Influence of Lightning Characteristics on Back Flashover in Extra High Voltage Transmission Line: A case study

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Abstract. Lightning is one of the primary sources that cause failure on over head transmission system. It can lead to the transmission line insulator to be over voltage. Commonly, transmissions lines are equipped with ground wire and consist of one or two ground wire which it is depending on tower construction. Over voltage on the transmission line can occur in two ways viz., direct lightning strike on phase line and ground wire produce propagating wave to both sides the phase line and result in damage on insulator. Direct lightning stroke on ground wire or the tower structure of transmission can cause phenomenon back flashover (BFO) on insulator. The lightning current characteristic is distinguished in lightning maximum current and steepness of lightning current. This paper discusses influence of in different lightning characteristics on BFO in extra high voltage transmission line in simulation using ATP draw.

The lightning surge currents of IEC and VDE standards were injected to the ground wire and phase lines. As the implementation, this paper used the data of extra high voltage transmission line of 275 kV, Galang - Binjai, North Sumatra Province, Indonesia.

1. Introduction
Lightning is one of the primary sources that cause failure on over head transmission system and it can lead to the transmission system to over voltage. The permanent failure of power system equipment by caused lightning stroke on the transmission line can reach 5% to 10% [1]. Transmissions are equipped with one or two ground wire which it is depending on the tower construction. The purpose is for shielding phase lines from direct lighting stroke. The lightning can stroke phase line when shielding failure occur and create the phase lines get over voltage. Striking to the ground wire can lead to induce over voltage on phase line and generally is low. The direct stroke to phase transmission lines can cause flashover even insulator breakdown. It injects currents propagate toward tower footing resistance and all lines connected until a transformer in substation if do not protect.

Direct lightning stroke on ground wire or the tower structure of transmission can cause phenomenon back flashover (BFO) on insulator. Commonly, high voltage transmission lines use string insulator type. The BFO is one of the several phenomena in high voltage which it can cause the insulator string damage. The BFO will occur when the insulator subjected to voltages exceed the line critical flashover (CFO) [2]. The CFO is influenced by number of insulators installed on the transmission tower.
Studies about lightning striking by using ATP EMTP to observe the performance of high voltage lines were carried out in [3, 4]. In paper [3] shows that influence of the characteristics of lightning arrester performance when gets lightning stroke. Whereas [4] presents modelling a 400 kV extra high voltage transmission line for calculating over voltage on insulator while lightning stroke to a tower or ground wire and stroke to a phase conductor line. In other publications [5] used PSCAD/EMTDC to simulation back flashover on 115 kV transmission. This paper presents the modelling of transmission line systems include lightning current, tower, insulator and tower footing resistance.

Effect of the lightning characteristics on the insulator that causes back flashover on the insulator is important to the study in transmission line planning against lightning strikes. In this study is carried simulation of lightning stroke on tower/ground wire and conductor phase line. Lightning surge characteristics used are IEC and VDE standards. Modelling of the transmission line, tower, footing tower resistance and lightning surge using ATP draw. A case study is carried out by implementing a 275 kV transmission line of Galang – Binjai, North Sumatra Province to find out the magnitude of surge current leads insulator back flashover and the phases voltage.

2. Methodology

2.1. Lightning impulse current

Impulse wave a damped a periodic such as when the charge of a capacitor passes through an inductive resistance. The waveform consists of the wave front, T_f and the wave tail T_t. The wave front has a steep shape whereas the wave tail is more sloping. The wave front is defined as a part of the wave starting from zero points to crest and the rest is referred to as wave tail.

Lightning impulse current is stated as 1.2/50 $\mu$s, it means the current has the value of T_f and T_t are 1.2 $\mu$s and 50 $\mu$s, respectively. Several of standards impulse waveform values are presented in Table 1.

| Standard | $T_f$ ($\mu$s) | $T_t$ ($\mu$s) |
|----------|---------------|---------------|
| Japan    | 1             | 40            |
| VDE      | 1             | 50            |
| United State | 1.5     | 50            |
| EIC      | 1.2           | 50            |
| CIGRE    | 3.3           | 77.3          |

2.2. Surge impedance

2.2.1 Transmission tower and impedance. A 275 kV transmission tower configuration used in Galang to Binjai is shown in Figure 1. The transmission is using double circuit and two ground wires which are located above. Phase lines are using ACSR Zebra conductor type have the reactance of 0.0674 $\Omega/km$, the inductance of 0.222 $\Omega/km$ and diameter of 2.862 cm. Ground wires are galvanized steel has the reactance of 0.364 $\Omega/km$, the inductance of 0.290 $\Omega/km$ and diameter of 1.227cm. The transmission tower is identification as C type [7] and the magnitude impedance is

$$Z_t = 30 \ln \left( \frac{2(h^2 + r^2)}{r^2} \right)$$

where

$Z_t$ is tower surge impedance ($\Omega$)

h is total height of the tower (m)

r is the vertical distance of the wire (m)
Phase lines and transmission tower are separated by using string insulator. The critical flashover voltage on insulator can be determined by an equation [6],

\[ V_{50\%} = (K_1 + \frac{K_2}{t^{0.75}}) \times 10^3 \text{ kV} \]  

(2)

Where,

- \( V_{50\%} \) is insulator breakdown voltage (kV)
- \( K_1 = 0.4 \text{ W} \)
- \( K_2 = 0.71 \text{ W} \)
- \( W \) is total the length of the insulator (m)
- \( t \) is flashover time of the insulator (\( \mu \text{s} \))

2.2.2. Footing grounding surge impedance. Tower grounding system used is driven rod consist of four ground rods installed on each tower foot is shown in Figure 2.

![Figure 1. 275 kV Transmission tower configuration of Galang - Binjai](image)

![Figure 2. Tower grounding of four ground rods](image)
\[ R = \frac{\rho}{2\pi l} \left( \ln \frac{2l}{\sqrt[3]{2^{1/3} s_2^2 r^4}} \right) \text{ Ohm} \]  

\[ L = \frac{\rho}{2} \left( \ln \frac{l}{r s_1 s_2} \right) \times 10^9 \text{ Henry} \]  

\[ C = \frac{\varepsilon r l}{9\pi \frac{2l}{\sqrt[3]{2^{1/3} s_2^2 r^4}}} \times 10^{-9} \text{ Farad} \]

Where

- \( l \) is the conductor length (m)
- \( S \) is the distance between ground rods (m)
- \( r \) is the conductor radius (m)
- \( \varepsilon \) is the permittivity of earth
- \( \rho \) is earth resistivity (ohm-m)

The data of Galang – Binjai tower footing with conductor length of 5 m, 3.81cm diameter and the distance between the conductor, \( s_1 \) and \( s_2 \) are 10 m.

2.3. Modelling of the transmission line system

The simulation was carried out by injecting a surge current that varies from 20 kA to 100 kA with a current interval of 10 kA into a ground wire and also phase line separately and earth resistance of 10 \( \Omega \) constant. The lightning characteristics were modelled as difference wave front, \( T_f \) and wave tail \( T_t \) according to IEC and VDE standards. If a black flashover occurs at a certain value, the simulation is repeated to obtain the minimum surge current value. The BFO of the insulator in simulation is shown with the intersection between the volt-time curves of insulators with lightning impulses. The circuit model of the transmission is shown in Figure 3.
3. Result

3.1. Simulation result when lightning surge striking on the ground wire

Effect of the surge current characteristics of IEC and VDE standards on the insulator is shown in Table 2. The Table explains insulator conditions that are given “Yes” and “No” words label. The Words “No” mean does not BFO occur and “Yes” mean BFO occurs.

Table 2. The insulator condition when getting striking lightning on the ground wire

| Surge current (kA) | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|-------------------|----|----|----|----|----|----|----|----|-----|
| Phase- A          |    |    |    |    |    |    |    |    |     |
| IEC Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |
| VDE Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |
| Phase- B          |    |    |    |    |    |    |    |    |     |
| IEC Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |
| VDE Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |
| Phase- C          |    |    |    |    |    |    |    |    |     |
| IEC Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |
| VDE Standard      | No | No | No | Yes | Yes | Yes | Yes | Yes | Yes |

Words “No” mean does not BFO occur and “Yes” mean BFO occurs.
Table 2 can be observed that there is no difference lightning characteristic of both standards that causes the BFO insulator. The impulse current value can cause the insulator flashover is less than 50 kA and greater than 40 kA. For obtaining the critical value of flashover is carried repeating simulation by impulse current smaller increment. The critical surge current that causes CFO is obtained is 48.1 kA. The voltage of phase’s waveform is shown in Figure 4. From this Figure, the current leads to increase in the maximum voltage in each insulator, phase-A of 2.877 MV, phase-B of 2.490 MV and phase-C of 2.373 MV. From the Figure can be observed, flashover occurs in insulator phase-A only. The same values also were obtained for surge current of VDE standard, because the impulse current of the standard is not significantly different.

![Figure 4](image)

**Figure 4.** The phase voltages waveform caused by impulse current of 48.1 kA, IEC standard and CFO curve

### 3.2. Simulation result when lightning surge striking on the phase line

In this case, phase-A line gets striking lightning because is at the very top. The simulation result is shown in Table 3. Therefore the surge characteristic for IEC and VDE standards is not significant different, so the surge current cause insulator BFO is similar. The surge current causes BFO in the phase-A insulator in ranges 20 kA to 30 kA. But for phase-B and phase-C the insulators BFO are higher in ranges 50 kA to 60 kA. The BFO of insulator caused by surge current for striking on phase line is smaller and faster than the lightning stroke on ground wire or tower.

| Surge current (kA) | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|--------------------|----|----|----|----|----|----|----|----|-----|
| **Phase-A**        |    |    |    |    |    |    |    |    |     |
| IEC Standard       | No | Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes  |
| VDE Standard       | No | Yes| Yes| Yes| Yes| Yes| Yes| Yes| Yes  |
| **Phase-B**        |    |    |    |    |    |    |    |    |     |
| IEC Standard       | No | No | No | No | Yes| Yes| Yes| Yes| Yes  |
| VDE Standard       | No | No | No | No | Yes| Yes| Yes| Yes| Yes  |
| **Phase-C**        |    |    |    |    |    |    |    |    |     |

Table 3. The insulator condition when getting striking lightning on the phase line
IEC Standard | No | No | No | No | Yes | Yes | Yes | Yes
VDE Standard | No | No | No | No | Yes | Yes | Yes | Yes

No” mean does not BFO occur and “Yes” mean BFO occurs

The minimum current leads the insulator BFO for each phase is 26.4 kA in phase-A, 50.3 kA in phase-B and 53 kA in phase-C. The voltage waveform of phase lines when was injected by the minimum surge current of 26.4 kA and CFO is shown in Figure 5. The phase-A voltage increases to be 3.337 MV cause the insulator flashover. For two other phases, the voltages are phase-B of 1.479 MV and phase-C of 1.411 MV, so the insulators did not flashover.

![Figure 5. The phase voltages waveform caused by impulse current of 26.4 kA, IEC standard and CFO curve](image)

4. Conclusion
The simulation results presented are important notes for transmission line planning includes determination of insulator number used in the transmission line. This is related to critical voltage leads to insulator CFO. The characteristic of lightning surge current has a great effect on BFO insulator and the higher current the greater the probability of BFO occurs. Location of lightning striking takes effect also on BFO insulator. The lightning striking directly on ground wire or transmission tower causes the voltage at insulator terminal to increase and it can cause insulator BFO. The minimum current leads to BFO of the lightning striking directly on the phase line is 26.4 kA which it is smaller than the striking on ground wire.

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