Electronics Engineers

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Natural phenomena like lightning occurs almost everyday in the world. This could cause the travelling waves between the devices connected to the transmission line. Lightning causes the temporary increment of voltage in the transmission line system and this could harm the insulator of the line and devices connected to it. In order to maintain failure rate at the lowest level, it is necessary to provide the high quality and avoiding damages to the electrical equipment. Plenty of studies regarding the performance of the transmission line system has been conducted [1].

Protecting the transmission line against the lightning stroke can be achieved by designing the suitable surge arrester to maintain good performance of the transmission line system. It is important to explore the importance of this study since the lightning overvoltage is one of major concern for insulation design of protection in power system equipment. The phenomena happen whenever lightning strike at the top of tower, lightning current flows down to the bottom of the tower and this cause the voltage to increase and eventually result in Backflashover [2].This also happen when the lightning stroke does not terminate at the tower or shield wire but on the phase itself, this phenomenon called Shielding Failure [3]. Both of the cases will damage the equipment connected to the transmission line itself. Since the high frequency range associated with the lightning, the suitable of model are necessary to analyse and the simulation of studies require detailed in modelling of network component, which include the towers and also lightning component itself.

The purpose of this project is to investigate the shielding failure phenomena on transmission line and determine which the best option for surge arrester installation. This simulation tools used in this project are PSCAD/EMTDC. The simulation result will be obtained by injecting different magnitude of lightning current at the tower of transmission line. This also includes evaluating the implementation of several types of surge arrester which comprise of surge arresters from IEEE Frequency – dependant model, Pincetti Model and Fernandaz-Diaz model on the 132kV overhead transmission line.

1.2 Motivation

Lightning has been one of the important problems for the insulation designs in power system and it still the main cause of outages of transmission and distribution lines. A complete awareness of the parameters of the lightning strike is essential for the prediction of the severity of the transient voltages generated across power equipment either by a direct strike to the power line or by indirect stroke. Since the lightning travelling waves cause the temporary increase in voltage to the transmission line system, it is necessary to analyse such increase in voltage in order to design the surge arrester that necessity for the application and the performance of the transmission line system

1.3 Problem Statement

Lightning interruption has become a major problem for electrical power system. The lightning caused the interruption by shielding failure and backflashes. The installation of surge arrester possible to reduce direct stroke to the phase conductor, but this does not necessarily mean that the line will have perfect lightning performance. The studies will show the application of surge arrester consume a better performance than shield wire and thus will improve the transmission line performance due to lightning [2].

1.4 Objectives

The objectives of this project are stated as follows:-

i. To model 132kV Overhead Transmission Line by using PSCAD for shielding failure analysis.
ii. To model several types of surge arrester, the IEEE frequency-dependant model, Pincetti model and Fernandez-Diaz model for 132kV Overhead Transmission Line.
iii. To analyse and select the most accurate model of surge arresters based on the comparison between the simulation result and the datasheet.

1.5 Scope of Work

Based on the project milestone, this project focused on:-

- The model of the transmission line system is conducted in simulation tools called, PSCAD.
- The modelling of 132kV Overhead Transmission Line which include modelling of transmission tower and stroke of lightning current
- Modelled on three different types of surge arrester model which are IEEE model, Pincetti Giannettoni model and Fernandez-Diaz model.
- Evaluate the transmission line performance due to shielding failure.
- Concern about the effectiveness of surge arrester installation on transmission line system

1.6 Thesis Outline

This report comprises into five chapters. These five chapters include the literature review, introduction, methodology, simulation result, analysis and discussion also concluded with conclusion and recommendation part.

Chapter 1 briefly explain in the introduction of the project and these include the project background, motivation, problem statement, scope of work and thesis outline. Chapter 2 explicate the literature review on this project, for example the theories on lightning phenomena, fundamental on surge arrester and transmission line parameter.

Chapter 3 interpreted on the process and methodology of the project in order to achieve the objective of the project. This chapter includes the method of developing the surge arrester, lightning stroke using PSCAD simulation. This section summarises in flowchart.

Chapter 4 consist of the results and discussions. This includes the lightning stroke simulation and surge arrester model injected with three different of lightning strike magnitude. The result then presented in table to compare with the manufacturer datasheet. The discussion on comparison was made to select the best model to implement in 132kV Overhead Transmission Line.

Lastly, Chapter 5 concludes on the works and studies that have presented in previous four chapters. This chapter also includes some recommendation for future development.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Protecting the overhead transmission line against lightning strikes is one of the crucial tasks to secure the electrical power system since the lightning phenomena is main causes of faults in overhead transmission lines. Performance of the power system are mainly depends on the performance of transmission lines which continues operation of transmission lines without sudden outages is severely important not only for the system stability but also the efficiency of power delivery. The lightning performance of overhead lines can be measured by the flashover rate, usually presented as number of flashover by 100km and year [1].

In Malaysia, Tenaga Nasional Berhad has implemented the installation of line surge arrester for the transmission line lightning performance improvement since 1995[4]. Line arresters are usually installed on all phase conductors of one circuit of the double circuit. In this project, the line arresters are installed on the tower of the considered 132kV line. Several lines of surge arrester installation parameters are studied to improve the performance of the transmission lines [4], [5].

2.2 Lightning

Lightning occur almost about every day in the world. Lightning also more prevalent in tropical region, for example South East Asia. According to United State National Lightning Safety Institution reported that Malaysia was ranked at the top of lightning activities in the world. It is stated in the report that the average-thunder day level for Malaysia's capital Kuala Lumpur within 180 - 260 days per annum [6]. This interruption of high number of power outages due to lightning owing to the high isokeraunic level that to be found in Malaysia. The isokeraunic level is estimated approximately around 200 thunderstorm days a year and the lightning ground flash density is about 15-20 strike per km^2 per year [5].

Lightning consume an extreme high density of current, high capacity of voltage and transient electric discharge. The transient discharges of static electricity are needed to re-establish on electrostatic equilibrium within the storm environments [7]. It is need to be concerned that Malaysia located near the equator and therefore it is categorized as prone to experienced high lightning and thunderstorm activities. Malaysian Meteorological Services has indicated that thunders possibly can occur almost 200 days a year in Malaysia. Thunderstorms caused merely between 50% and 60 % of the transient tripping in the distribution networks and transmission for Tenaga Nasional Berhad (TNB). The main reason could be short of precise and consistent lightning data in Malaysia to enable trough studies on lightning and its mitigation [4].

Lightning generated when the charges separates within the cloud due to the electric breakdown of the air from high electric fields. The facts shows that when the thunder clouds are charged, the temperature of the cloud is usually below -20°C where the negative charge is located at the lower part of it. The originally positive charged region at the base of the cloud usually stated at 0°C of temperature [8].

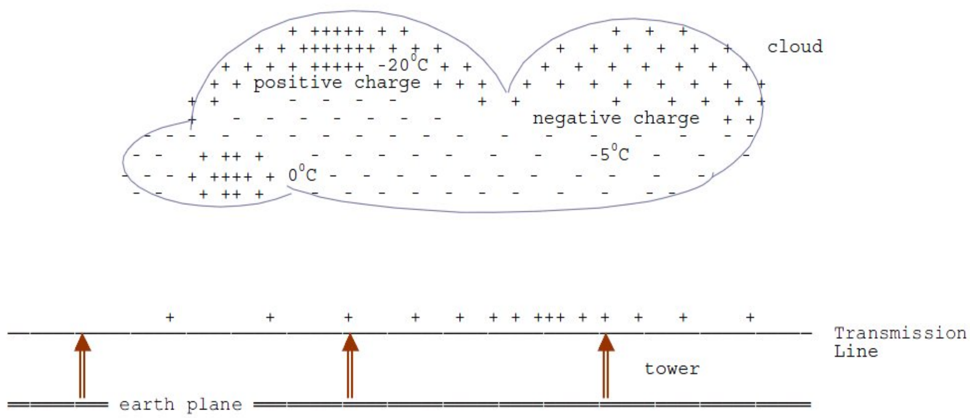

Figure 2.1 Induced charges on transmission line

When the lightning discharge occurs at the lower portion of the cloud, the air starts to break down in steps and it is called stepper leader. The sufficient field intensity on the earth for upward steamer to form and link to the remaining gap occur is when the stepper leader is approached to 15m to 50m down to earth. It is proportional since the charged develops follow as stepper leader progresses get closer to the ground. If the more positive charge collects on the earth, the short upward leader extends to meet the downward negative stepper leader

Thunder happens when high intense of pressure wave exists due to interaction between the downward leaders and upward leader. Based on previous research, the impulse current due to return stroke can flow from minimum as 20kA and may exceed to 200kA. It is also estimated the propagation of return stroke happens around 20% of speed of light by releasing charge and develop a current of tens of thousands of ampere peaking in a few microsecond [5]. If the second leader propagates continuously stroke again to the earth, this subsequent leader stroke will propagates to existed energised channel called dart leader.

The heavy current during the stroke that is only being considered when comes to urge calculation. During this time, the waveform are represented by a double exponential of the form in Equation 2.1[9].

$$i = I(e^{-\alpha t} - e^{-\beta t}) \tag{2.1}$$

With the wavefront times of 0.5-10us, and the wavetail times of 20-200 us. (Average lighning current waveform would have a wavefront of the other of 8us and a wavetail of the order of 20 us) [10].

2.3 Lightning Effect on Transmission Line

2.3.1 Shielding Failure Flashover

The charged clouds are always discharges directly to the transmission line. If the lines get struck at a long distance from a station or substation, the surge will flow along the line in directions, shattering insulators and might be wrecking poles until the total energy of the surge is spent. When the lightning strike on phase conductor, the current magnitude and the natural frequency of the stroke causes the voltage surge to be propagated equally in both directions from the point of the strike occurred. The term of Shielding Failure use to describe when the lightning stroke to the phase conductor. Most of the unshielded line, all strokes to the line are shielding failures. But not all shielding failure results in insulator string flashover. Flashover across the insulator string occurs when the value of overvoltage are higher than the critical flashover voltage (CFO). The lightning stroke current for particular conductor can be calculated by using Equation 2.2 [8].

$$I_c = \frac{2 * (CFO)}{Z_{surge}} \tag{2.2}$$

$$Z_{surge} = 60\ ?\ \overline{\ln\frac{2h}{r}\ln\frac{2h}{R_c}} \tag{2.3}$$

Where:

CFO: lightning impulse negative polarity critical flashover voltage

Z: conductor surge impedance;

h: the average of conductor height;

r: the conductor radius;

Rc: the corona radius of the conductor at a gradient of 1500kV/m(m) [8];

2.3.2 Backflashover

Back flashover event occur when the lightning strikes a ground conductor or structure. In this case, flashovers proceed backwards from the tower metal to the insulated conductor. The lightning stroke, terminating on the overhead ground wire or shield wire, produces waves of the current and voltage that travel along the shield wire [2]. At the pole of tower, these waves are reflected back toward the struck point and are transmitted down to the pole toward the ground and outward onto the adjacent shield wire. Riding along with these surge voltage are other surge voltage coupled into the phase conductors. These waves continue to be transmitted and reflected at all points of impedance discontinuity. The surge voltages are built up at the pole, across the phase-ground insulation, across the air insulation between the phase conductor and along the span across the air insulation from the shield wire to the phase conductor. If these surge voltages exceed the insulation strength, flashover occurs. This insulation strength can be measured by using critical flashover (CFO) voltage as the flashover occurs only when the overvoltage exceeded the value of CFO [8].

2.4 Surge Arrester

2.4.1 Metal Oxide Surge Arrester

The main part of a modern surge arrester is the varistor also known as variable resistor (non-linear resistance) which made of a ZnO material. The physical body of a varistor is housed in a cylinder and surrounded with a polymeric insulation [10].

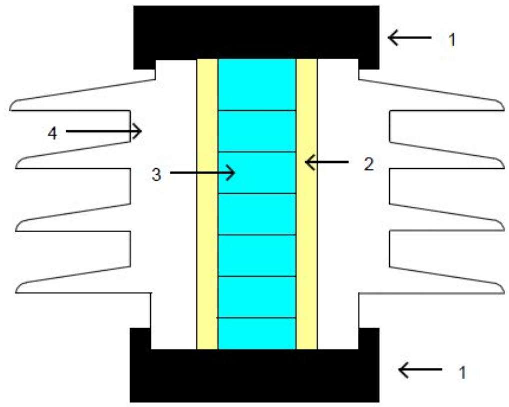

Figure 2.2 Cut – off of a typical metal oxide gapless surge arrester

(1: electrodes, 2: fiber glass, 3: varistor, 4: insulation) [11]

Surge arresters usually appear as high resistance (MΩ) under normal operating conditions but in a low resistance under overvoltage conditions of a network. If an overvoltage across the terminals of an arrester is applied, the value of arrester's resistance will become low, hence induced the conducting path or overvoltage current to the earth. In this case, the residual voltage at the surge arrester's terminals cannot exceed its specific value. The specific value of residual voltage of the arrester is depends on the inserted overvoltage and the voltage –current characteristic of the varistor [10].

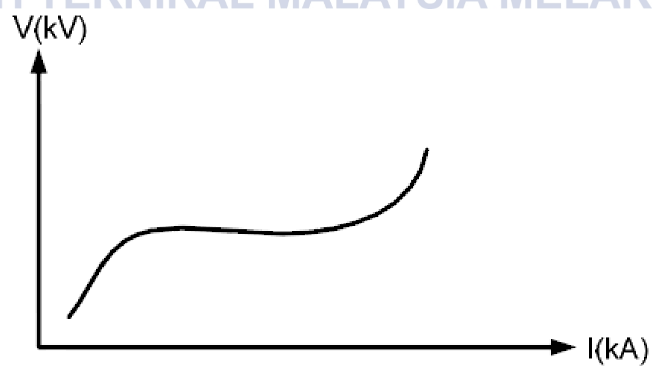

Figure 2.3 Voltage current characteristic of a typical metal oxide gapless surge arrester [11]

According to standard IEC 60099-4 [8], the most significant technical characteristics of a metal oxide gapless surge arrester are:

- The continuous operating voltage, U_c is designed with rms value of power frequency voltage that applied continuously between the terminals of the arrester.
- The rated voltage, U_r is the maximum allowable rms value of power frequency voltage between arrester terminals which the arrester is designed to operate correctly under temporary overvoltages (TOV).
- The discharge current is the impulse current that flows through the arrester, under fault current condition.
- The residual voltage, U_{res} is the peak value of the voltage. Its appears across the arrester's terminals, and when a discharge current is injected through it.
- The rated discharge current, I_r, is the peak value of lightning current impulse, which functions to classify an arrester.
- The lightning impulse protective level is the voltage drop across the arrester, where the rated discharge current flows through it.
- The energy absorption capability is the maximum level of energy injected into the arrester which it still can cool back down to its normal operating temperature. Various manufacturers present thermal energy absorption capability in kJ/kV (U_c), defined as the maximum permissible energy that an arrester may be subjected to two impulses according to IEC [12], without damage and without loss of thermal stability [12], [13].

2.4.2 Surge Arrester Models

2.4.2.1 The IEEE Frequency- Dependent Model

The model proposed by IEEE Working Group (WG) 3.4.11 is frequency-dependent model which combines the characteristic of two nonlinear resistors A0 and A1. The element that's been composed in IEEE model are inductance L0 together with the magnetic field of the surge arrester, resistive element, R_0 acts as stabilizing used to calculate the probability of instabilities. The filter between two nonlinear resistances consisting of L_1 and R_1, and the terminal capacitance, C of the surge arrester [14].

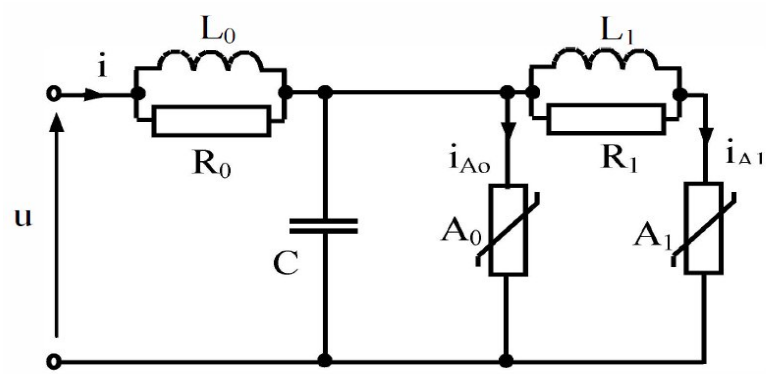

Figure 2.4 IEEE Frequency- Dependent Model [14]

These elements are compute from Equation (2.7) to (2.11) [14]:

$$R_0 = 100.\frac{d}{n}[\Omega] \tag{2.4}$$

$$L_0 = 0.2.\frac{d}{n}[\mu H] \tag{2.5}$$

$$R_1 = 65.\frac{d}{n}[\Omega] \tag{2.6}$$

$$L_1 = 15.\frac{d}{n}[\mu H] \tag{2.7}$$

$$C = 100.\frac{n}{d}[pF] \tag{2.8}$$

Where

d = the estimated height of the surge arrester in meter (m) and

n = the number of parallel columns of the metal oxide in surge arrester [14]

The R_1-L_1 has low impedance impact for slow front surge which implies that the two nonlinear resistances A0 and A1, and for the fast front surge, the filter that has high impedance which shows high current density that passing through the A0 nonlinear resistance.

2.4.2.2 Pincetti- Giannettoni Model

The modelled suggested by Pinceti and Giannettoni [15], [16] is a simplified version of the IEEE model as shown in Figure 2.4. The capacitance C is removed due to its negligible influence in this simplified version [17]. The resistances R_0 and R_1 were replaced by one resistance, R to reduce the possible instabilities.

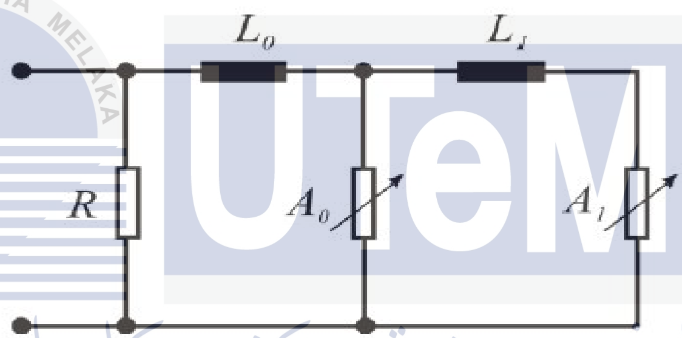

Figure 2.5 Simplified surge arrester model [17]

The characteristics of the A0 and A1 as nonlinear resistors are similar to that of the IEEE model (Table 3.2). The parameters L_0 and L_1 of this simplified surge arrester model can be formulated from [17]:

$$L_0 = \frac{1}{12} \cdot \frac{V_{r1/T\_2} - V_{r8/20}}{V_{r8/20}} \cdot V_r \qquad (2.9)$$

$$L_1 = \frac{1}{4} \cdot \frac{V_{r1/T\_2} - V_{r8/20}}{V_{r8/20}} \cdot V_r \qquad (2.10)$$

Where:-

V_r = surge arrester rated voltage

$V_{r1/T2}$ = residual voltage for a 10 kA fast front current surge (1/T2)

$V_{r8/20}$ = residual voltage for a 10 kA current surge with 8/20 µs shape.

R = 1 MΩ.

2.4.2.3 Fernandez Diaz Model

The proposed model is shown in Figure 2.6 and derives from that in the IEEE frequency dependant model. It is intended for the simulation of the dynamic characteristics for discharge currents with front times starting from 8 ms. As in [3], between the non-linear resistances A0 and A1 only the inductance L_1 is taken into account. R_0 and L_0 are neglected. C_0 represents the terminal-to-terminal capacitance of the arrester. The resistance R in parallel to A0 is intended to avoid numerical oscillations. The model in Figure 2.6 works essentially in the same way as that proposed in the IEEE model. Table 2.1 shows the valve block of 1kV rated voltage with lightning discharge current of 5kA and 10kA. This table used to determine the value of L_1.

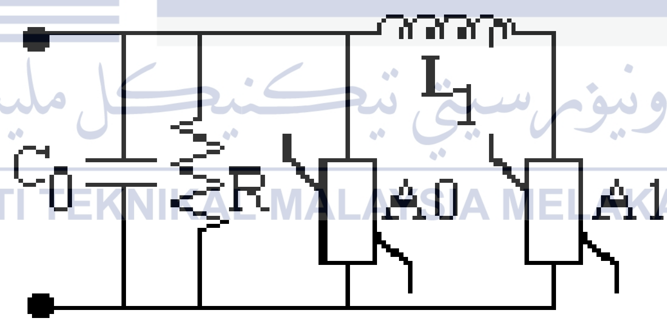

Figure 2.6 Simplified surge arrester model [18]

Table 2.1 Maximum residual voltage for elementary valve block of 1kV rated voltage with lightning discharge current of 5kA and 10kA [18]

Maximum Residual voltage (kV)		8/20 us lightning discharge current (A)		
5kA block	10kA block	?$_{8/20}$ (A)	?$_0$ (A)	?$_1$ (A)
2.87	2.73	1500	30	1470

3.07	2.90	3000	60	2940
3.27	3.07	5000	100	4900
3.60	3.33	10000	200	9800
4.27	3.77	20000	400	19600
5.30	4.53	40000	800	39200

The percent increase of the residual voltage results:

$$\Delta V_{res}\% = \frac{V_{ln,t1} - V_{ln\ 8,20}}{V_{ln\ 8,20}} . 100 \qquad (2.11)$$

The scale factor of the arrester:

$$n = \frac{U_{ln\ 8/20}\text{for the complete arrester}}{U_{ln\ 8/20}\text{for the 1kV valve block}} \qquad (2.12$$

$$?_1 = nL' \qquad (2.13)$$

The terminal-to-terminal capacitance C0 is given by:

$$C_{0} = \frac{100}{d} \qquad (2.14)$$

Where;

V_{In}, 8/20 = the residual voltage for the lightning discharge current of nominal amplitude

$V_{In,T1}$ = residual voltage for a discharge current with front time T1 and nominal amplitude.

C0 is in pF;

d =the overall height of the arrester in m.

2.5 Selection of Surge Arrester rating

The main focus in arrester application is to select the suitable rated value of surge arrester that will be able to provide adequate overall protection for maximum satisfactory service life when it is connected to the transmission line system [10]. For better protection of the insulation, the arrester voltage rating needs to be lower to achieve the lower discharge voltage. The lower rated arrester also more practical in terms of cost. When the arresters are connected to the power system, they continually monitor the system operating voltage. For each arrester rating, there is the limitation to the magnitude of voltage that continuously applied at the arrester. This term called Maximum continuous operating Voltage (MCOV). The selected arrester need to have a MCOV rating greater than or equal to the maximum continuous system voltage. [14]. In PSCAD simulation, fast front model of arrester are based on a surge arrester having its 10kA discharge voltage at 1.6 per unit (crest value). To determine the arrester voltage rating in kV, the following formula is used [19].

$$\text{Arrester Voltage Rating} = \frac{V_{10}}{1.6} \tag{2.15}$$

Where V_{10} is 10kA discharge voltage in kV for actual arrester under consideration

2.6 Transmission Tower

The main supporting structure of overhead transmission line is transmission tower. Transmission towers function to carry the heavy transmission conductor at a suitable safe height from ground. A power transmission tower consists of the following parts,

a. Peak of transmission tower
b. Cross Arm of transmission tower
c. Boom of transmission tower
d. Cage of transmission tower
e. Transmission Tower Body
f. Leg of transmission tower
g. Stub/Anchor Bolt and Base plate assembly of transmission tower

The main parts among these are:

- Peak of Transmission tower

The section where it's above the top cross arm is called peak of transmission tower. Earth shield wires are connected to the tip of this peak.

- Cross arm of Transmission Tower

Cross arms of transmission tower grasp the transmission conductor. The dimension of cross arm depends on factors of the level of transmission voltage, configuration and minimum forming angle for stress distribution

- Cage of Transmission tower

The area between tower body and peak is the cage of transmission tower. This portion of the tower connected to the cross arms.

- Transmission tower body

The section from bottom crosses arms up to the ground level. This area of the tower plays important role for maintaining required ground clearance of the bottom conductor of the transmission line [20], [21].

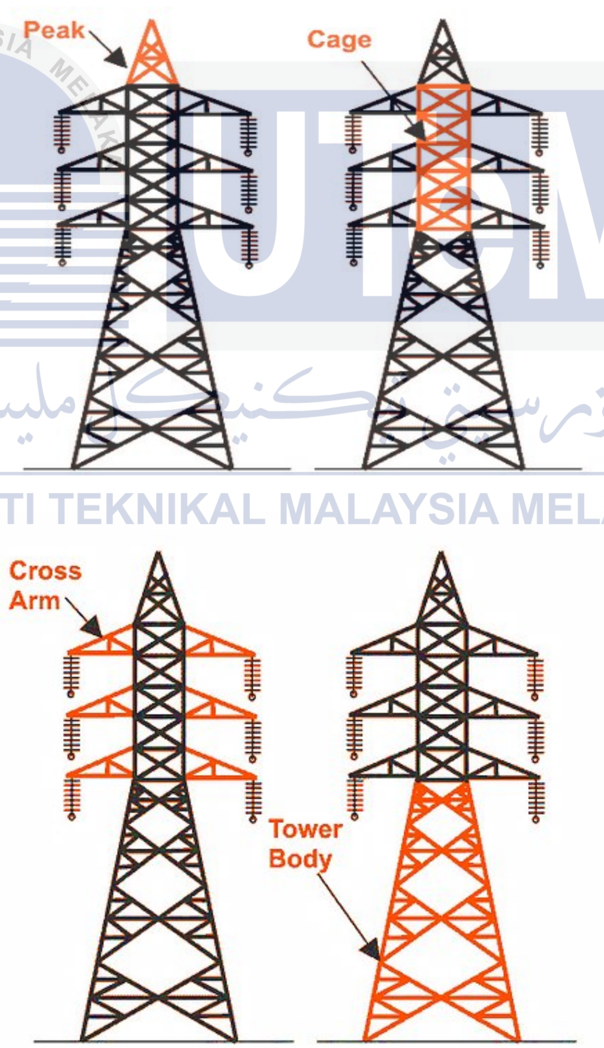

Figure 2.7 Parts of Transmission Line [20]

2.6.1 Design of Transmission Tower

To design a transmission tower, there thing to consider which are:-

a) The minimum ground clearance of the lowest conductor point above the ground level.

b) The length of the insulator string.

c) The minimum clearance to be maintained between conductors and between conductor and tower.

d) The location of ground wire with respect to outer most conductors.

e) The mid span clearance required from considerations of the dynamic behaviour of conductor and lightening protection of the line [3].

To determine the actual transmission tower height by considering the above points, the total heights of tower are divided in four parts:-

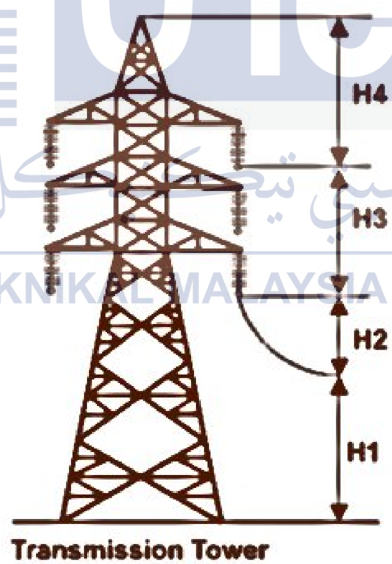

Figure 2.8 Transmission Tower [20], [21]

Where:

H1: Minimum permissible ground clearance

H2: Maximum sag of the conductor

H3: Vertical spacing between top and bottom conductors

H4: Vertical clearance between ground wire and top conductor

Transmission tower can be modelled as vertical, single conductor Bergeron distributed line model in PSCAD. The travel times of wave propagation down the tower are required with value of parameter of surge impedance of the transmission line tower. The Bergeron Model parameters' line can described by the following equation:-

Surge impedance,

$$Z_c = ?\,\overline{\frac{L}{C}} \tag{2.17}$$

Phase Velocity,

$$v = \frac{1}{\sqrt{LC}} \tag{2.18}$$

Based on the previous studies, the tower surge impedance reduces from 300-400 ohms at the shield wire to less than 100 ohms. If a backflashover is to be simulated, the associate crossarm can be modelled with the presented of surge impedance representative applied. Wave propagation velocity down a smooth conductor, such as tubular steel structure, is close to the speed of light. For lattice structure impede the velocity of propagation and along with the crossarm effect, effective wave propagation velocity may be 80-85% the speed of light [19].

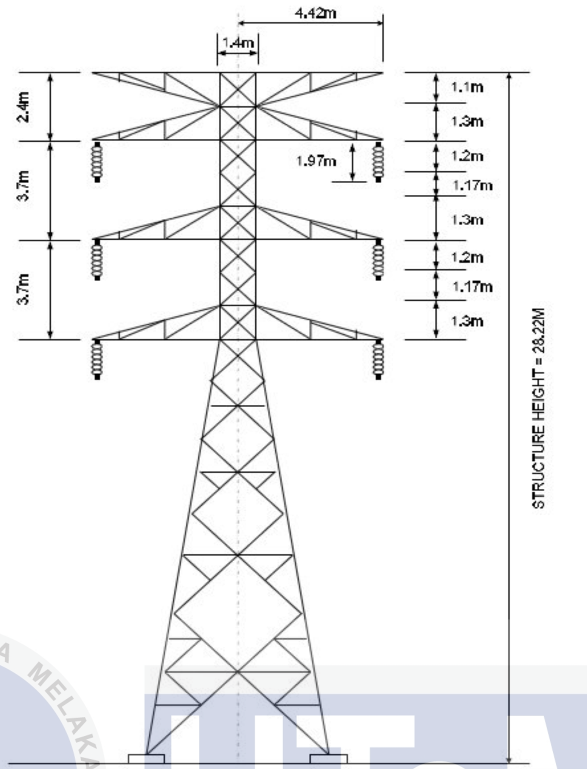

Figure 2.9 Actual model of a Bergeron tower for 132kV transmission line [22]

2.6.1.1 Tower Footing Resistance

For the 30 metres from the tower base, a variable grounding resistance approximation can be calculated by using formula:-

$$R_T = \frac{R_g}{1 + \frac{I}{I_g}} \tag{2.19}$$

Where:-

R_t = Tower Footing Resistance (ohm)

R_g = Tower Footing Resistance at low current and low frequency (ohm)

I = Surge impedance to the ground (kA)

I_g = Limiting current initiating soil ionization (kA)

$$I_g = \frac{1}{2} \cdot \frac{E_{op}}{R_g} \tag{2.20}$$

Where:-

p = soil resisteivity (ohm-meter)

Eo = soil ionization gradient (about 300kV/m) [4].

2.7 Transmission Line System

Transmission segments are always to be electrically short in length. This may also be represented using an equivalent π-section representation. Otherwise it can represent by using either the π-section component in the master library. Only the impedance and admittance data of the line segment are required, otherwise by using the π-section equivalent component creator feature in the Line Constants Program (LCP). π-sections are network of passive elements, and thus do not represent propagation delay [19].

The simplest representation is lossless distributed parameter transmission line, characterized by surge impedance and travel time.

$$Z_o = 60 \log_e \left(\frac{d}{r}\right) \Omega \qquad (2.21)$$

The line termination at each side of the model important to avoid reflection that could affect the simulated overvoltages around the point of impact is represented by a long enough section with its surge impedance [19].

By using the data provided by the cross-sectional definition of its segment, the cables and transmission lines can be modelled using one of three distributed (travelling wave) models:

a. Bergeron model

The Bergeron model presented the parameter of L and C elements of a π-section in a distributed manner. It is acceptable only at the specified frequency and permissible for studies where the specified frequency load-flow is considered. When applying the

Bergeron model, it is not always important to use a tower component to represent a transmission line. But for instance, if modelling a three-phase system, then the line data can be enter, in admittance or impedance format, which directly by substituting the Manual Entry of Y, Z component [19].

b. The Frequency-Dependent (Mode) model

This represents the frequency dependence of all parameters (not just at the specified frequency as in the Bergeron model). This model approximates the phase to mode transformation modal techniques to solve the line constants. It is therefore only ideal for systems of equally transposed conductors or single conductors [19].

c. Frequency Dependent (Phase) model

The frequency Dependant (phase) model uses curve fitting to duplicate the frequency response of a line or cable. It is the most advance time domain model available on any simulator as it represents the full frequency dependence of all line parameter which include the effect of a frequency dependent transformation. It is a useful wherever the transient or harmonic behaviour of the line or cable is important.

The most precise of these is the Frequency Dependent (Phase) model, where its represents all of frequency dependent effects of a transmission line, it also should be used whenever in doubt. When using the Bergeron model, impedance or admittance of data can be entered directly to represent the transmission segment [19].

Frequency Dependent (Phase) Model Options

Travel Time Interpolation:	On
Curve Fitting Starting Frequency:	0.5 [Hz]
Curve Fitting End Frequency:	1.0E6 [Hz]
Total Number of Frequency Increments:	100
Maximum Order of Fitting for YSurge:	20
Maximum Order of Fitting for Prop. Func.:	20
Maximum Fitting Error for YSurge:	1.0 [%]
Maximum Fitting Error for Prop. Func.:	1.0 [%]

Bergeron Model Options

Travel Time Interpolation:	On
Reflectionless Line (ie Infinite Length):	No

Frequency Dependent (Mode) Model Options

Travel Time Interpolation:	On
Curve Fitting Starting Frequency:	0.5 [Hz]
Curve Fitting End Frequency:	1.0E6 [Hz]
Maximum Order of Fitting for ZSurge:	20
Maximum Order of Fitting for Prop. Func.:	20
Maximum Fitting Error for ZSurge:	1.0 [%]
Maximum Fitting Error for Prop. Func.:	1.0 [%]

Figure 2.10 The line constant component for three distributed line model available in Master Library

Based on the Tlines pages in Master Library, configuration of overhead distribution line can be selected. The distributed transmission line models operate on the principle of traveling waves. Voltage disturbance will travel along a conductor at its propagation velocity (merely to speed of light) until it is reflected at the end of the lines [19].

2.8 Insulator string

The insulator is modelled based on per string by representing in parallel by circuit breaker together with the capacitor which connected between tower and phase conductor. The insulator that's being used here is the string that made of from glass insulator. When the electric stress takes place between conductor and the condition of the tower cross arm exceed the critical withstand voltage of the string, the flashover will take place along the insulator string. This breakdown of insulator is characterised by volt-time characteristic curve which lead to flashover interpretation [22].

2.9 Lightning Sources

The positive conductor is operating at a less insulation level than the negative one under most of negative descending flashes. The simulation carried out by adding a negative lightning current at the positive conductor. The output channel represent by the lightning current generated were controlled by a bi-exponential function shown in Equation (2.22)

$$i = I_0 \left(e^{(-\alpha t)} - e^{(-\beta t)}\right) \qquad (2.22)$$

Where:

I_0 = lightning stroke current amplitude

α, β = constant

t_f = wave-front time

t_{half} = half amplitude time

In the double-exponential formula shown in Equation (2.25), the constants α and β are usually difficult to fit the impulse waveforms of lightning currents.

Due to this reason, the A-factor must be introduced to generate the differences of impulse waveform more precisely. A-factor is crucial to create the double-exponential impulse waveforms in different amplitudes and parameters [9], [14]

Based on the Equation (2.22), the modified formula with additional of A-factor can be expressed as:

$$i = AI_0 \left(e^{(-\alpha t)} - e^{(-\beta t)}\right) \qquad (2.23)$$

And it is derived as

$$\frac{di(t)}{dt} = AI_0 \left(-\alpha e^{(-\alpha t)} + \beta\, e^{(-\beta t)}\right) \qquad (2.24)$$

At the peak value I_0, Equation. (2.22), where $t = t_{max}$ should satisfy the following condition

$$\frac{di(t_{max})}{dt} = AI_0\,?-\alpha e^{(-\alpha t_{max})} + \beta\, e^{(-\beta\, t_{max})}? = 0 \qquad (2.25)$$

As t_{max} is the time from the beginning of the current impulse to its peak/ maximum value. T_{max} can be expressed as

$$t_{?\,??} = \frac{??\,? - ??\,?}{?\,-?} \qquad (2.26)$$

By substituting Equation (2.26) to (2.24), its yield to

$$?(?_{?\,??}) = ?\,?_0\,??^{(-?\,?_{?\,??})} - ?^{(-?\,?_{?\,??})}? \qquad (2.27)$$

And thus, the A-factor can be obtain by

$$?\,(?\,,?\,) = \left(?^{\left(-?\frac{??\,?-??\,?}{?-?}\right)} - ?^{\left(-?\frac{??\,?-??\,?}{?-?}\right)}\right) \qquad (2.29)$$

Based on the Equation (2.22) to (2.29), it is possible to create arbitrary double exponential expression for lightning current waveform by changing α, β and A.

Figure 2.11 illustrated a double exponential lightning current waveform. The rise time t_1 and the pulse length t_2 are shows here.

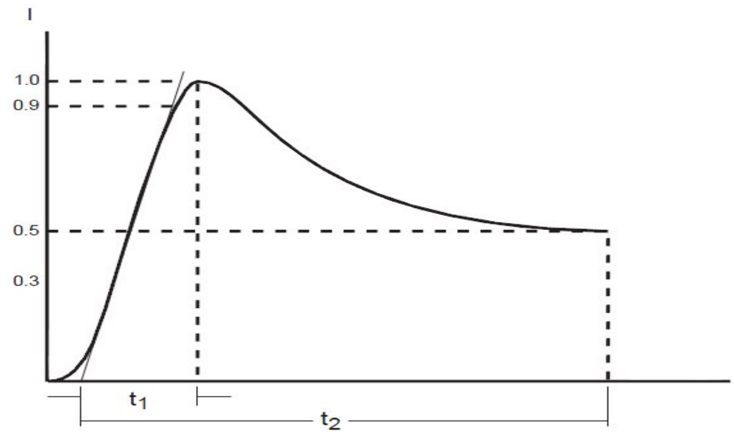

Figure 2.11 Typical Lightning Current Waveform [9]

The IEEE standard [14] suggested for an 8/20 μs current wave for testing equipment. It was originally derived from the response time of gapped Silicon Carbide arresters. This has been widely used for testing but the various types of values also give an impact for different type of result.

2.10 Review from previous research

Title of Research	**Analysis of Surge Arrester Energy for 132kv Overhead Transmission Line due to Back Flashover and Shielding Failure**	**Modelling of Overhead Transmission Line with The Line Surge Arrester for Lightning Overvoltages**	**Comparison of Different Metal Oxide Surge Arrester Models**
Author	Ab Halim Abu Bakar, Nor Hidayah Nor Hassan, Hazlie Mokhlis	M.Jaroszewski, J.Pospieszna, P.Ranachowski, F.Rejmund	Dino Lovric, Slavko Vujevic, Tonci Modric
Analysis and Finding	-Shielding failure occurs when lightning strike less than or equal to 20kA bypass the overhead ground wire -Backflashover occur when the exceed the line critical flashover (CFO) -Only backflashover phenomena will increase the energy discharge as footing resistance increase.	-Stroke to phase conductor are limited in magnitude to the maximum shield failure current, which usual line is between 5 and 15kA. -The addition of surge arrester reduces the interruption rate by 34% over shield wire alone	-complexity of IEEE model to approximate the surge arrester characteristic using data provided by manufacturer. -Simplified model proposed by Pincetti makes modelling of surge arrester considerably easier. - For fast front surge of 1/5us wave shape, simplified model yields more accurate result than the IEEE model in all cases. -For fast front surges of an 8/20us wave shape, both model display similar accuracy degrees and has the highest percentage of error for 20kA amplitude. For slow front surge of 30/60us, the IEEE model shows greater accuracy degree than the simplified model of all cases.

2.11 Summary

As summarize, this chapter discussed on the protection of the transmission line, lightning overvoltage and the problem caused by lightning itself to the power transmission line. Other than that, this chapter illustrate about the component of modelling 132kV transmission line which includes the modelling of overhead transmission line, lightning stroke, transmission tower, insulator and shielding failure phenomena. The suggested parameter of modelling of 132kV transmission line component was selected from previous research.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Generally, project methodology defines methods/steps necessary for successful completion of a project. This chapter describes the project's methodology flow chart and the software used in this project.

3.1.1 Flow of works

The flow chart describes activities or tasks to be done in each stage of the project's planning, as it is important to ensure successful completion of the project.

a. Literature review

   Literature review elaborates on facts, research trough the paper and journal, reference book, internet, etc. The main function is to provide better understanding of the project.

b. Design and develop 132kV Overhead Transmission Line and Surge Arrester models using PSCAD

   The next step is modelling the 132kV overhead transmission line. PSCAD is the simulation tool for power system in transient analysis. This study modelled eleven spans of transmission towers and several type of surge arrester. The full transmission-line model includes wires (shield wires and phase conductors), towers, insulator strings, cross- arms, tower surge impedance.

c. Develop lightning stroke model

The lightning source is model based on IEC triangular wave shape [14]. A peak current of different magnitude has been used in this project.

d. Model verification simulation

Three magnitudes of lightning current will be injected into the top tower of one of the transmission lines. Shielding failure voltage pattern across line insulation will be observed for all three phases.

e. Discussion on waveform analysis

This part analyses the waveform obtained from simulation results, and discusses the results.

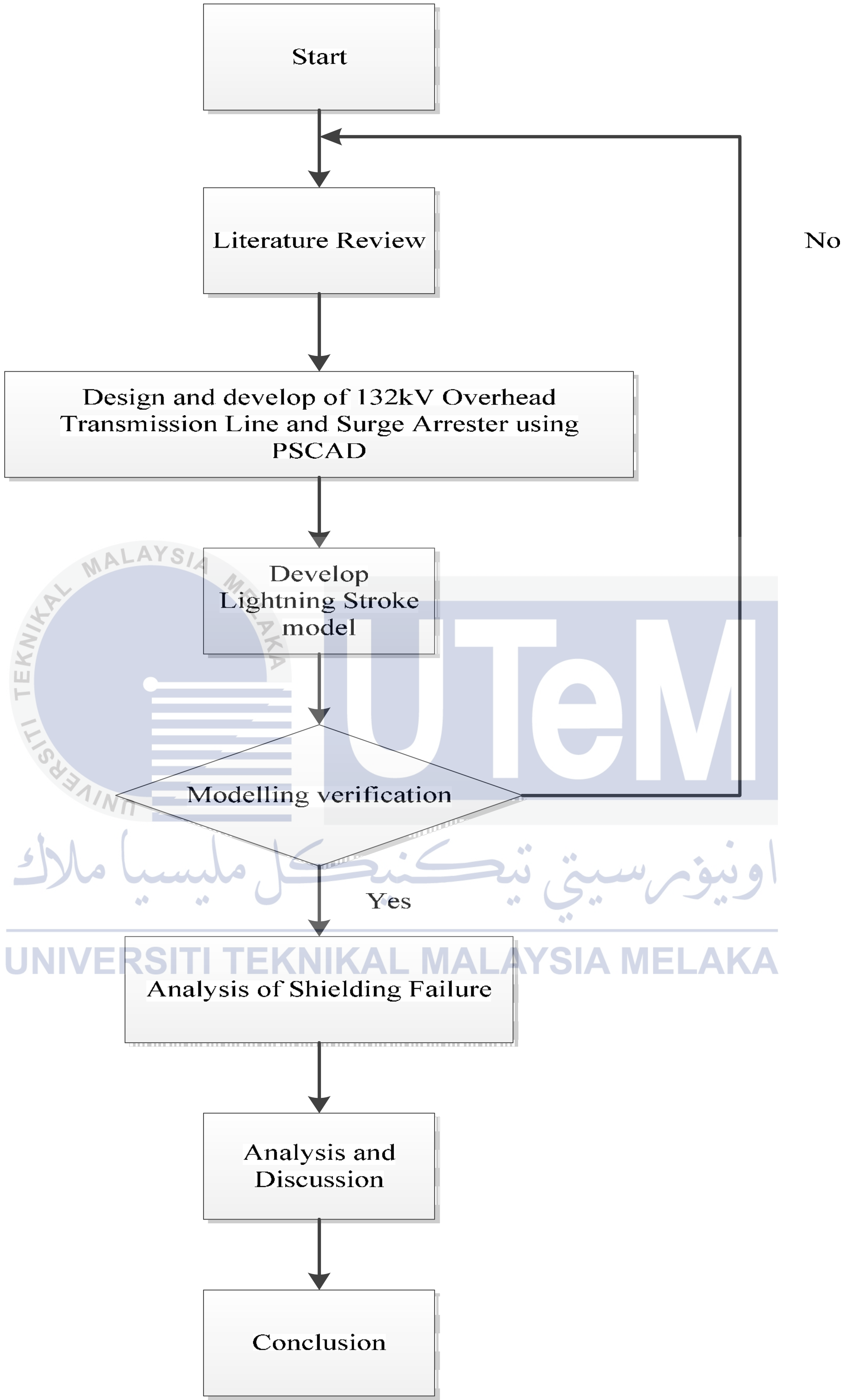

Figure 3.1 Flowchart of the Project

3.2 Power System Computer Aided Design

PSCAD (Power Systems Computer Aided Design) is an effective and flexible graphical user interface, EMTDC known as electromagnetic transient simulation engine. The PSCAD was developed by at the Manitoba HVDC Research Centre [20]. PSCAD let user to construct schematically a circuit, run a simulation of modelling, analyse the results, and manage the data in a completely integrated, graphical environment. PSCAD also offers Online plotting functions, controls and meters to simulate and enabling the user to alter models parameters during a simulation run and at the same time can view the effects while the simulation is in progress [19].

3.2.1 Modelling of 132kV Overhead Transmission Line and Tower

For simulation of overvoltage it is important for modelling the tower model, pole line model and their combination characterized by their electrical parameters. The tower and conductor geometry is necessary to calculate the line constant for the transmission line models in PSCAD.

This study modelled a 132kV double circuit with two overhead ground wire transmission towers. The phase conductor and ground wire are explicitly modelled between tower and eleven tower spans were used. The Bergeron overhead line model was used for modelling in PSCAD as it is the most common type of transmission line for 132kV overhead transmission line system. The Frequency Dependant (Phase) model typically chosen to model the tower component. The height of the modelled tower was 30m. The tower represented basically by a simple distributed line between the cross-arm and insulator string. Figure 3.2 shows the line and tower interface component used in this study. Figure 3.3 illustrated the line constant component needed to model the transmission by using Bergeron Model [19].

To construct an overhead line in PSCAD, the first is the original method (referred to as the Remote Ends method), which involves a Transmission Line Configuration component with two Overhead Line Interface components, representing the sending and receiving ends of the line. The purpose of the interface components is to connect the transmission line to the greater electric network [19].

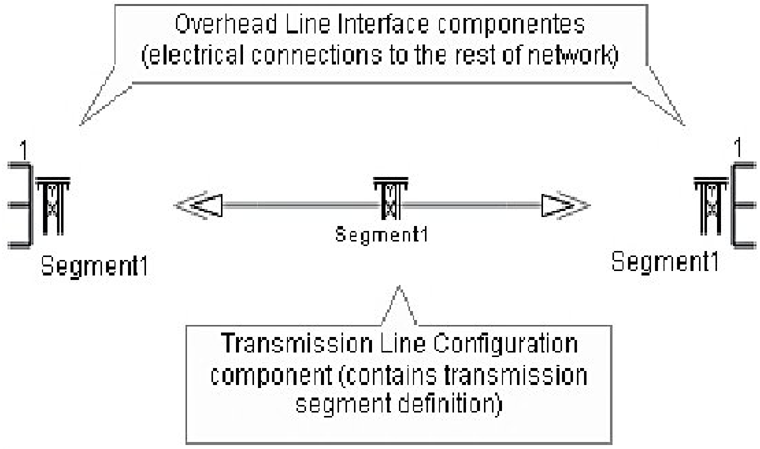

Figure 3.2 The transmission line interface component [19]

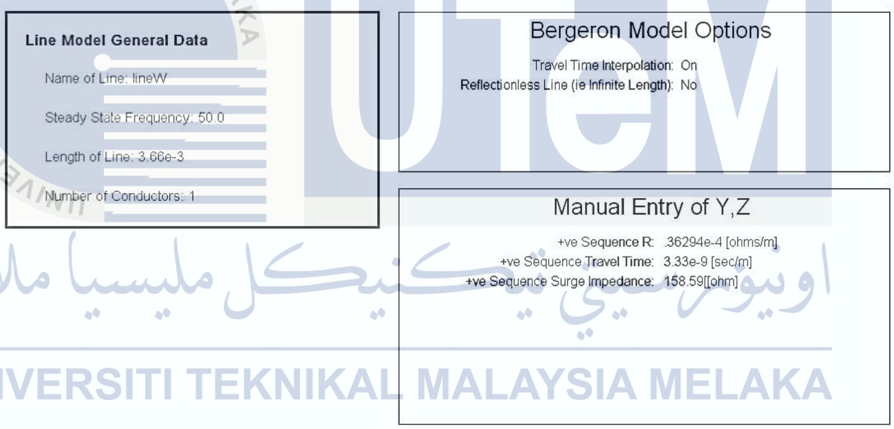

Figure 3.3 The Line Constant components for Bergeron Model

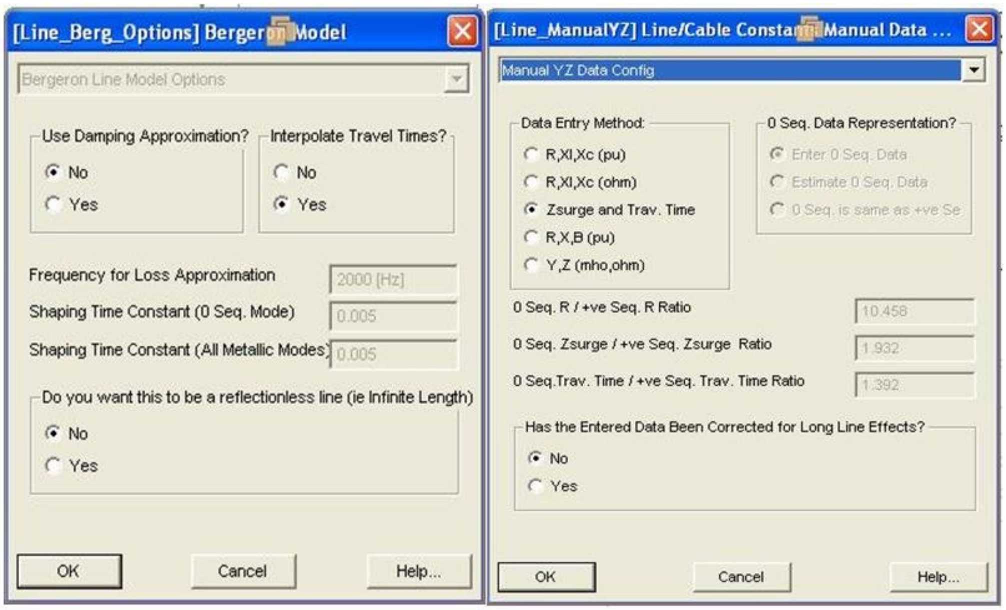

Figure 3.4 Editing the Line Constant Component for the Bergeron model

Figure 3.4 shows the line constant component in Frequency Dependant (phase) model. The standard data for this system type includes:

a. **Steady state frequency** – base frequency applied to whole system
b. **Length of line** – length of the overhead line [km]
c. **No of conductor** – number of conductors connected.
d. **Ground resistivity** (ohm) of homogeneous earth

In this project, the value selected for base frequency was 50 Hz, the ground resistive value was 100 ohm and for the distance or length, 300m (spans between the towers). The system line has six phases including two shield wire or ground wire. All the input data are based on the actual data taken from reliable sources. Figure 3.5 shows the detailed of the input data are as follows:

a. **Tower name**
b. **Height of the lowest conductor**
c. **Vertical offset of conductor**
d. **Horizontal spacing between phases**

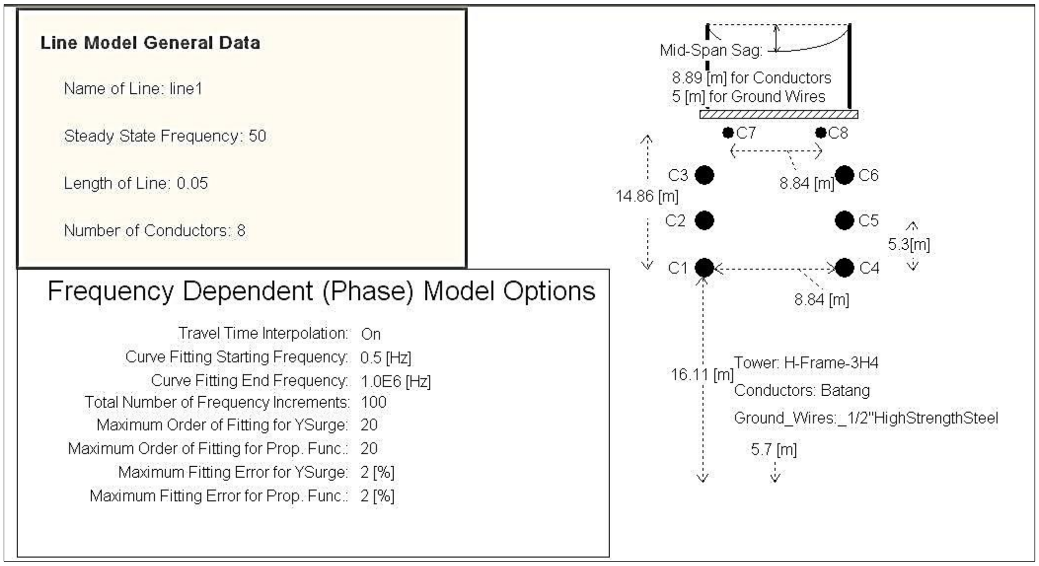

Figure 3.5 The Line Constant components for Frequency Dependent (Phase) model

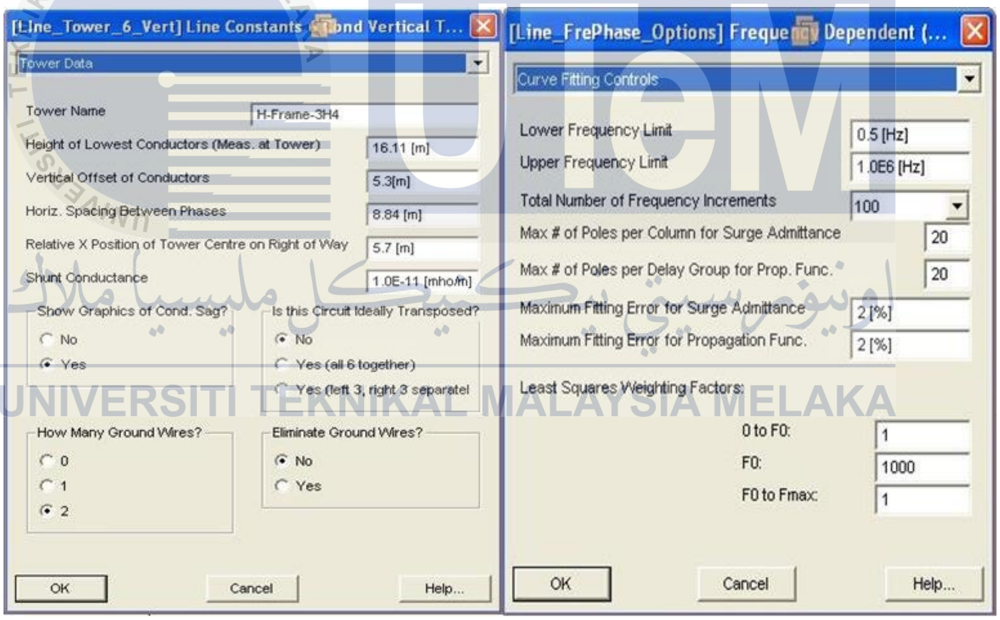

Figure 3.6 Editing the Line Constant Component for the Frequency Dependent (Phase)

3.2.2 Modelling of lightning strike

A lightning stroke is modelled as ideal current sources whose parameter, also the polarity and multiplicity are randomly selected according to the distribution density function recommended in literature review. As suggested in literature [14], the lightning current can be control by using the exponential function, Time Signal Variable, Single Input Comparator, Multiplier, Two-Input Selector, Summing/Difference Junction and Real Constant with the Slider to control the lightning amplitude manually. When the simulation time is shorter than the threshold input value at the Comparator, the Comparator outputs a low level; otherwise, a high level will be output. The input control signals of the Two- Input Selector can be controlled by the low and high level, whose output will be the signal connected to A, a delayed bi-exponential waveform, with the high level input, or the zero signal connected to B, with the low level input. The delay time of the doubleexponential function are known by the rise time of the working voltage on the two polar conductors [21].

3.2.2.1 Typical Lightning Characteristic

Based on the Equation (2.22) to (2.29), the impulse waveform of lightning current suggested is 8/20us. The formula constants α, β and A can be determined numerically by a trial and error procedure. Then, the double-exponential expression for lightning current waveforms can be obtained from the formula constants α, β and A [9],[23]. In Table 3.1 below gives the standard and calculated value based on standard lightning current waveform [9].

Table 3.1 Typical Lightning Stroke Current [9], [23]

Parameter	**A**	**α (s)**	**β(s)**
1.2/50 μs	1.037	1.47 x 10^4	2.47 x 10^6
2.6/50 μs	1.058	1.50 x 10^4	1.86 x 10^6

8/20 µs	4.00	0.866 x 10^5	1.732 x 10^5
300/1000 µs	1.75	1.233 x 10^3	6.78 x 10^3

As referred to Figure 3.6, the input values entered in simulation are:

The amplitude of lightning current = 10kA

The value of A-factor = 4.00

α = 0.866 x 10^5

β = 1.732 x 10^5

If the multiplier (A-factor) is 4 and the desired current is 10kA, the input entered in the PSCAD is 40kA.

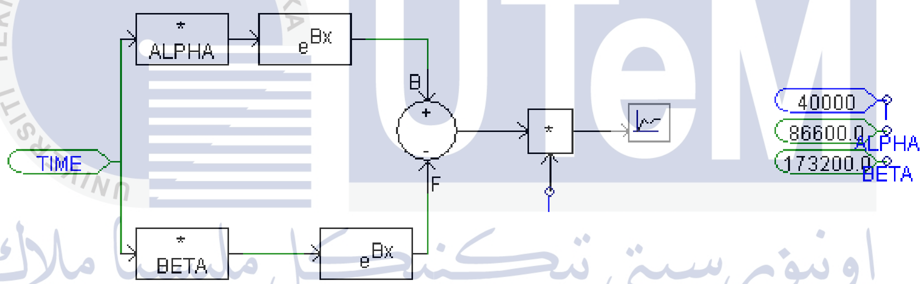

Figure 3.7 Develop Lightning Model for 10kA, 8/20us lighting current waveform

3.2.3 Modelling of Surge Arrester

According to IEC 60099-4 [11], the standard of surge arrester height is 1216mm and the number of parallel column of metal oxide disc is 1 for 132kV electrical power system.

Generally for 132kV electrical power system, it should +10% voltage regulation, meaning 132kV plus +10% of voltage regulation which is equal to 145.2kV from the data sheet [13] for maximum system voltage, U_m.

For IEC 60099-4 [11], the continuous operating voltage of surge arrester, U_c and the rated voltage of surge arrester, U_r can be calculated using equation below.

$$U_c \geq \frac{U_m}{\sqrt{3}} x1.05 \tag{3.1}$$

$$U_c \geq \frac{145k}{\sqrt{3}} x1.05$$

$U_c \geq\geq$ 87.9kV(Category 92kV has been chosen)

Thus, for the continuous operating voltage category 92kV has been chosen.

$$U_r \geq U_c \text{ x } 1.25 \tag{3.2}$$

$U_r \geq$ 92k x 1.25

$U_r \geq$ 115kV(Category 120kV has been chosen)

Thus, for the rated voltage category 120kV has been chosen

As the conclusion, following value are used to obtain all the parameter of surge arrester:

- Maximum system voltage (U_m) is 145.2kVrms
- Rated voltage (U_r) for arrester is 120kVrms
- Maximum continuous operating voltage (MCOV) is 98kVrms
- Height of arrester, d = 1216mm
- Number of parallel column of metal oxide disc, n = 1

3.2.3.1 IEEE frequency dependant model

The IEEE frequency dependant model parameters were calculated from the standard data sheet obtained from the manufacturer [16]. The effectiveness of the model was tested and compared with the residual voltage test result for typical lightning surge of 8/20us.

In modelling using PSCAD, Insulation design for distribution arresters is based on fast front transients. For the fast front transient model, there are two part of non-linear resistance designated A0 and A1. Each comprised of the surge arrester model used for switching surge transients. The two parts are separated by an R-L filter.

For slow front surges, this R-L filter has very little impedance, but is significant for fast front surges. Characteristic A0 shows a higher voltage for a given current than A1, but if these two non-linear resistances are puts in parallel when the R-L filter is not acting significantly, their characteristic works perfectly for slow front surge (switching surges).

The fast front model parameters which is the initial parameter for L_0, C, L_1 and R_1 need to determine by using Equation (2.4) to (2.8). Where d=1.216 and n=1.

$$L_0 = 0.2.\frac{d}{n} = 0.24\mu H \tag{3.3}$$

$$R_1 = 65.\frac{d}{n} = 79.04\Omega \tag{3.4}$$

$$L_1 = 15.\frac{d}{n} = 18.24\mu H \tag{3.5}$$

$$C = 100.\frac{n}{d} = 82.24pF \tag{3.6}$$

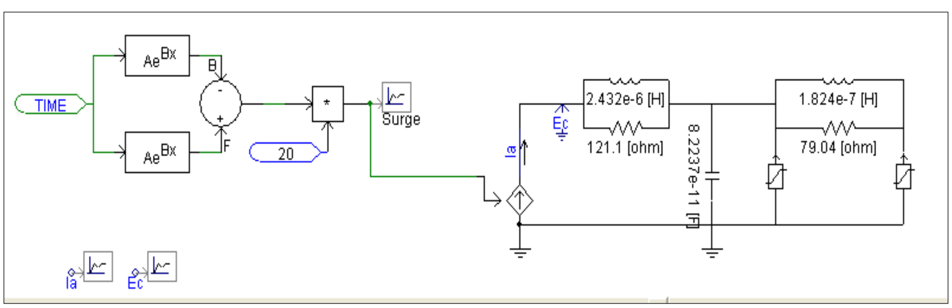

Figure 3.8 IEEE model arrester

It is important to ensure the “I-V characteristic” for both A0 and A1 section are entered into the surge arrester component.

Table 3.2 I-V characteristic for A0 and A1 section for entry in surge arrester component [14]

X-axis current (kA)	A0 Y-axis volts (p.u)	A1 Y-axis volts (p.u)
1.0E-7	1.1	0.27
1.0E-6	1.28	1.0
1.0E-5	1.33	1.08
1.0E-4	1.37	1.11
0.001	1.39	1.15
0.01	1.42	1.18
0.1	1.52	1.22
1.0	1.65	1.32
3.816	1.75	1.40
10.0	1.9	1.55
100.0	3.8	1.95

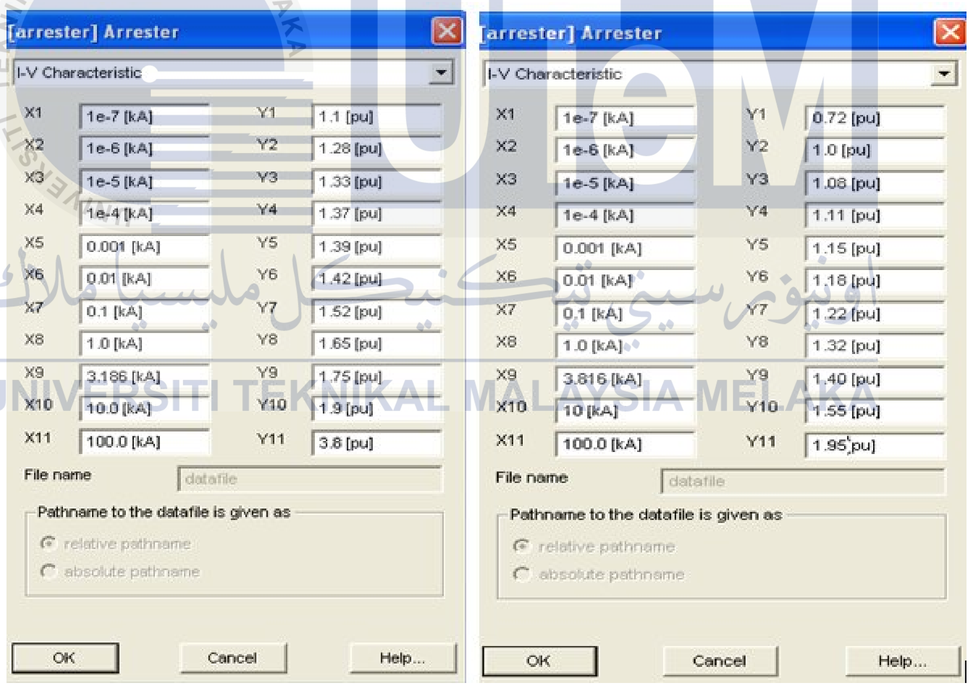

Figure 3.9 I-V characteristic A0 and A1 respectively entered in component dialog

The magnitude of current injected to the surge arrester are similar to magnitude produced in waveshape since the current used by the manufacturer to determine the switching surge discharge voltage. The injected of the switching surge test current and examine the resulting peak voltage. The current impulse produced by two exponential functions is formulated in Equation (2.22).

3.2.3.2 Pincetti-Giannettoni model

The Pincetti-Giannettoni model parameters were also calculated from the standard data sheet obtained from the manufacturer [13]. The effectiveness of the model was tested and compared with the residual voltage test result for typical lightning surge of 8/20us. Table 3.3 shows data from manufacturer for the arrester to be modelled.

Table 3.3 Arrester data (ABB MWA) [13]

Rated Voltage [kV]	**Max. Cont. Operating Voltage [kV]**	**Residual voltage with waveform at discharge current (kV)**		
		8/20us (lightning current)		
		5kA	**10kA**	**20kA**
120	92	260	273	299

The value of arrester parameter can be entered from manufacture data as:

V_r = 120kV

$V_{r8/20}$ = 273kV

$V_{r1/T2}$ = 285kV [17]

By using the Equation (2.9) and (2.10), the value of inductive element can be determined as follows:

$$L_0 = \frac{1}{12}.\frac{285-273}{273}.120 = 2.45\text{uH}$$

$$L_1 = \frac{1}{4}.\frac{285-273}{273}.120 = 0.81\text{uH}$$

It is important to ensure the “I-V characteristic” for both A0 and A1 section are entered into the surge arrester component. The points of the I-V characteristics are similar to the characteristic of IEEE model as shown in Table 3.2 above.

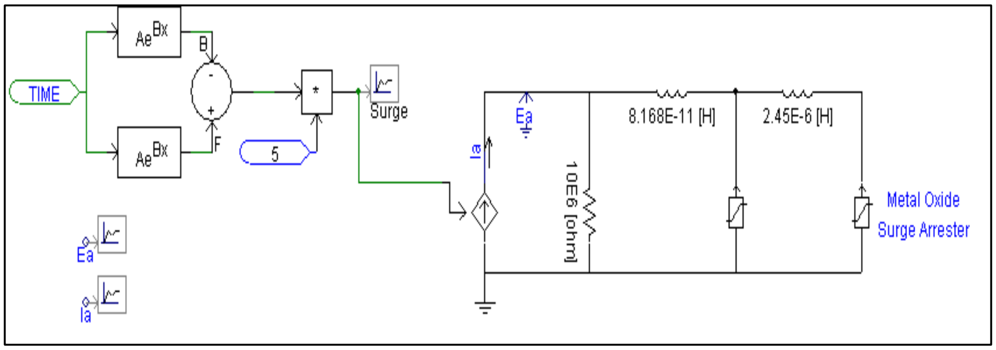

Figure 3.10 Pincetti model arrester

Figure 3.10 illustrate the modelling of Pincetti arrester with the given manufacturer data and calculated using the Equation (2.9) and (2.10).

3.2.3.3 Fernandez-Diaz Model

The Fernandez Diaz model parameters were also calculated from the standard data sheet obtained from the manufacturer [13]. The effectiveness of the model was tested and compared with the residual voltage test result for typical lightning surge of 8/20us. The parameter of the surge arrester obtained from the Equation (2.11) to (2.14) as follow:-

The percent increase of the residual voltage results:

$$\Delta V_{res}\% = \frac{286 - 270}{286}.100 = 5.98\%$$

The scale factor of the arrester:

From the curve for front time 1us [24], the inductance of L’ = 0.07uH is selected.

$$n = \frac{39200}{959} = 40.87$$

$$L = nL' = 0.07 \text{ x } 40.87 = 2.87uH$$

The terminal-to-terminal capacitance C0 is given by:

$$C_{0} = \frac{100}{d} = 82.24$$

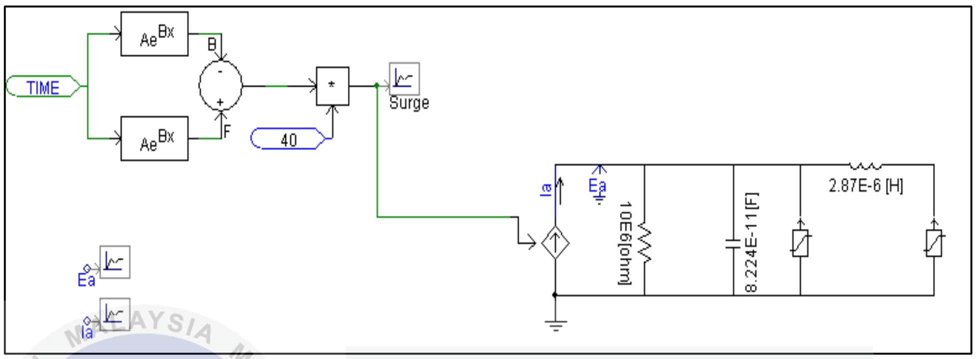

Figure 3.11 Fernandez Diaz model arrester

Figure 3.11 illustrate the modelling of Fernandez Diaz model arrester with the given manufacturer data and calculated using the Equation (2.11) to (2.14).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The result of this project is obtained from the PSCAD simulation. The graph showed the value of the impulse current surge and the residual voltage that simulated with surge arrester. The concern in this chapter shows the significant differences on each of surge arrester models with manufacture data. The discussion explains on related issues in this project, the comparison of simulation and manufacture data, the effect of surge arrester on the transmission line, and the shielding failure analysis.

4.2 Lightning Current Waveform

The simulation was conducted was based on the typical lightning behaviour in Malaysia for shielding failure [4]. Figure 4.1 shows the output of the lightning stroke model, which is double exponential waveform output, current versus time in PSCAD software by using an output channel component.

i. Lightning current impulse of 5kA

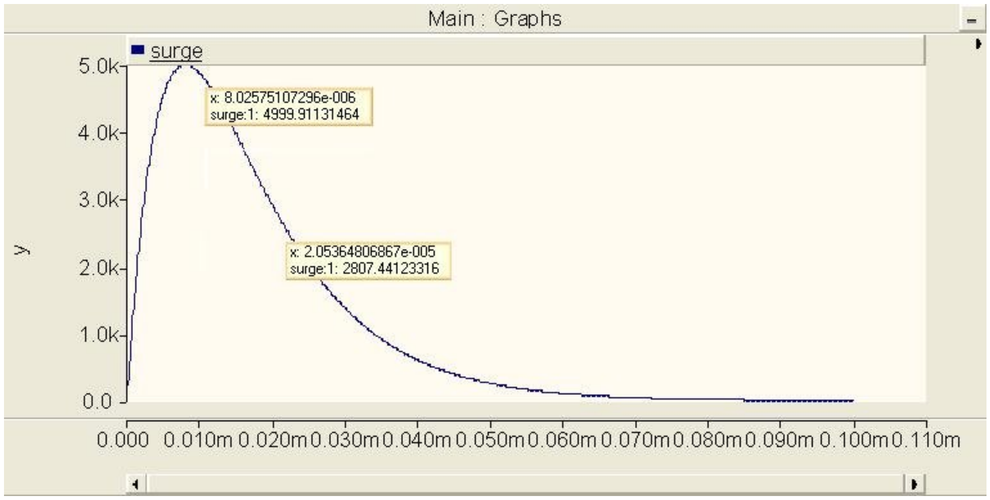

Figure 4.1 Lightning current impulse waveform of 5kA

The result shows at the front time of 8us, the current is approaching the value of 5kA which is slightly the same as expected value. For the tail time of 20us, the current value is 2.8kA which is slightly higher than the expected value of 2.5kA that is 50% of the front time, 5kA [25].

ii. Lightning current impulse of 10kA

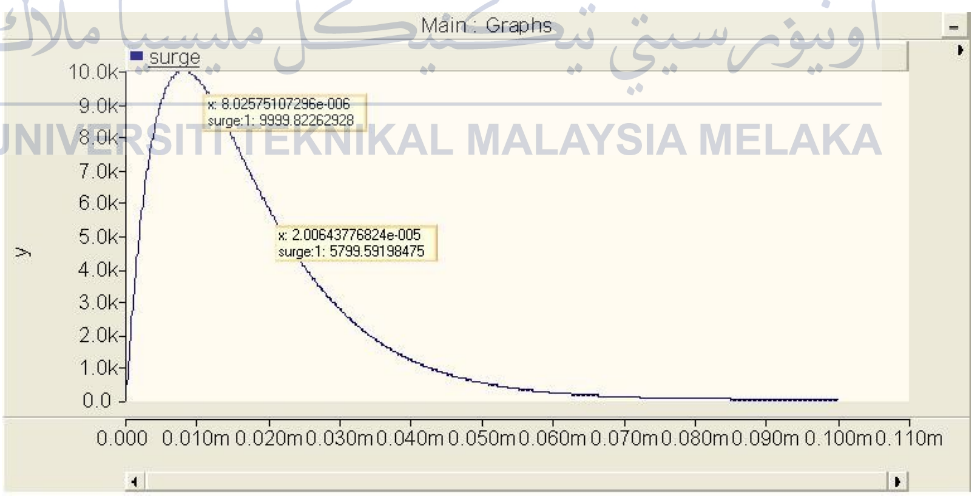

Figure 4.2 Lightning current impulse waveform of 10kA

The result shows at the front time of 8us, the current is approaching the value of 10kA which is slightly the same as expected value. For the tail time of 20us, the current value is 5.7kA which is slightly higher than the expected value of 5kA that is 50% of the front time, 10kA [25].

iii. Lightning current impulse of 20kA

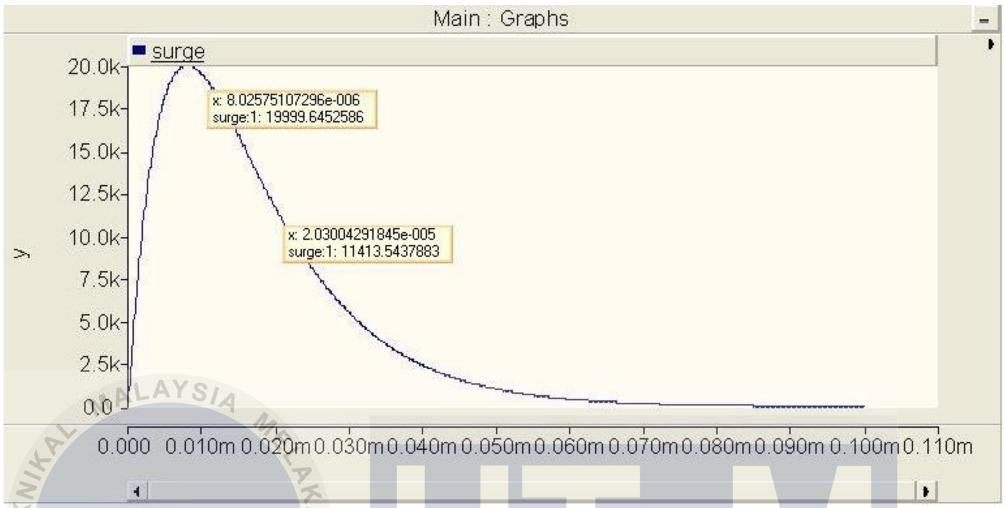

Figure 4.3 Lightning current impulse waveform of 20kA

The result shows at the front time of 8us, the current is approaching the value of 20kA which is slightly the same as expected value. For the tail time of 20us, the current value is 11kA which is slightly higher than the expected value of 10kA that is 50% of the front time, 20kA [25].

4.3 Evaluation on Surge Arrester Model

The result presented the comparison of simulation of surge arrester in two different of manufacturer data which is, ABB Manufacture and Toshiba Manufacture.

4.3.1 ABB Manufacture Data

The table shows the residual voltage for multiple range of current impulse of ABB Manufacture data. As stated in Table 4.1, the arrester voltage rating for lightning level from the Equation (2.15).

Table 4.1 Residual Voltage and Arrester Voltage Rating of ABB Manufacture Data [13]

Lightning current impulse, 8/20µ (kA)	Manufacturer residual voltage (kV)	Arrester Voltage Rating (kV)
5	260	162.500
10	273	170.625
20	299	186.875

The Table 4.1 above shows the arrester voltage rating based on the ABB manufacturer residual voltage. Different value of residual voltage gives different value of arrester voltage rating since the surge arrester having its residual voltage at 1.6 per unit (crest value)[19]. These arrester rating are calculated by using Equation (2.15).

The following graph in Figure 4.5 to Figure 4.12 illustrate the result of residual voltage simulated based on the value from Table 4.1 above. The graphs in Figure 4.4 to Figure 4.7 show the result of the IEEE model of surge arrester when injected with magnitude of lightning current of 5kA, 10kA and 20kA respectively. For Figure 4.8 to Figure 4.9, the result was from Pincetti model of surge arrester and for Figure 4.10 to 4.12 the result was from Fernandez Diaz model of surge arrester.

IEEE Frequency Dependant model of Surge Arrester

i. Residual voltage based on 5kA lightning current

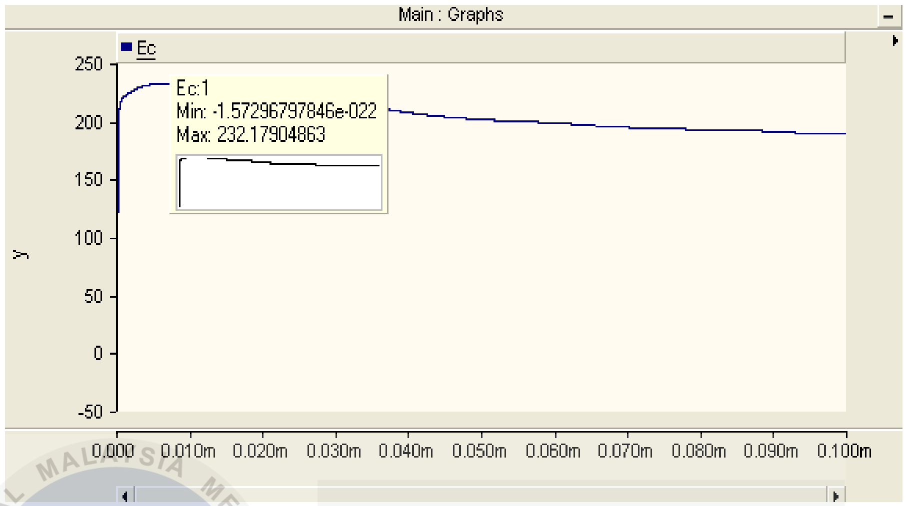

Figure 4.4 IEEE model with 5 kA, 8/20 µs

ii. Residual voltage based on 10kA lightning current

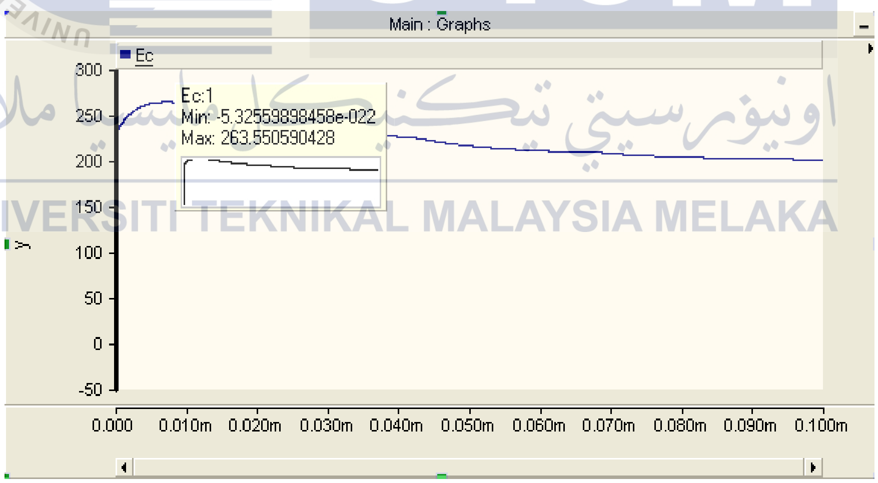

Figure 4.5 IEEE model with 10 kA, 8/20 µs

iii. Residual voltage based on 20kA lightning current

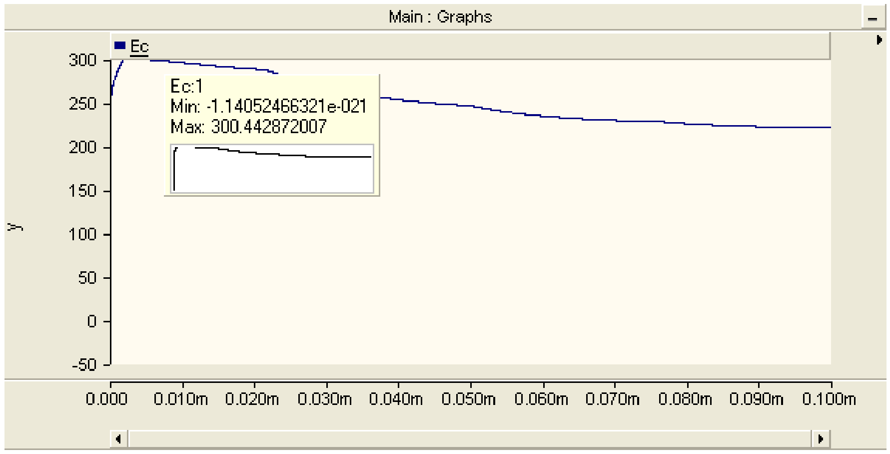

Figure 4.6 IEEE model with 20 kA, 8/20 µs

Pincetti model of Surge Arrester

i. Residual voltage based on 5kA lightning current

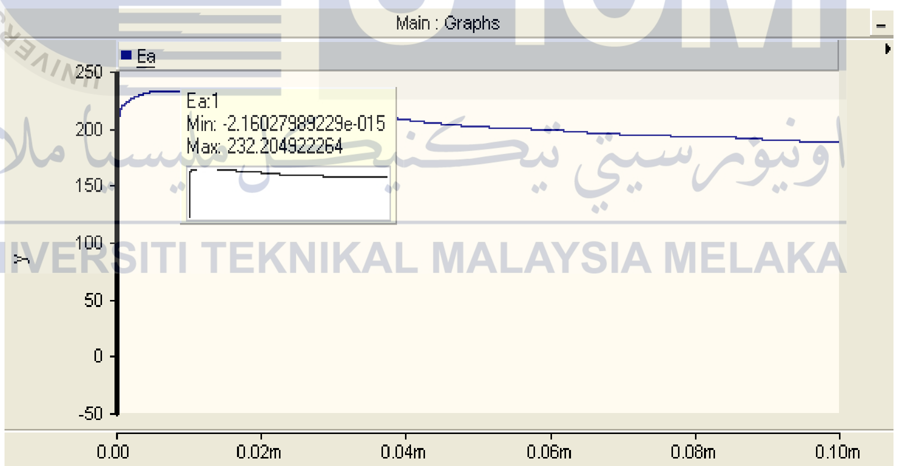

Figure 4.7 Pincetti model with 5 kA, 8/20 µs

ii. Residual voltage based on 10kA lightning current

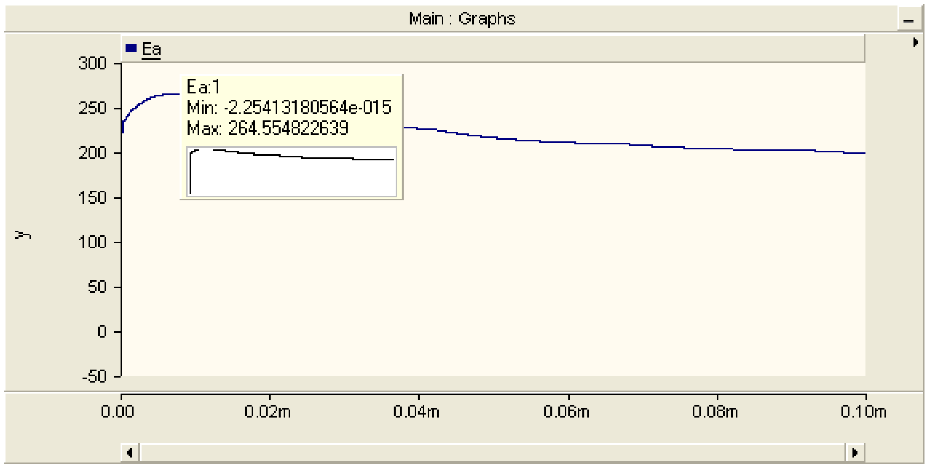

Figure 4.8 Pincetti model with 10 kA, 8/20 µs

iii. Residual voltage based on 20kA lightning current

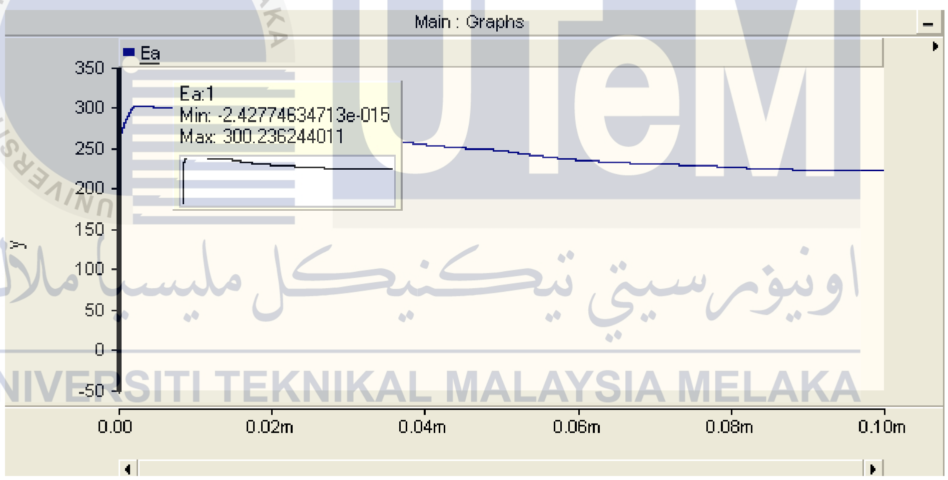

Figure 4.9 Pincetti model with 20 kA, 8/20 µs

Fernandez-Diaz model of Surge Arrester

i. Residual voltage based on 5kA lightning current

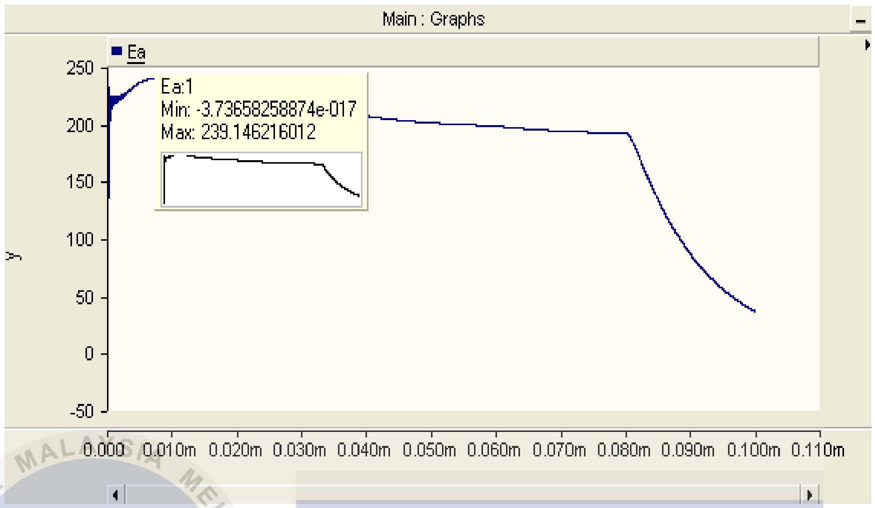

Figure 4.10 Fernandez Diaz model with 5 kA, 8/20 µs

ii. Residual voltage based on 10kA lightning current

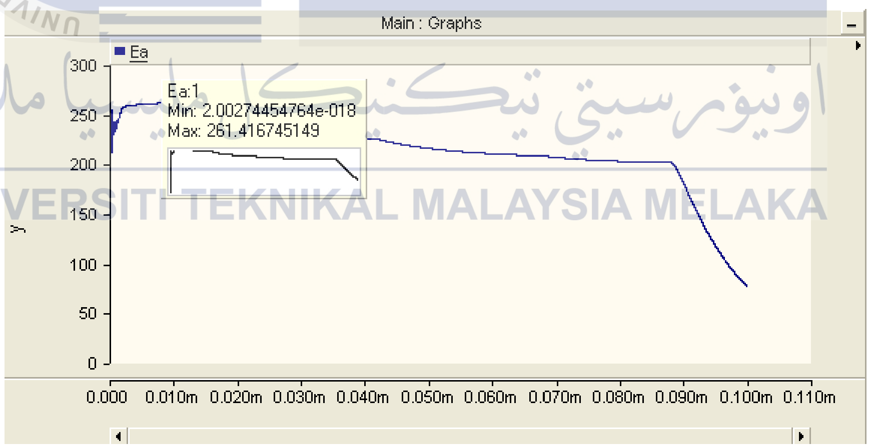

Figure 4.11 Fernandez Diaz model with 10 kA, 8/20 µs

iii. Residual voltage based on 20kA lightning current

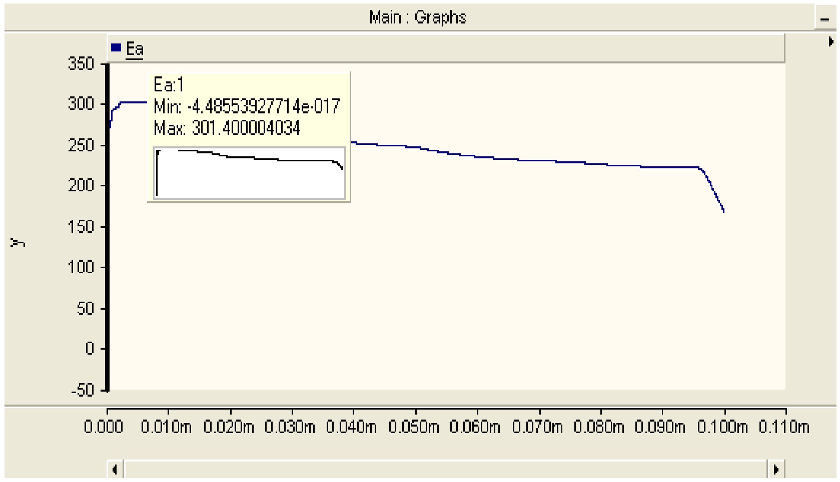

Figure 4.12 Fernandez Diaz model with 20 kA, 8/20 μs

Table 4.2 Residual Voltage of simulation based on ABB Manufacture Arrester Rating

I (kA)	Residual Voltage (kV)						
	Manufacturer Datasheet (kV)	IEEE model (kV)	Error (%)	Pincetti model (kV)	Error (%)	Fernandez Diaz model (kV)	Error (%)
5	260	244.95	-0.10	232.21	-10.7	239.15	-8.02
10	273	263.55	-2.50	263.55	-6.09	261.42	-4.24
20	299	300.49	0.50	300.44	0.415	301.40	0.80

Figure 4.5 to Figure 4.12 shows the characteristic of residual voltage for each surge arrester model when the 8/20us impulse current with the amplitude of 5kA, 10kA and 20kA has been injected to each model. The data of residual voltage value are recorded in the Table 4.2. The result show that the different manufacturer comes with different voltage arrester rating, this might due to the different type of material used in manufacturing their arrester product.

As according to IEC 60099-4 [11], the accuracy of the surge arrester can be determine in several way such as through the residual voltage, the front and tail time of current waveform and the front and tail time of voltage waveform. In this project, the residual voltage is used to determine the validation of the surge arrester model. It is stated that the closer the residual voltage to the standard waveform, the higher protection level of surge arrester. The acceptable range of the related between manufacturer data and simulation result is less than 6% [11].

Based on the Table 4.2, the percentage error for all models are within the acceptable range that is less than 6%. The Fernandez Diaz models have higher percentage of error compare to other model, this error indicates that Fernandez model have the worst performance of lightning performance between these three models. The Pincetti having slightly lower of percentage error for 5kA and 10kA of current impulse. The IEEE model having slightly higher percentage of error for 5kA, 10kA and 20kA of impulse current, this model considered has the best lightning protection compared to the Pincetti model and Fernandez Diaz model. This can be proved as the IEEE surge arrester model is more stable than others.

4.3.2 Toshiba Manufacture Data

The table shows the residual voltage for multiple range of current impulse of Toshiba Manufacture data. The arrester voltage rating that stated in Table 4.3 is for lightning level from the Equation (2.15).

Table 4.3 Residual Voltage and Arrester Voltage Rating of Toshiba Manufacture Data [13]

Lightning current impulse, 8/20μ (kA)	Manufacturer residual voltage (kV)	Arrester Voltage Rating (kV)
5	301	188.125
10	329	205.625
20	378	236.250

The Table 4.3 above shows the arrester voltage rating based on the Toshiba manufacturer residual voltage. Different value of residual voltage gives different value of arrester voltage rating since the surge arrester having its residual voltage at 1.6 per unit (crest value) [19]. These arrester rating are calculated by using Equation (2.15).

The following graph in Figure 4.13 to Figure 4.21 illustrate the result simulated based on the value from Table 4.1 above. The graphs in Figure 4.13 to Figure 4.15 show the result of the IEEE model of surge arrester when injected with magnitude of lightning current of 5kA, 10kA and 20kA respectively. For Figure 4.8 to Figure 4.9, the result was from Pincetti model of surge arrester and for Figure 4.10 to 4.12 the result was from Fernandez Diaz model of surge arrester

IEEE Frequency Dependant model of Surge Arrester

i. Residual voltage based on 5kA lightning current

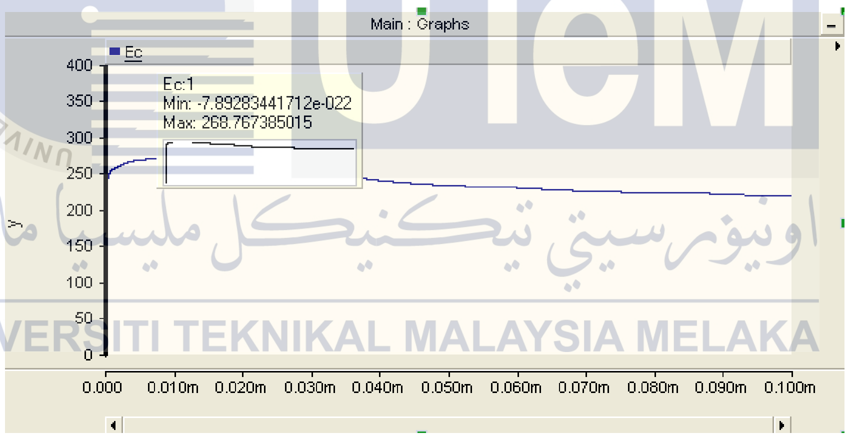

Figure 4.13 IEEE model with 5 kA, 8/20 µs

ii. Residual voltage based on 10kA lightning current

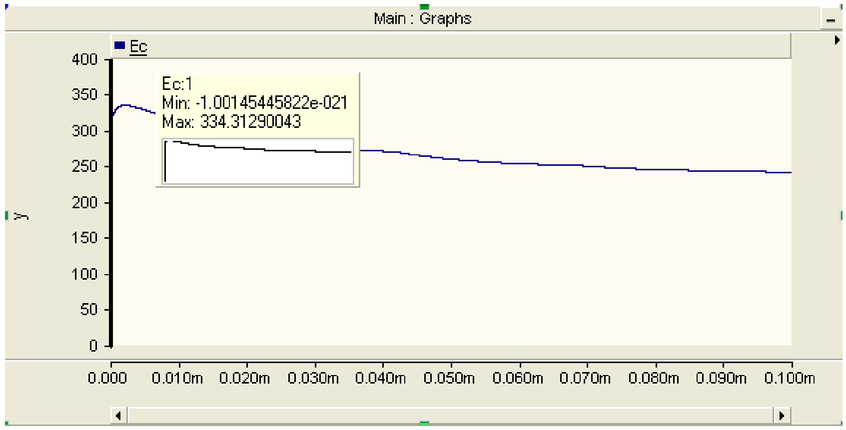

Figure 4.14 IEEE model with 10 kA, 8/20 µs

iii. Residual voltage based on 20kA lightning current

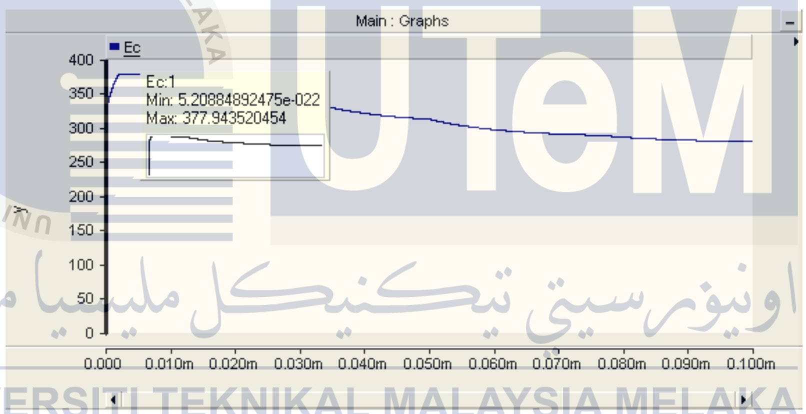

Figure 4.15 IEEE model with 20 kA, 8/20 µs

Pincetti model of Surge Arrester

i. Residual voltage based on 5kA lightning current

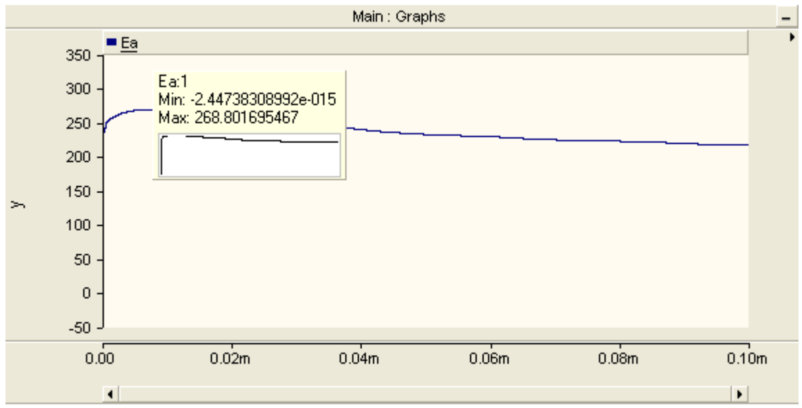

Figure 4.16 Pincetti model with 5 kA, 8/20 μs

ii. Residual voltage based on 10kA lightning current

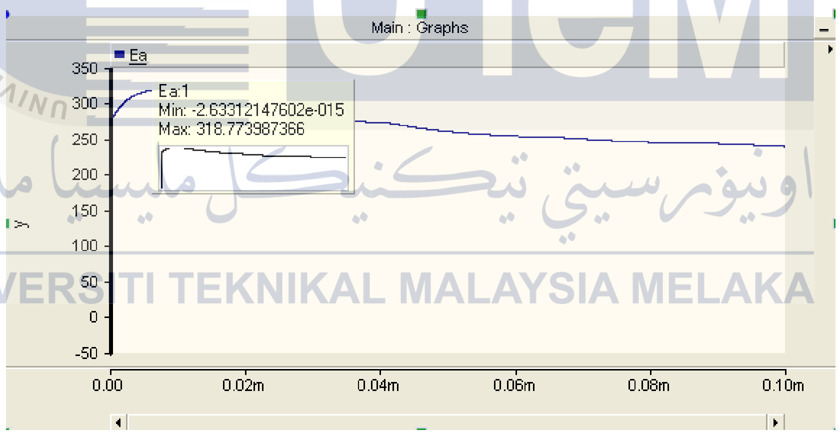

Figure 4.17 Pincetti model with 10 kA, 8/20 μs

iii. Residual voltage based on 20kA lightning current

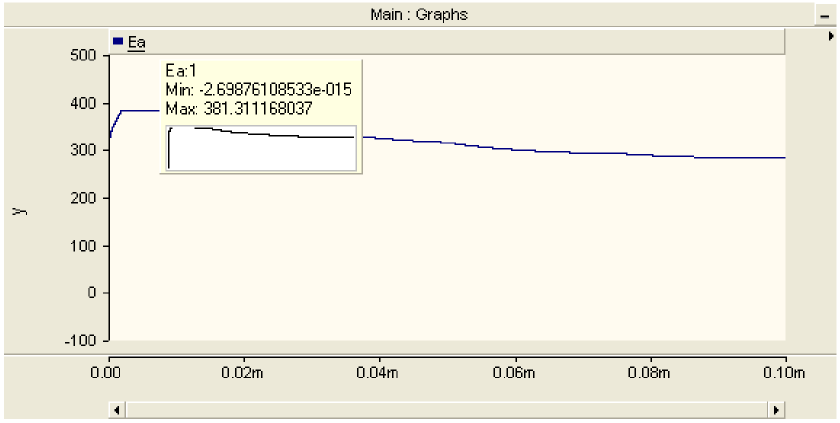

Figure 4.18 Pincetti model with 20 kA, 8/20 µs

Fernandez-Diaz model of Surge Arrester

i. Residual voltage based on 5kA lightning current

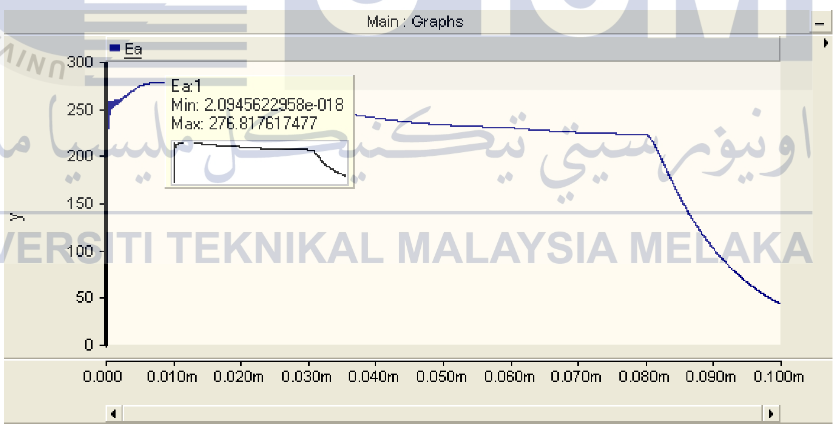

Figure 4.19 Fernandez - Diaz model with 5 kA, 8/20 µs

ii. Residual voltage based on 10kA lightning current

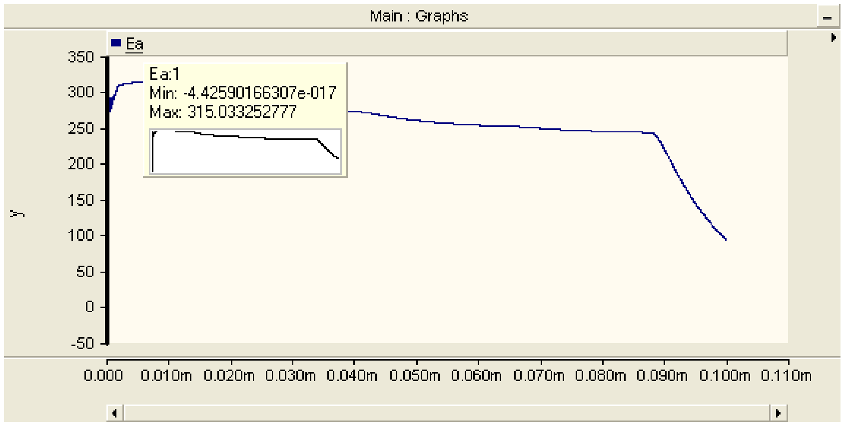

Figure 4.20 Fernandez - Diaz model with 10 kA, 8/20 µs

iii. Residual voltage based on 20kA lightning current

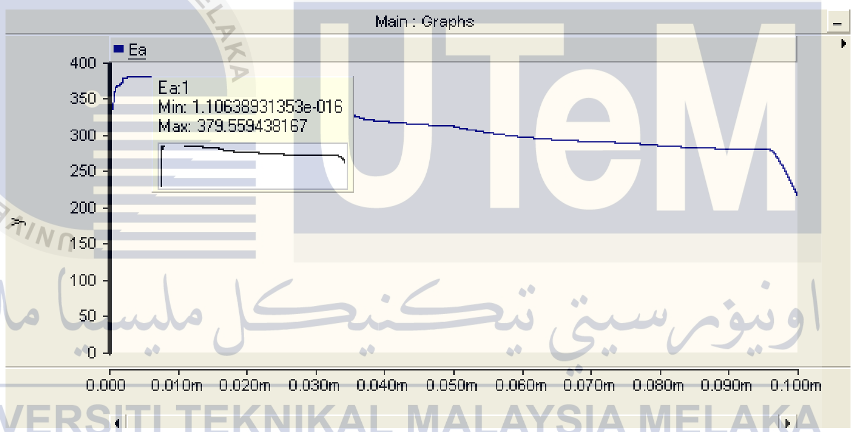

Figure 4.21 Fernandez - Diaz model with 20 kA, 8/20 µs

Table 4.4 Residual Voltage of simulation based on Toshiba Manufacture Arrester Rating

I (kA)	Residual Voltage (kV)						
	Manufacturer Datasheet (kV)	IEEE model (kV)	Error (%)	Pincetti model (kV)	Error (%)	Fernandez Diaz model (kV)	Error (%)
5	301	268.80	-9.30	268.81	-10.71	276.82	-8.02
10	329	344.41	1.60	318.77	-5.11	315.03	-4.24
20	378	377.61	0.02	381.31	0.876	379.56	0.41

Figure 4.13 to Figure 4.21 shows the characteristic of residual voltage for each surge arrester model when the 8/20us impulse current with the amplitude of 5kA, 10kA and 20kA has been injected to each model. The data of residual voltage value are recorded in the Table 4.4. The result show that the different manufacturer comes with different voltage arrester rating, this also might due to the different type of material used in manufacturing their arrester product as mention above.

Based on the Table 4.4, the percentage error for all models are within the acceptable range that is less than 6%. The Fernandez Diaz models have higher percentage of error compare to other model, this error indicates that Fernandez model have the worst performance of lightning performance between these three models. The Fernandez model considered as unstable since it does not compose with the resistor. The internal resistor that exists in the inductor and capacitor was unable to discharge on very high current impulse. This also caused some spark due to the high temperature. The Pincetti having slightly lower of percentage error for 5kA and 10kA of current impulse. This also might due to elimination of capacitor as function to smooth down the discharge process. Thus, this characteristic shows that the Fernandez Diaz model does no stable as IEEE model and Pincetti model.

The IEEE model having slightly higher percentage of error for 10kA of impulse current, this model considered has the best lightning protection compared to the Pincetti model and Fernandez Diaz model. This might due to the existence of resistor that functions to withstand high temperature and thus make it more stable and reliable.

Based on the explanation above, the IEEE model was selected to implement to the transmission line in order to investigate the performance of shielding failure. Based on the result shows that different manufacturer does not affect much in term of performance. The differences of arrester residual voltage value only due to different type of material used by the manufacturer.

4.4 Evaluation on Shielding Failure on 132kV Transmission Line

Eleven (11) of 132kV overhead transmission towers were modelled as single conductor distributed parameter line (Bergeron model travelling wave) as shown in Figure 4.21 below. It is to ensure that the propagation of travelling waves distributed along the tower is equal to the light velocity [26]. The direct lightning strokes to the tower #6 are analysed.

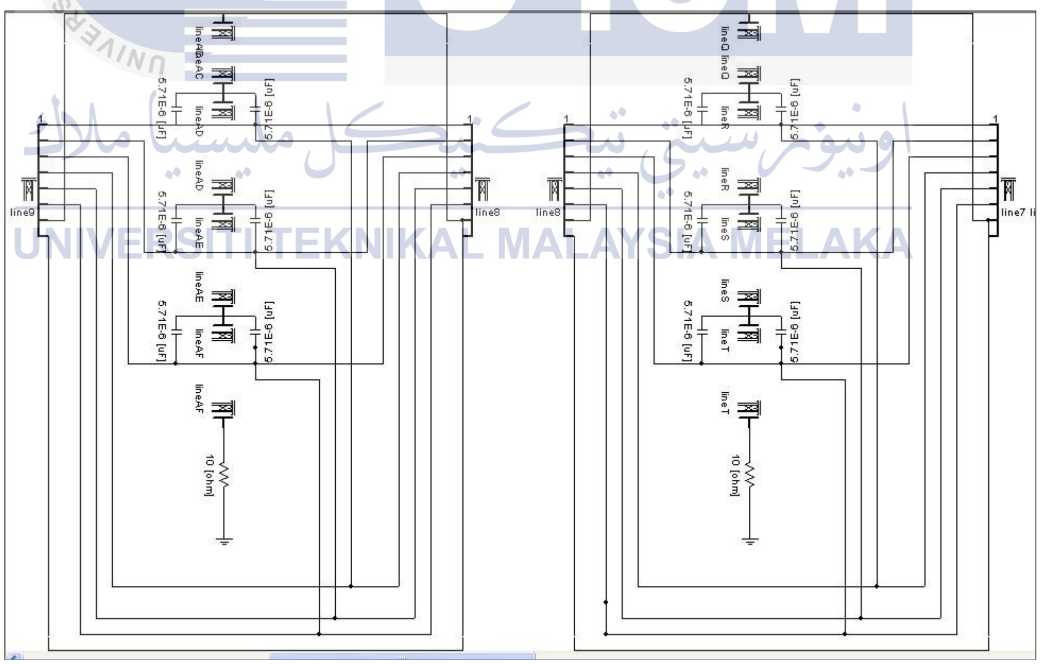

Figure 4.22 Transmission line model in PSCAD

Figure 4.23 and Figure 4.24 shows the given lightning surge was at the Phase A at the transmission line were used to investigate the phenomena of shielding failure.

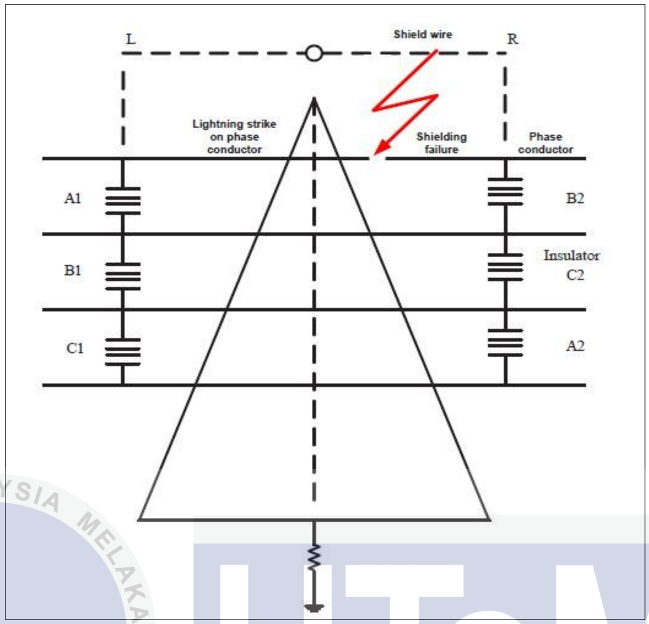

Figure 4.23 Lightning strikes on a phase conductor.

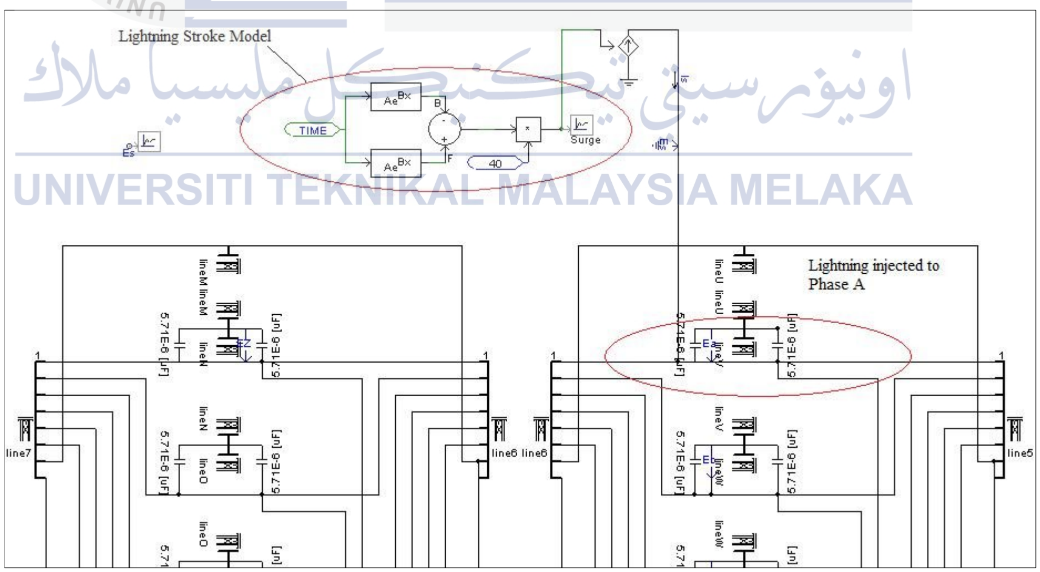

Figure 4.24 Lightning strikes on a phase conductor at Phase A.

As the purpose of study, a peak current source of different magnitudes was selected to investigate the effect in shielding failure phenomena. As the lightning surge studied based on the behaviour of lightning occurred in Malaysia, the range stroke current of shielding failure is between 5kA to 20kA. For over than 50% of lightning stroke are happens at more than one stroke, this also known as multiple stroke lightning (MSL) [22]. However, in this particular study, single stroke lightning (SSL) current magnitude was only considered. For this simulation, three level of lightning strike to investigating the effect of transmission line performance: 5kA, 10kA, and 20kA.

The transmission shielding failures were simulated by injected single stroke current to the line phase of the sixth tower. This simulation based on the time to rise t_r and time to half, t_f chosen as 8/20us. The 8/20 current wave shape is used because it develops a voltage across the arrester similar to a lightning surge [27].

For the simulation, shielding failure voltage across insulator string was measured at each phase, for single-circuit line, by using probe voltage. As has been explained, flashover occurs when voltage across the insulator string is equal or greater than Critical Flashover Voltage (CFO), which is determined from Basic Insulation Level (BIL). According to ANSI C92 IEEE1313.1, the suggested BIL for 132kV nominal voltage is 650kV, so, with this BIL value the CFO is approximately 650kV; this value will be used throughout the analysis [23].

a. Injected lightning surge, 5kA

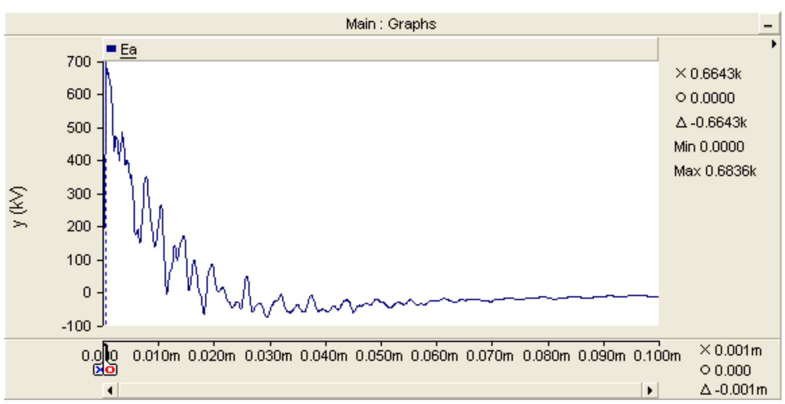

Figure 4.25 Voltage across insulator string of Phase A with 5kA, 8/20us lightning impulse

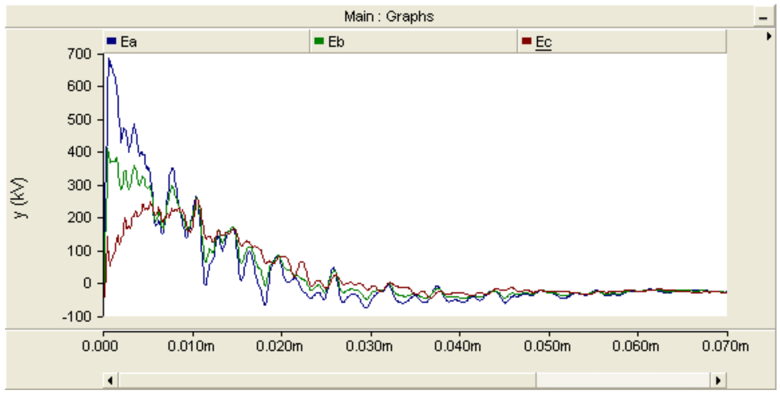

Figure 4.26 Voltage across insulator string of Phase A, B and C with 5kA, 8/20us lightning impulse

Based on the Figure 4.25 and Figure 4.26 , the waveform indicated that the flashover across the insulator string only occurs at the upper phase (Phase A) and does not affect the middle phase (Phase B) and also to the lower phase (Phase C). The voltage across the insulator string exceeded the standard value for flashover voltage (650kV) for nominal voltage of 132kV.

b. Injected lightning surge, 10kA

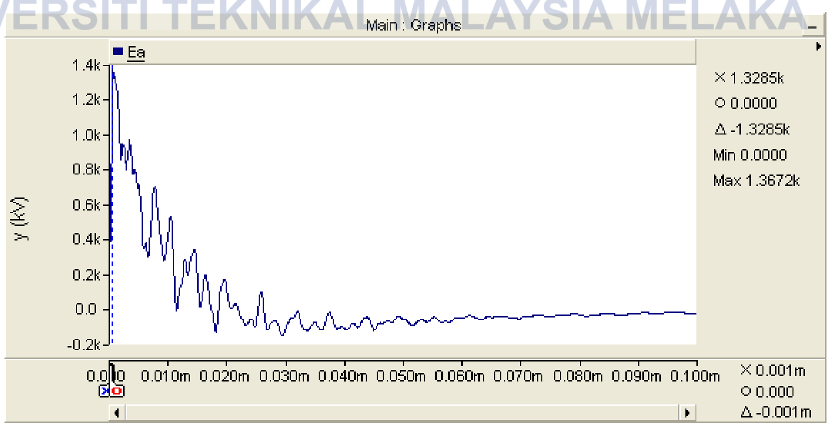

Figure 4.27 Voltage across insulator string of Phase A with 10kA, 8/20us lightning impulse

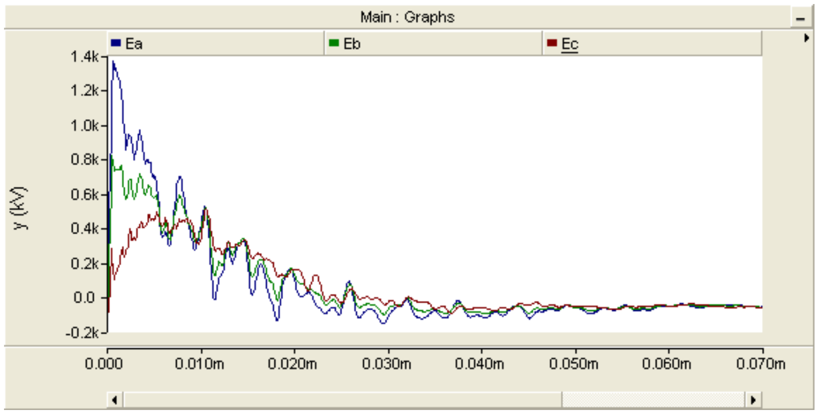

Figure 4.28 Voltage across insulator string of Phase A, B and C with 10kA, 8/20us lightning impulse

As referred to the Figure 4.27 and Figure 4.28, the waveform indicated that the flashover across the insulator string occurs at the upper phase (Phase A) and also the middle phase (Phase B) and does not affect to the lower phase (Phase C) as the voltage at lower phase does not exceed the minimum value of CFO. The voltage across the insulator string at Phase A and Phase B exceeded the standard value for flashover voltage (650kV) for nominal voltage of 132kV.

c. Injected lightning surge, 20kA

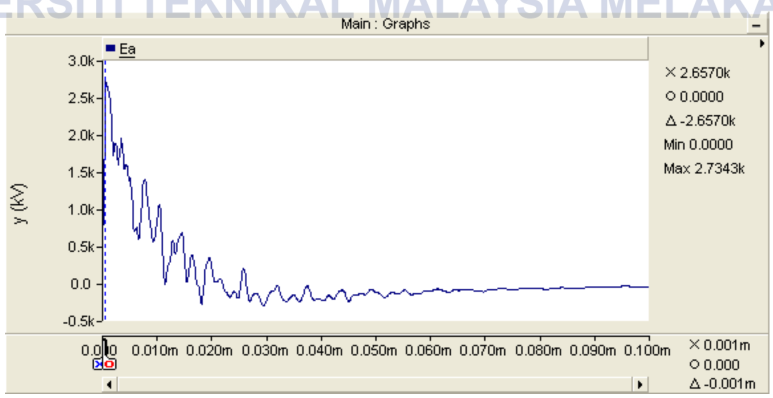

Figure 4.29 Voltage across insulator string of Phase A with 20kA, 8/20us lightning impulse

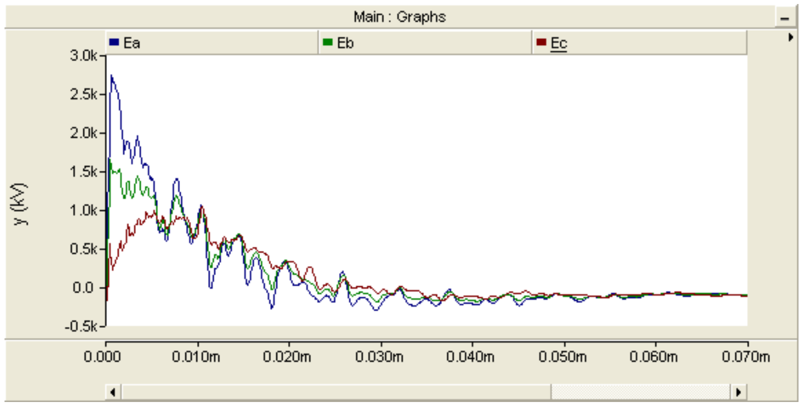

Figure 4.30 Voltage across insulator string of Phase A, B and C with 20kA, 8/20us lightning impulse

For the highest current injected in the simulation, the output had produces the flashover across the insulator string to the all three phases of the tower. Figure 4.30 show that all the phases are exceeding the discussed value of standard CFO.

The result above can be summarised in the Table 4.5 below:-

Table 4.5 Evaluation of Shielding Failure on Transmission Tower

Phase	5kA		10kA		20kA	
	Residual Voltage (kV)	Flashover	Residual Voltage (kV)	Flashover	Residual Voltage (kV)	Flashover
A	684.10	Yes	1368.95	Yes	2737.49	Yes
B	411.87	No	823.64	Yes	1645.86	Yes
C	246.46	No	429.91	No	1026.46	Yes

Based on the result above, the voltage across insulation string waveform develops when the transmission line injected with the lightning stroke at the phase conductor. Based on Figure 4.25 to Figure 4.30, obviously, the flashover across the insulator string occurs at the Phase A since the overvoltage has exceeded the critical flashover voltage of insulator string for nominal voltage of 132kV which is 650kV. The subsequent of the phase also affected with the flashover for injecting current for more than 5kA as the flashover had occurred to the upper phase (Phase A) and the middle phase (Phase B) when the phase conductor are injected with 10kA lightning impulse current. For lightning impulse current higher 20kA, the flashover occurred to the all of three phases.

4.5 Shielding Failure Analysis with IEEE Surge Arrester Implementation

In this part, the line surge arrester is installed to transmission line in the way to improve their line overhead lines and thus reduce the risk of the shielding failure phenomena. The surge arrester are installed parallel with the insulator string with the injected of lightning surge. Figure 4.31 shows the surge arrester are installed at the Phase A at the transmission line were used to investigate the phenomena of shielding failure.

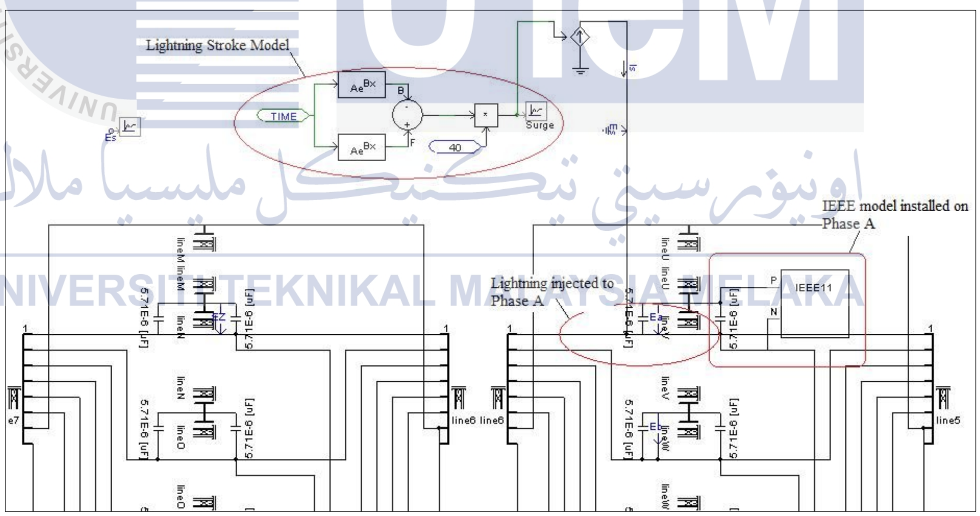

Figure 4.31 Lightning strikes on a phase conductor at Phase A with IEEE surge arrester.

Figure 4.32 to Figure 4.35 shows the result of installation of surge arrester on Phase A with 5kA and 10kA of lightning impulse current. For the impulse current of 20kA, the surge arresters are installed to all of three phases. The result and analysis from the graph are summarised in Table 4.6.

a. IEEE frequency dependant model, 5kA

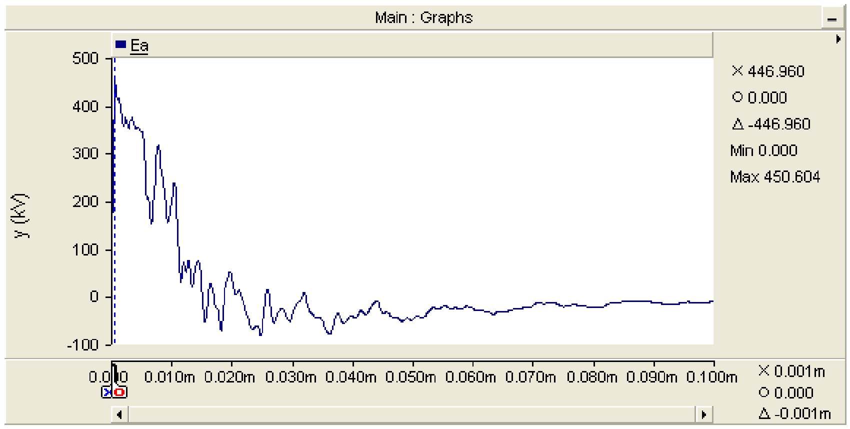

Figure 4.32 Voltage across insulator at Phase A

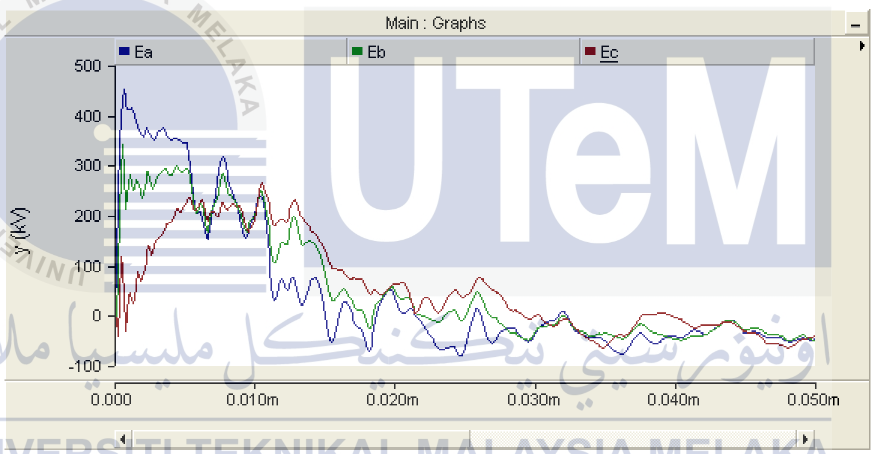

Figure 4.33 Voltage across insulator at Phase A, B and C

b. IEEE frequency dependant model,10kA

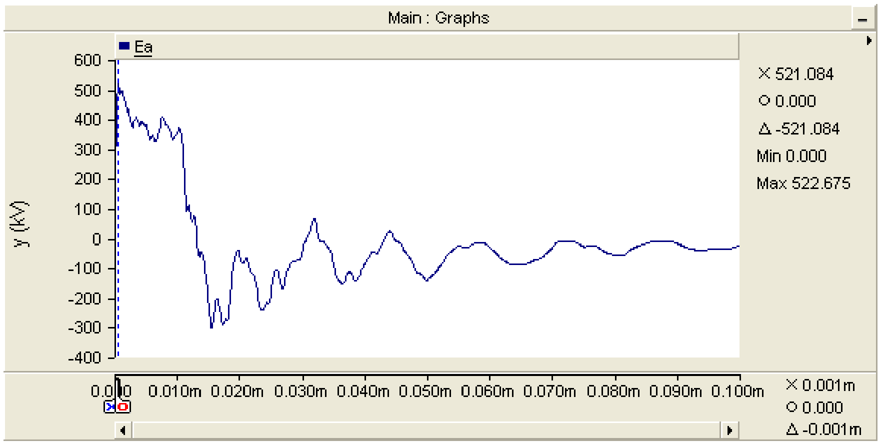

Figure 4.34 Voltage across insulator at Phase A

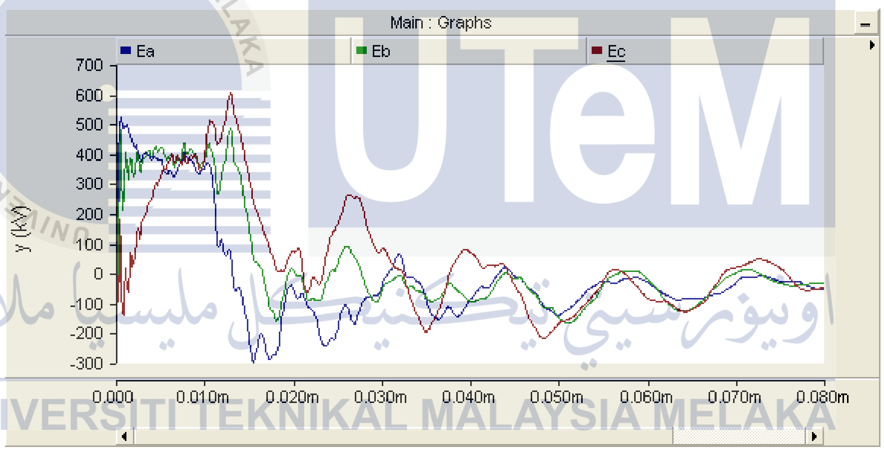

Figure 4.35 Voltage across insulator at Phase A, B and C

c. IEEE frequency dependant model, 20kA

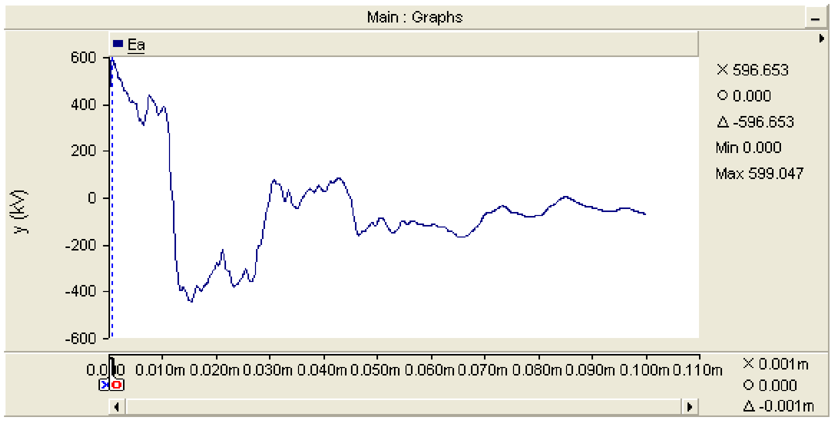

Figure 4.36 Voltage across insulator at Phase A

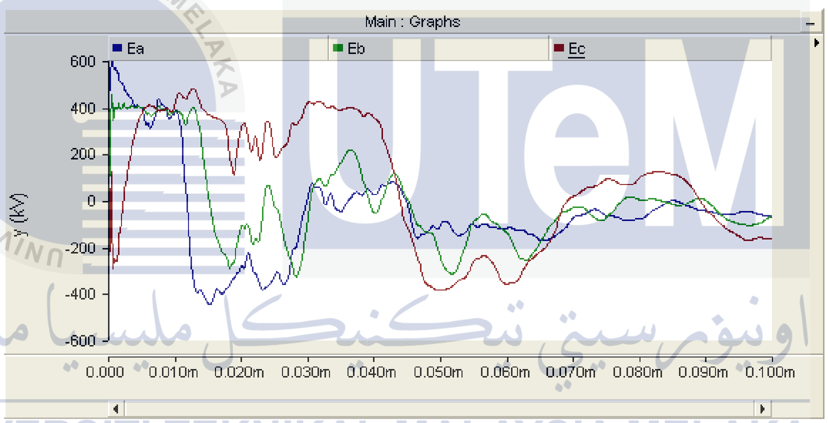

Figure 4.37 Voltage across insulator at Phase A, B and C

The result above can be summarised in the Table 4.5 below:-

Table 4.6 Evaluation of Shielding Failure on Transmission Tower with Surge Arrester installed

Phase	5kA		10kA		20kA	
	Residual Voltage (kV)	Flashover	Residual Voltage (kV)	Flashover	Residual Voltage (kV)	Flashover
A	450.66	No	522.67	No	599.05	No
B	340.46	No	485.22	No	454.30	No
C	263.24	No	603.61	No	477.15	No

The result shows when the surge arresters are installed parallel with the insulator string, there is no flashover occurs and seems like the phases conductor protected by the surge arrester completely from lightning. Based on the waveform in Figure 4.32 to Figure 4.35, the Phase A which injected with the5kA and 10kA lightning current impulse are protected from the flashover after the installation of surge arrester. The following phases which are the middle phase (Phase B) and the lower phase (Phase C) also protected by the surge arrester from flashover. The three different magnitude of lightning current does not influence the surge arrester capabilities since its does not reach to the CFO value.

However for the lightning impulse more than 20kA, the installation of surge arrester to all of three phases are needed in order to protect the transmission line from flashover since the surge arrester as installed only in Phase A could not protect the subsequence phases, middle phase (Phase B) and lower phase (Phase C). The waveform from the Figure 4.36 and Figure 4.37 shows the phases are completely protected after installation of IEEE surge arrester to all three phases as the voltage across the insulator string does not exceed the CFO value.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

As the conclusion, it is observed that flashover would occur on an insulator string when a lightning strikes a conductor where an insulator is installed. Improvement can be achieved by installing arrester on the phase or phases where the lightning is expected to strike. This study assumed that the top conductor susceptible to lightning strikes is the main reason why much focus is on the top conductor.

This project presented the result of a study whose main goal was to model the various type surge arrester for 132kV overhead transmission line. The surge arrester model from IEEE frequency dependant, Pincetti, Fernandez are simulated and compared to two different manufacturers. The comparison stated that both manufacturer give significant result for these three surge arrester model in terms of residual voltage. For this project, the IEEE surge arrester model to be chosen for implementation in 132kV overhead transmission line system for shielding failure analysis. The installation of surge arrester at the upper phase (Phase A) of the transmission line causes no flashover at the insulator string for impulse current between 5kA and 10kA. However for 20kA, in order to protect the line from flashover, the surge arrester was installed to all of three phases

The result shows the shielding failures tend to occur for lightning current between 5kA up to 200kA. After the installation of IEEE surge arrester model parallel to the insulator string, the line performances are improved compared to the absence of the arrester. Thus, the transmission line is fully protected from the lightning strike. It is also stated clearly that the suggested alternatives in this study do not always give the best performance but it should be noted that the improvement of the transmission line performances does not alone guarantee a complete protection.

5.2 Recommendations

The importance effect about line surge arrester can be expected in future are:

1. The comparison between surge arrester can be made by developing surge arrester using different types of simulation software such as EMTP/ATP.

2. Study on characteristic of surge arrester that will consider other current impulse wave shape and multiple strokes lightning (MSL).

3. The application of line surge arrester will be explore to increase their reliability in terms of protecting transmission system and other electrical equipment. This can be realise by developing software to compare between the simulation result and the manufacturer as suggestion to determine the optimal number, location and the rating of the line surge arrester.

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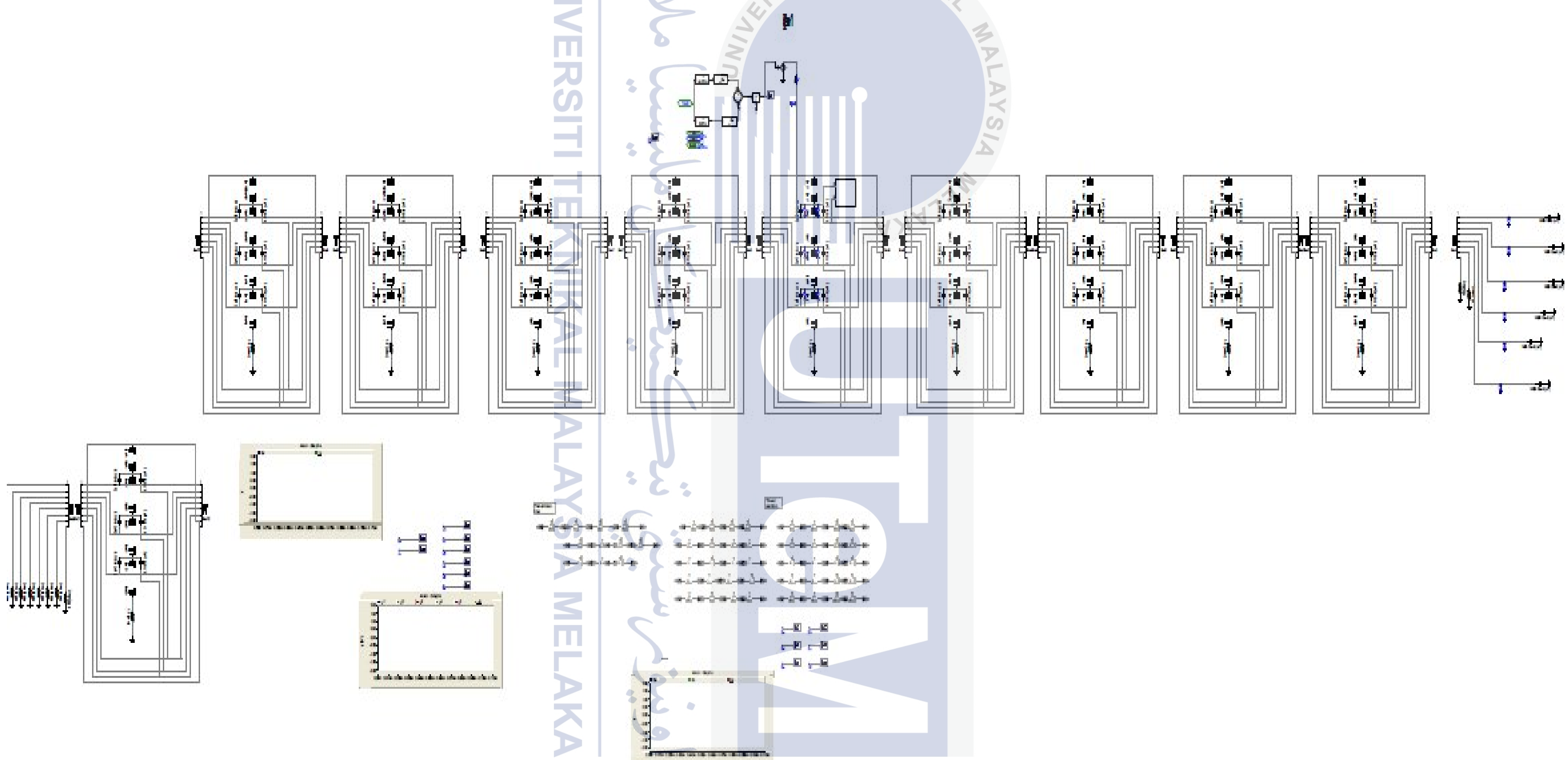
Appendix A



Appendix B

Semester	FYP I														FYP II														
Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Study about Lightning characteristics																													
Study the characteristics of Transmission Line System																													
Study on Surge Arrester																													
Modelling of 132kV Transmission Line																													
Writing report for FYP I																													
Presentation of FYP I																													
Modelling each of surge arrester, IEEE model, Pincetti model and Fernandez Diaz model																													
Implementation of Surge Arrester to 132kV Transmission Line																													
Writing the report for FYP II																													
Presentation of FYP II																													