Modelling of 132kV Overhead Transmission Lines by Using ATP/EMTP for Shielding Failure Pattern Recognition

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Abstract

Lightning overvoltage is the major cause of the transmission line interruption in Malaysia. It is the main reason that endangers the safety and reliability of transmission line system. The phenomenon is a dominant factor considered in designing substations and transmission-line insulation, therefore its investigation is important. This work modelled a 132kV overhead transmission line for shielding failure pattern recognition by using ATP-EMTP software, as they are vital to the evaluation of lightning performance. The modelled transmission-line is divided into few parts: wires (shield wires and phase conductors), towers, cross-arms, insulator strings, tower-surge impedance and tower-footing resistance. The developed model is simulated with four different magnitudes of lightning-strike current on each phase conductor in order to investigate the shielding failure voltage pattern across the line insulation in the transmission line system. When the lightning-strike current is injected from upper phase to lower phase conductor, the magnitude of the maximum induced voltage across the insulator string at those phases has been decreased. On the other hand, as the magnitude of the lightning-strike current has been increased, the magnitude of the maximum induced voltage across the insulator string at each phase will be increased. Flashover occurs when the voltage induced across the insulator string at each phase is equal or exceeds the CFO voltage. These analyses have been done based on the waveforms obtained from the simulations on developed model.

Keywords: Lightning overvoltage; shielding failure; phase conductor; lightning-strike current.

1. Introduction

Lightning-overvoltage behavior is important to be studied to designing insulation of electric power system. This is because insulation design of power equipment is based on frequent occurrence of a specific event, distribution of the overvoltage probability corresponding to the event and to failure probability of the insulation [1]. Thus, the lightning overvoltage is a significant factor for the protection of power plant and substation equipment [2].

Lightning might strike on shield wire or phase conductors. Strikes at phase conductor may result to shielding failure whereas strikes at transmission tower or shield wire may result to back flashover. When lightning strike current directly hit on the phase conductor, a high voltage will be developed across the insulator string of that phase conductor. If the voltage equals or exceeds the line’s critical flashover voltage (CFO), flashover occurs, known as shielding failure. This paper focuses on shielding failure studies as they are important to the evaluation of lightning performance.

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Lightning-overvoltage is a main concern for 132kV/275kV transmission line systems in Malaysia. Since, observation of lightning-overvoltage in an experiment method is difficult, numerical simulation such as modelling of the overhead transmission-line by using appropriate software is the best approach. ATP-EMTP software is one of the commonly used tools for modelling transmission-line systems. Nowadays, many researchers use ATP-EMTP software widely in power system transient analysis studies. In this paper, the model was developed by using ATP-EMTP software. Four different magnitudes of lightning currents were injected into each phase conductor of the transmission line system, to study the shielding failure voltage pattern at each phase.

2. Transmission Line Model

This paper modelled a 132kV double circuit with two overhead ground wire transmission towers. Phase conductors and ground wire are explicitly modelled between the towers where seven tower spans were used. Line termination at each side of the model was to avoid any reflection that might affect the simulated over-voltages around the point of impact [4]. This has been done by terminating the phase conductor with AC operation voltages, and by grounding the shield wire. Fig.1 shows the span of seven towers with line termination at each side of the model.

![Fig. 1. Span of seven towers](image)

2.1 Transmission Line System

The transmission line represented by means of several multi-phase un-transposed distributed-parameter line spans on both sides of impact point. The representation can be obtained by using either a frequency-dependent, or a constant-parameter, model [4]. There are few models that can be used for transmission-line system in ATP-EMTP software:

1) Bergeron: constant-parameter K.C. Lee or Clark models
2) PI: nominal PI-equivalent (short lines)
3) J. Marti: Frequency-dependent model with constant transformation matrix
4) Noda: frequency-dependent model
5) Semlyen: frequency-dependent simple fitted model.

Bergeron model, the PI model, and the J. Marti model are the most usually used transmission line and tower models. This work used the Bergeron model to represent overhead transmission lines and cables as Malaysian’s transmission line is more suitable to be modelled using Bergeron model.

The Bergeron model is a very simple model. It based on distributed LC-parameter travelling wave line model with lumped resistance. This time-domain Bergeron model is commonly used in power system transient fault analyses [5]. It represents in distributed manner, the L and the C elements of a PI section.

The Bergeron Model has a lossless distributed parameters’ line as described by the following two values:

\[
\text{Surge Impedance, } Z_s = \frac{L}{\sqrt{C}}
\]

\[
\text{Phase Velocity, } v = \frac{1}{\sqrt{LC}}
\]

Bergeron model accurately represents only fundamental frequency (50Hz) similar to PI sections model.; therefore the surge impedance is constant. It also represents impedances at other frequencies, as long as the losses do not change. Fig.2 shows tower configuration of 132kV transmission line system in Malaysia.
2.2 Transmission Tower

In recent years, there are various models of transmission tower proposed by the researchers. One of the more well-known models is the multistory model designed by Masaru Ishii [6]. A multistory tower model basically is composed of distributed parameter lines with parallel RL circuits and has been recommended by the Japanese Guideline of insulation design/coordination against lightning [2]. This model is widely used for lightning-surge analysis in Japan. Fig.3 shows the multistory tower model.

However, the design of the multistory tower model was based on 500kV transmission line. Thus, multistory tower model is not relevant to Malaysia’s lower-voltage transmission line system (such as 132kV and 275kV). Based on the investigation done by [2], a simple distributed line model is adequate to represent a low-voltage transmission line system model in ATP-EMTP software. Therefore, this model will be used to design the transmission tower in this work. A cross-arms model and an insulator-strings model need to be included to represent a real transmission tower. Fig.4 shows a simple distributed line model without cross-arms and insulator strings.
2.3 Cross Arms

In Malaysia, most cross-arms for 132kV and 275kV transmission lines are made of hard wood (especially the Chengal species). Usually, cross-arms are used as transmission-line supports for 132kV and 275kV towers [7].

In ATP- EMTP software, transmission-line system cross-arms are represented by distributed constant lines branched at junction point, their surge impedance given by:

\[
Z_{AK} = 60 \ln \left( \frac{2h}{r_A} \right)
\]

where \( h \) is height of the cross-arms, m
\( r_A \) is radius of the cross-arms, m

According to research investigations, eq. 3 proves applicable to cylindrical arms and to scale-model arms when equivalent radius is chosen as \( \frac{1}{4} \) of arms’ width at junction point [8].

2.4 Line-Insulator Flashover

The traditional model for insulator flashover uses measured volt-time curve specifically determined for a gap or insulator string that has the standard 1.2/50 \( \mu \)s wave shape. However, as insulator string is subject to non-standard impulse wave shapes, empirical volt-time curves bear little resemblance to physical breakdown process. Thus, a better line-insulation model is leader progression model [9].

2.5 Leader Progression Model

Leader progression model is the best model for designing insulator strings in transmission line. It can be used for non-standard lightning voltages [10]. According to it, the flashover mechanism comprises three steps which are corona inception, streamer propagation, and leader propagation. Streamers propagate along insulator string when applied voltage exceeds corona inception voltage. If this voltage remains very high, the streamers become leader channel. When the leader crosses the gap between cross-arm and conductor, a flashover occurs. Time-to-flashover total can thus be expressed as:

\[
t_f = t_c + t_s + t_l
\]

where \( t_i \) is corona inception time, \( \mu \)s
\( t_s \) is streamer propagation time, \( \mu \)s
\( t_l \) is leader propagation time, \( \mu \)s
\( t_c \) is neglected, as it is very short compared with the other two times.
According to [4], \( t_s \) can be calculated as follows:

\[
    t_s = \frac{E_{50}}{1.25E - 0.95E_{50}}
\]  

(5)

where \( E_{50} \) is average gradient at critical flashover-voltage

\( E \) is maximum gradient in the gap before breakdown.

Leader propagation time, \( t_l \) can be obtained from the following equation:

\[
    \frac{dl}{dt} = K_l V(t) \left[ \frac{v(t)}{g - 1} - E_{10} \right]
\]  

(6)

where \( V(t) \) is voltage across gap, kV

\( g \) is gap length, m

\( l \) is leader length, m

\( E_{10} \) is critical leader-inception gradient, kV/m

\( K_l \) is leader coefficient.

Leader propagation stops if gradient in un-bridged part of the gap falls below \( E_{10} \).

2.6 Lightning Source

Impulse-current magnitude due to lightning charge is a probability function. Low (about 5-22 kA) discharge levels of lightning current may increase the tendency for lightning-strike to pass by shield wires (ground wires), instead striking a phase-conductor. Lightning impulse currents of large magnitudes will strike a tower top or overhead ground wire, causing back flashover across insulator string [11].

In ATP- EMTP software, lightning-strike model is represented by a current source with parallel resistance. The parallel resistance is actually lightning-path impedance. The model used in this study is the Heidler current model, where four characteristics of lightning current quantities at striking point must be considered: lightning-current peak, maximum of current-steepness, rise time, and decay time [12]. Fig.5 shows the Heidler model in ATP- EMTP. Fig.6 below shows the lightning-strike waveform for the Heidler model.
Heidler’s function that represents lightning-current waveform is [13]:

\[ i(t) = \frac{I_0}{\eta} \left[ \frac{t}{\tau_1} \right]^n \left[ \frac{t}{\tau_2} \right] e^{-t/\eta} \]  \tag{7}

where

\[ \eta = e^{\left[ \frac{\tau_1}{\tau_2} \right] q t / n} \]  \tag{8}

and

- \( I_0 \): lightning current peak,
- \( \tau_1 \): time constant determining current rise-time;
- \( \tau_2 \): time constant determining current decay-time;
- \( n \): current steepness factor

2.7 Tower Surge-Impedance

In this work, surge impedance was determined from surge-impedance formula for cylindrical tower. M.A. Sargent and M. Darveniza [14] stated that surge impedance of a cylindrical tower varies with waveshape of the current impressed. Tower surge impedance for a cylindrical tower is approximated by:

\[ Z = 60 \ln \left[ \sqrt{2} \left( \frac{2h}{r} \right) - 1 \right] \]  \tag{9}

where \( h \) is tower height and \( r \) the tower radius. Eq. 9, however, is an approximation, as surge impedance is a time-varying quantity.

2.8 Tower- Footing Resistance

An accurate footing-impedance model is important for decreased resistance value when discharge current value increases. Resistance value is agreed to be greater when lightning currents are small. Its variation to low current and low frequency values is only significant for large soil resistivities [4]. A footing-impedance model incorporating soil ionization effect can be approximated as follows:

\[ R_f = \frac{R_o}{\sqrt{1 + \left( \frac{I}{I_g} \right)^2}} \]  \tag{10}

where \( R_o \) is footing resistance at low current and low frequency, \( I_g \) the limiting current to initiate sufficient soil ionization, and \( I \) the strike current through resistance. The limiting current is given by

\[ I_g = \frac{E_0 \rho}{2 \pi R_o^2} \]  \tag{11}

where \( \rho \) is soil resistivity (ohm-m), and \( E_0 \) is soil ionization gradient (400kV/m).

3. Simulations Results

The modelled 132kV overhead transmission line with seven towers was used for lightning-surge simulation. The towers were modelled in Simple Distributed Line Model.

In this study, four amplitudes of lightning current (positive polarity) were used to perform shielding failure pattern analysis on the modelled circuit. The simulation is based basically on lightning behavior in Malaysia, which has an average 34.5kA lightning-strike current. Minimum lightning-strike current is 20kA. The typical values of lightning-strike current
obtained in Malaysia are 50kA and 100kA. Simulations are thus conducted with 4 levels of lightning-strike current: 20kA, 34.5kA, 50kA and 100kA.

For the simulation, lightning-surge current was injected into each phase conductors of the fourth tower (middle tower). Shielding failure voltage across insulator string was measured at each phase, by using probe branch voltage. Flashover occurs when voltage across line insulation is equal to or greater than Critical Flashover Voltage (CFO), which is determined from Basic Insulation Level (BIL) calculated via the equation below [3]:

$$BIL = CFO \left(1 - 1.28 \frac{\sigma_f}{CFO}\right)$$

where $\sigma_f$ is coefficient of the variation, known as sigma. For lightning, the sigma is 2% to 3% [3]. According to ANSI C92 IEEE1313.1 [15], the suggested BIL for 150kV is 650kV, so, with this BIL value and 2% sigma, the CFO is approximately 650kV; this value will be used throughout the analysis. Table 1 gives lightning-current amplitudes, front times, and tail times, of the lightning waveform used in the analysis.

| Lightning Current Amplitude | Front Time and Tail Time |
|-----------------------------|-------------------------|
| 20kA                        | 1/30.2 $\mu$s           |
| 34.5kA                      | 1/30.2 $\mu$s           |
| 50kA                        | 1.2/50 $\mu$s           |
| 100kA                       | 2/77.5 $\mu$s           |

Fig. 7 to Fig. 9 show amplitudes of induced voltage across insulator strings when lightning-strike current of 34.5kA is injected into each phase conductor of the fourth transmission-tower.
According to Fig.7, when the lightning-strike current is injected in the upper phase conductor, the maximum voltage induced across the insulator string is observed in the upper phase, followed by middle phase and finally lower phase. According to the CFO determined for this analysis (650kV), voltage at the upper phase, middle phase and lower phase exceeds 650kV; flashover thus occurred in all these phases. This phenomenon is known as Shielding Failure. Fig.8 shows the maximum voltage induced across the insulator string is observed in the middle phase, followed by upper phase and
finally lower phase when the lightning-strike current is injected in the middle phase conductor. Since the voltage at these phases is greater than the CFO voltage, flashover occurred in all these phases. On the other hand, Fig.9 shows maximum induced voltage across insulator string in the lower phase followed by middle phase and finally upper phase when the lightning-strike current is injected in lower phase conductor. Same as previous, flashover occurred in all these three phases since the voltage induced is greater than the CFO voltage.

The similar pattern of waveform obtained when 20kA, 50kA and 100kA lightning-strike currents were injected into the each phase conductor of the fourth transmission tower. Table 2 illustrates the results obtained for 20kA, 50kA and 100kA lightning-strike currents. However, when the lightning-strike current of 20kA injected in the upper phase conductor, flashover only occurred in the upper and middle phase only. In general, it is observed that as the lightning-strike current is injected from upper phase to lower phase conductor, the magnitude of the maximum induced voltage across the insulator string at those phases has been decreased. However, the magnitude of the maximum induced voltage across the insulator string at each phase has been increased as the magnitude of the lightning-strike current will be increased. This can be proven by referring Fig.10 to Fig.12. The analyses were done with the standard 132kV tower-footing resistance of 10Ω.

Table 2. Flashover Phases And Tripping Sequence For 20ka, 50ka And 100ka Lightning-Strike Current

| Lightning Strike Current | Phase Conductor being Injected | Upper Phase | Middle Phase | Lower Phase | Tripping Sequence |
|--------------------------|--------------------------------|-------------|--------------|-------------|-------------------|
| 20kA                     | Upper Phase Conductor          | ✓           | ✓            | X           | 1st= upper phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          | Middle Phase Conductor         | ✓           | ✓            | ✓           | 1st= middle phase |
|                          |                                |             |              |             | 2nd= upper phase  |
|                          | Lower Phase Conductor          | ✓           | ✓            | ✓           | 1st= lower phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          |                                |             |              |             | 3rd= upper phase  |
| 50kA                     | Upper Phase Conductor          | ✓           | ✓            | ✓           | 1st= upper phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          | Middle Phase Conductor         | ✓           | ✓            | ✓           | 1st= middle phase |
|                          |                                |             |              |             | 2nd= upper phase  |
|                          | Lower Phase Conductor          | ✓           | ✓            | ✓           | 1st= lower phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          |                                |             |              |             | 3rd= upper phase  |
| 100kA                    | Upper Phase Conductor          | ✓           | ✓            | ✓           | 1st= upper phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          | Middle Phase Conductor         | ✓           | ✓            | ✓           | 1st= middle phase |
|                          |                                |             |              |             | 2nd= upper phase  |
|                          | Lower Phase Conductor          | ✓           | ✓            | ✓           | 1st= lower phase  |
|                          |                                |             |              |             | 2nd= middle phase |
|                          |                                |             |              |             | 3rd= upper phase  |

✓ = Flashover  
X = No Flashover

4. Conclusion

This paper modelled a 132kV overhead transmission-line model using ATP-EMTP software for shielding failure pattern recognition. Steps and procedures required to design the model were studied. The model was essential for the investigation of lightning over-voltage performance on overhead transmission-line system. Shielding failure voltages obtained across insulator strings were investigated by injecting four different magnitudes of lightning-strike current into each phase conductor of the transmission tower. Results obtained from simulation showed that as the lightning-strike current is injected from upper phase to lower phase conductor, the magnitude of the maximum induced voltage across the insulator string at those phases has been decreased. Conversely, as the magnitude of the lightning-strike current has been increased, the magnitude of the maximum induced voltage across the insulator string at each phase will be increased. Flashover occurs when the voltage induced across the insulator string at each phase is equal or exceeds the CFO voltage.
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