Lightning back flashover double circuit tripping pattern of 132 kV lines in Malaysia

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1. Introduction

Malaysia experiences a high number of thunderstorms, which is 220 days per year and records a flash density of 20 flashes/km/year. The lightning current varies from 3 kA to 200 kA and the mean is 31 kA [1]. According to the statistics, it is estimated that lightning has caused about 70% of the total annual line outages [2]. The types of flashovers which occur when a lightning hits the transmission lines are back flashover and shielding failure. Back flashover occurs when the lightning strikes on a shield wire or tower, where the resultant voltage across the insulator is large enough to cause a flashover from the tower to the line conductors. This voltage depends on the surge characteristics of the tower footing resistance, surge impedances of the shield wire, tower and phase conductors and the lightning magnitude and rise time [3]. Shielding failure occurs when lightning strikes on the phase conductor [4]. Since vast majority of the strokes and flashes terminate on the tower or ground wires, only back flashover is considered in this work [5,6].

Back flashover pattern studies have been conducted by various researchers. In most of the studies, the tripping patterns due to back flashover are usually considered in a single or double circuit phase conductor. They are grouped into upper, middle and lower phase conductors to determine the lightning performance [7]. However, in this study, a specific flashover according to the phase conductor for both circuits were determined by considering power frequency voltage, coupling effects, footing resistance and lightning current. The patterns of back flashover across each phase for double circuit were investigated to determine the most effective location for the installation of TLAs to eliminate back flashover. The actual line parameters were modelled using EMTP software and the simulations results were compared to the actual site data. The method for determining the pattern of a specific back flashover for 132 kV double circuit transmission line with chosen parameters are summarised in this paper.

2. Model description

2.1. Lightning current

A lightning current model proposed by Bruce and Godle was used in the simulation [8]. The proposed lightning current waveform is a double exponential function with a front time of 8 μs and tail time of 50 μs and is given by

\[ I(t) = I_0 \left( e^{-at} - e^{-bt} \right) \quad (1) \]

where \( I_0 \) is the peak of lightning current; \( I_d(t) \), the instantaneous lightning current; \( α, β \) are wave-head and wave-tail attenuation quotient of lightning current; and \( k \) is the waveform correction index.

A lightning waveform of 8/20 μs was used in the simulation. This waveform is commonly used to determine the behaviour of protection components which in this study is the insulator of the conductor line during current greater than 1 kA. A typical value of \( α, β \) and \( k \) for the 8/20 μs lightning current are 1.473 × 10^4, 0.5, and 0.5, respectively.
2.08 \times 10^6 \text{ and } 1.043 \text{ respectively}. Fig. 1a shows the lightning current model where, $Z_0$ represents the lightning channel surge impedance (generally 400 $\Omega$), $A$ represents the lightning strike point and $Z$ represents the impedance between the breakdown point and the ground. Fig. 1b shows the lightning current waveform.

### 2.2. Insulator string flashover model

An insulator string of the transmission line was modelled as a capacitor connected in parallel with a voltage controlled switch, as shown in Fig. 2. The voltage controlled switch determines the flashover across the insulator string. It operates based on the equal area flashover model recommended by T. Sadovic, S. Sadovic. Flashover will only occur if Eq. (2) is fulfilled.

$$\int_0^{t_f} (|V_{\text{gap}}(t)| - V_0)^k \geq D$$  

where $V_{\text{gap}}$ is the voltage across insulator string

$$V_0 = 0.9V_{50\%} = 0.9 \left( 400 + \frac{710}{e^{0.75}} \right) d$$

$k = 1$

$D = 0.2045 \, d$

$d = \text{length of gap between arc horn}$

$t = \text{tail time of lightning current waveform}$

### 2.3. Tower model

The tower height of a 132 kV overhead transmission line in peninsular Malaysia is 28.22 m. A double circuit vertical phase conductor configuration with two ground wires is usually used, as shown in Fig. 3. Due to this, lumped inductance model was selected as the tower model for the simulation in this study because it is able to provide an acceptable accuracy for tower lower than 30 m [9]. A lumped inductance model is also relatively simple compared to other tower models, such as multiconductor and multistorey tower models [7]. This reduces the complexity of the model. Fig. 4 shows a lumped inductance model where,

$$L_n = \frac{Z_t}{c} \times l_n \quad \text{(H)}$$

where $Z_t$ is the tower surge impedance ($\Omega$); $c$, the speed of light ($3 \times 10^8$ m s$^{-1}$) and $n = 1, 2 \text{ and } 3$.

There are several equations to calculate the surge impedance of the tower. As a basis, the formula given in [10] for “waist tower shape” and recommended by IEEE and CIGRE [11] is used:

$$Z_t = 60 \ln \left[ \cot(0.5 \tan^{-1} \left( \frac{R}{H} \right)) \right]$$

where,

### 2.4. Phase conductor and ground wire model

Generally, there are three types of transmission line models; PI-model, Bergeron model and Frequency-Dependent model (J-Marti model). PI-model is a lumped model and frequency-independent and it is applicable for medium lines. Bergeron model is similar to combination of numberless PI-model. It consists of discrete inductance and capacitance parameters. It can only roughly reflect an impedance variation in different frequencies. Frequency Dependent Line model can accurately describe the transient travelling wave propagation process in a wider frequency range. This is because its parameters vary with the frequency [12]. Since the latter is the most accurate model among the three, Frequency Dependent Line model was used in the simulation.

### 2.5. Tower footing resistance model

The lightning performance of transmission lines is strongly influenced by the tower footing resistance. The tower footing resistance, $R_F$ for fast transient surge or at high frequency (impulse footing resistance, $R_i$) is less than that of measured at low frequency. This is due to significant ground current causes the voltage gradient sufficient enough to breakdown the soil around the ground rod. Thus, a variable grounding resistance approximation which is surge current dependent can be used, given by
where $R_i$ is the tower footing resistance (Ω); $R_g$, the tower footing resistance at low current and frequency (Ω); and $I_g$ is the limiting current initiating soil ionization (kA).

$$I_g = \frac{1}{2\pi} \left( \frac{E_0 \rho_0}{R_g^2} \right)$$

(9)

where $\rho_0$ is the soil resistivity (Ω m) and $E_0$ is the soil ionization gradient.

The tower footing resistance was modelled by a controlled non-linear resistor and the model is based on Eqs. (8) and (9).

3. Discussion of parameters relationship with specific double circuit tripping

3.1. Power frequency voltage

Two separate ac sources are used for double circuit transmission line as illustrated in Fig. 5. Source 1 is the supply for circuit 1 while source 2 is for circuit 2. Both of the sources are synchronised with each other, as shown in Figs. 6 and 7. Table 1 shows the simulation flashover results on a 132 kV double circuit transmission line. The footing resistance of the tower was kept constants.
at 10 Ω while the angle of the ac sources was varied to investigate the effect on flashover at a specific conductor tripping. The results from Table 1 and ac source voltage from Figs. 6 and 7 show that the angle of ac source voltage influences the phase of conductor tripping. The phase voltage which is higher than the other phases has the highest possibility for a flashover to occur. Since both ac sources are in synchronism, the results show that most of the flashovers occur at the same phase for both circuits. Between 0–60 and 310–360°, the red phase voltage is the highest. In Table 1, at 0–60 and 310–360°, flashover occurs at the red phase in circuits 1 and 2. Similarly, flashover occurs at blue phase at 60–180° and yellow phase at 180–300°. However, at certain angles, flashovers occur at one or two phases for different circuit. This is due to the crossover of phase voltages at the same angle and the nearby angle. At 60°, the red and blue phases are crossing each other but it is at 180° for the blue and yellow phases and at 300° for the yellow and red phases. However, from Table 1, at 70, 170, 180, 290 and 300°, a specific conductor tripping is not only dependent on the angle of ac source voltage, but also dependent on the coupling effect. The pattern of the results is similar for the tower with a footing resistance of 5–50 Ω. The results of the simulation are validated with the actual site data, as shown in Fig. 11.

3.2. Coupling effect

The effect of the coupling factor also determines a specific conductor tripping for double circuit line. Coupling effect is dependent on conductor position at the transmission line for each circuit. A conductor which is near to the ground has lower coupling factor compared to a conductor above it. A phase with lower coupling factor has usually the highest probability for flashover to occur [10]. Fig. 8 shows conductors position for each circuit. The relationship between coupling factor and conductor position on the transmission lines can be shown as follows:

\[
C = \frac{\text{average mutual surge impedance}}{\text{equivalent ground wire surge impedance}}
\]

(10)

Mutual surge impedance [9]:

\[
\text{Mutual surge impedance} = \text{Mutual impedance} 
\]
\[ Z_{nA} = 138 \log_{10} \frac{D_{nA}}{d_{nA}}, \quad n = \text{number of ground wires}; \]  \hspace{1cm} (11)  

\[ X = \frac{D_{0\theta}}{d_{0\theta}} \]  \hspace{1cm} (12)  

From Eqs. (10)-(12) and Fig. 9, it can be seen that a lower conductor which is near to the ground has a lower value of \( X \) and can be concluded as having lower surge impedance and coupling factor.

The coupling factor has to be considered when the ac source voltage of each phase at certain point of wave is crossing over or near to each other. The result in Table 1, which cannot be explained by the effect of the angle of power frequency voltage, is due to the effect of coupling factors. Figs. 6 and 7 show that at 290°, the voltages for yellow and red phases are near to each other and the possibility that flashovers occur at these two phases is high. Fig. 10 shows flashover occurs at the yellow conductor at the first circuit while flashover occurs at the red conductor of the second circuit. R' is at the bottom lower position compared to R in the first circuit. A lower conductor yields a lower coupling factor, which has higher probability of flashover to occur. Even though both circuits are in synchronism with each other, the effect of the position of the conductors on a transmission line will determine which phase will experience flashover.

### 3.3. Lightning current

There are also contributions of lightning current on the number of conductor tripping at the transmission line. The number of conductors that trip due to the lightning increases when the lightning current is higher at constant footing resistance. At certain phase of ac source voltage, a specific conductor tripping can also be determined. Simulation was performed at 100° with constant footing resistance of 10 Ω. The results of specific conductors tripping with lightning current are shown in Table 2.

Figs. 6 and 7 show the blue phase has the highest value at 100°, followed by the red and yellow phases. At low lightning current, the blue phase has the highest possibility for flashover to occur, followed by the red and yellow phases. The position of the phase conductor at the transmission was considered to determine the circuit where flashovers will occur first. The same phase conductor with lower position will experience flashover first, followed by the conductor on the other circuit. The results indicate that both lightning current and the position of the conductor at the transmission line are dependent on each other, which determine a specific conductor to trip due to flashover.

### 3.4. Footing resistance

Another parameter which influences flashover pattern is the footing resistance. From the EMTP simulation results, the footing resistance influences the occurrence of lightning current flashover on a transmission line. In order to observe this effect, a 100° voltage was chosen, the footing resistance was assigned with a certain value.
value while the lightning current magnitude was varied until a flashover occurs at the blue phase conductor at the first circuit.

The footing resistance was varied and the lightning current magnitude was recorded, as shown in Table 3.

The results in Table 3 show that the lightning current magnitude that causes flashover at the conductor is dependent on the tower footing resistance. When the footing resistance increases, the value of current is lower for a flashover to occur. At lower footing resistance, less negative reflections are produced from the tower base towards conductor line. Thus, this reduces the peak voltage at the tower. Therefore, lower footing resistances require higher lightning current to increase the peak voltage at the tower to the voltage across the insulator string to initiate flashover. This also indicates that the footing resistances and lightning current magnitude determine the phase of conductor tripping.

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4. Conclusion

An analysis of flashover pattern on a double circuit transmission line with vertical configuration has been successfully performed using EMTP. The results between simulation and the actual field data are within reasonable agreement to each other. Verification of the model in EMTP is able to identify the parameters that influence the flashover pattern. The identified parameters are power frequency voltage, coupling effects, lightning current and footing resistance. Therefore, from the results obtained in this work, lightning arresters can be economically installed on transmission lines according to the pattern of the tripping.

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References