Lightning protection of MEA’s 24 kV distribution lines
Using overhead ground wires

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Abstract—This paper employed Alternative Transient Program—Electromagnetic Transient Program (ATP-EMTP) as the main tool for system modeling and simulation to determine the impact of lightning current occurring in distribution system. The results show that when the average lightning strikes to distribution line the voltage across insulator is higher than 1500 kV which exceeds the critical-impulse-flashover of insulator (CFO) of 205 kV resulting in the power outage. We also found that if the grounding distance of distribution line increase from 40 meters to 200 meters, the back-flashover rate increase from 0.96 to 14.36 flashes/100 km/year. However, the critical lightning current of the distribution line system reduce from 107 kA to 8 kA on condition ground resistance is not more than 1 ohm. All the results in this paper could be served as a guideline for grounding system design and modification of grounding standard in distribution lines in the future.

Index Terms—EMTP, Lightning protection, Power distribution faults

I. INTRODUCTION
Thailand is in the tropical country with a high number of the thunderstorm days. For this reason, the distribution line of Metropolitan Electricity Authority (MEA) can be affected by the lightning phenomenon. The statistics recorded by MEA indicates a high unknown outage rate that may come from the direct lightning strike to the distribution line which later results in power outage. The calculation shows that a high number of lightning strike to Overhead Ground Wire (OHGW) of 2,722 times/year. The lightning strikes on distribution line are classified into two group; the direct strokes and induced strokes. When lightning strike to OHGW of distribution line, the magnitude will be very high and may inject currents up to about 100 kA into the distribution line after that the voltage is built up across the line insulators. If this voltage exceeds the critical flashover of insulators (CFO), flashover will occur. The voltage across insulator depends on many factors such as the grounding distance of OHGW, ground resistance and lightning current magnitude. In the literature of lightning current performance, several distribution models have been developed to be simulated in order to analyze overvoltage when lightning current occur with different lightning protection method. In [1], In Japan, surge arresters have been installed to protect equipment on 6.6 kV distribution lines against lightning. However, the large amount of energy which exceeds withstand capability that still occurs due to lightning, two methods are considered to effective to reduce the incidence of damage to surge arresters are to installation of an overhead ground wire and increase in withstand capability of surge arrester. In [2], presents the experiences of the Indonesian electric company. Which improve the lightning performance by using OHGW that installed both above and below the phase conductor to protect the direct lightning and indirect lightning strikes. In [3], focuses on behavior of over-voltage across the cross arm and back-flashover on insulator with different front times of lightning wave shape, the result indicate that the front time of lightning wave shape plays an important role for back-flashover voltage across insulator as well as the tower footing resistance. In [4], concluded that induce stroke is not a major problem in the distribution line if we design the critical flashover of insulator (CFO) is not more than 300 kV.

II. DATA AND MODEL FOR ANALYSIS

A. Data of distribution line configuration
The arrangement is based on the Thailand’s distribution line of Metropolitan Electricity Authority (MEA) 24 kV distribution line [5]. The arrangement consists of the three-phase conductor 185 mm2 all-aluminum space aerial cable (ASC) per phase and 1 x 50 mm2 overhead ground wire (OHGW). The pole is 12 m high and the ground rod is 16 mm in diameter and 2.4 m long as shown in Fig. 1.
B. Data for calculation of back flashover rate

The back-flashover rate (BFR) can be calculated by equation (1) [6].

\[
BFR = N_L P(I_p)
\]  
(1)

where BFR is the back-flashover rate (flashes/100 km/year), \(N_L\) is the number of strokes to OHGW (flashes/100km/year), \(P(I_p)\) is the probability of a flashover that the stroke current equals or exceeds the critical current (%).

1) The number of stroke to OHGW (\(N_L\))

The number of stroke to OHGW (NL) can be calculated by equation (2) [7].

\[
N_L = N_g \left( \frac{28h^{0.6} + b}{10} \right)
\]  
(2)

where \(h\) is the pole height (m), \(b\) is the structure width (m), \(N_g\) is the ground flash density (flashes/km2/year), \(NL\) is flashes/100 km/year. For most distribution lines, the structure width factor \(b\) is negligible. The ground flash density \((N_g)\) can be estimated from equation (3) [8].

\[
N_g = 0.000065T_d^{2.277}
\]  
(3)

where \(T_d\) is the number of thunderstorm days per year \((T_d = 75.88\) days per year in MEA, Thailand\)) [9].

2) The probability of a flashover

The probability of a flashover that the stroke current equals or exceeds the critical current (%) as shown by equation (4) [10]

\[
P(I_p) = \frac{1}{1 + (I / I_{50})^{0.09}}
\]  
(4)

where \(P(I_p)\) is the probability of a flashover that the stroke current equals or exceeds the critical current (%), \(I\) is the critical current of insulator (kA) are from simulation, \(I_{50}\) is the average lightning current = 40 kA (in Thailand) [4].

C. Model of lightning current

Negative lightning was assumed to stroke at the phase conductor or OHGW. The CIGRE lightning return stroke current wave shape was adopted using a CIGRE type15 current source, so as to consider the upwardly concave wave front observed in measured lightning current wave shapes [11]. The impedance of the return-stroke channel was represented by a 400 Ω resistor connected in parallel to the current source [12], [13]. For the lightning current wave shape parameters median values were utilized; actually, the time to half value was taken as 77.5 μs whereas the front time, \(t_f\) (μs), and maximum steepness, \(S_m\) (kA/μs), were considered as functions of the lightning current crest, \(I\) (kA) [11].

The lightning stroke hitting a OHGW was represented by a CIGRE concave shape shown in Fig. 2

The peak current magnitude and the tail time are important when observing the arrester energy, while the influence of the rise time is hardly noticeable in such a case. In contrast, the current wave front is an important parameter with regard to the insulator flashover. The CIGRE concave shape shown in Fig. 2 represents more accurately the concave front of a lightning stroke and usually gives more realistic results.
D. Model of ground rod

The ground rod is represented by a model that does not change when receiving high frequency. Calculated by equation (5) [14].

\[
R = \frac{\rho}{2 \pi L} \left( \ln \frac{4L}{a} - 1 \right)
\]

where \( R \) is the resistance of the ground rod (\( \Omega \)), \( \rho \) is the resistivity of the soil (\( \Omega \cdot m \)), \( L \) is the length of the ground rod (m), \( a \) is the radius of the ground rod (m).

E. Model of external ground wire

Zinc coated steel wire is used for external ground wire. Surge impedance of external ground wire can be calculated from equation (6) [15].

\[
Z = 60 \ln\left(\frac{h}{er}\right) - k \ln\left\{1 + \left(\frac{rc}{D}\right)^2\right\}
\]

where \( Z \) is the surge impedance of external ground wire (\( \Omega \)), \( h \) is the length of conductors (m), \( e \) is the base natural log \( = 2.71828 \), \( r \) is the radius of conductor (m), \( rc \) is the radius of the concrete pole (m), \( D \) is the distance between the surface of the pole and external ground wire (m). The \( k \) is calculated from the equation (7).

\[
k = 0.096 r_c + 13.95
\]

where \( k \) is constant, \( rc \) is the radius of the concrete pole (m).

F. Model of Insulator

Electrical insulator in MEA’s 24kV distribution line are used for fixing and separating three phase conductors from not moving closer. MEA uses Pin-Post insulator compliant with ANSI C56/57-2 standard as shown in Fig. 3. (Critical-impulse-flashover, negative equal to 205 kV). The model of Pin-Post insulator instead of capacitor has a capacitance approximately 100 pF [16].

III. SIMULATION AND RESULTS

A. Simulations

The Alternative Transient Program-Electromagnetic Transient Program) ATP-EMTP (is employed as the main tool for system modeling and simulation to determine the impact of lightning current occurring in the MEA distribution line system as shown in Figure 4. The simulation systems consist of lightning supply (surge source) of 24 kV single circuit and single conductor; it can be seen that the number of simulated distribution concrete pole is 6 poles along the route to study the effect of lightning striking voltage. Distribution line with frequency dependent parameter can be calculated by supporting routine Line Cable Constants (LCC) in ATP-EMTP.

The LCC model is based on geometrical and material data for an overhead line including the corresponding electrical data. The supply lightning strike simulation model is characterized by CIGRE type15 (CIGRE concave wave shape). The model of insulator instead of capacitor has a capacitance approximately 100 pF. The criteria are that when the lightning strikes to OHGW, voltage is built up across the pin-post insulator. If this voltage from simulation exceeds the critical impulse flashover of insulator (CFO = 205kV), flashover will occur resulting in the power outage later.

B. Parameters for analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning current</td>
<td>30-50 kA</td>
<td>Waveform [11]</td>
</tr>
<tr>
<td>Conductor (single)</td>
<td>16 mm</td>
<td>DC resistance</td>
</tr>
<tr>
<td>Overhead ground wire</td>
<td>7.93 mm</td>
<td>DC resistance</td>
</tr>
<tr>
<td>External ground wire</td>
<td>7.93 mm</td>
<td>Surge impedance</td>
</tr>
<tr>
<td>Voltage of lightning wave</td>
<td>408 \Omega</td>
<td></td>
</tr>
<tr>
<td>Concrete pole</td>
<td>40-200 m</td>
<td>Distance between pole</td>
</tr>
<tr>
<td>Ground rod</td>
<td>16 mm</td>
<td>Outside diameter</td>
</tr>
<tr>
<td>Ground resistance</td>
<td>1-30 \Omega</td>
<td>Length of ground rod</td>
</tr>
</tbody>
</table>

Figure 3. Electrical insulator in MEA, 24kV distribution line

Figure 4. Component of simulation model

TABLE I. PARAMETERS OF THE POWER SYSTEM USED IN THE DESIGN
C. Results

1) The results of voltage across insulator at various distance of overhead ground wire (OHGW)

By observing Fig. 5, the results show that when the average lightning of 40 kA in Thailand strikes to OHGW which is grounded for every pole (40 meters), it is obviously seen that the voltage across insulator is lower than the CFO of 205 kV in condition that the ground resistance is not more than 4 ohms. In some areas that do not keep the ground resistance within 4 ohms. In that case, increasing the CFO will be required to withstand the average lightning current. For example, in some areas have the ground resistance values of 10 ohms, CFO shall be increased from 205 kV to 268 kV. In addition, the grounding distance of OHGW increase from 40 meters to 80,120 meters resulting in the voltage across insulator increase from 268 kV to 324, 360 kV respectively as shown in Fig. 6-7. However, when the grounding distance of OHGW increase from 120 meters to 160, 200 meters, the voltage across insulator are constant of 360 kV as shown in Fig. 8-9. The optimum design of grounding distance of OHGW depends on the ground resistance and lightning current magnitude in each area. By changing the lightning current magnitude, it can be observed that the voltage across insulator tends to increase with the increase of the lightning current magnitude.

2) The results of the critical lightning current

The critical lightning current means the maximum lightning current that the distribution line system can still withstand the lightning current without the flashover. That means, any system with high the critical lightning currents, resulting in less opportunity of the flashover. From simulation and result show that the critical lightning current will increase if the grounding distance of OHGW decrease. For example, when decrease the grounding distance of OHGW from 200 meters to 40 meters resulting in the critical lightning current increase from 8 kA to 107 kA on condition 1 ohms ground resistance. However, the ground resistance is increased more than 30 ohms, the critical lightning current will nearly be equal for every grounding distance of OHGW as shown in Fig. 10.

3) The results of back flashover rate

The back-flashover rate (BFR) can be calculated by equation (1), \[ \text{BFR} = \text{NL} \times \text{Pip} \], the simulated and analyzed
results show that the back-flashover rate is minimum value when OHGW is grounded for every pole. For example, when Grounding Distance of OHGW reduce from 200 meters (every other four poles) to 40 meters (every pole) resulting in the back-flashover rate reduce from 14.36 to 0.69 flashes/100 km/year on condition that 1 ohm ground resistance. The ground resistance is increased more than 30 ohms, the back-flashover rate will nearly be equal for every grounding distance of OHGW as shown in Fig. 11.

![Figure 11. Back-flashover rate](image)

**IV. CONCLUSIONS**

The study can be concluded as the following; the OHGW is essential equipment to intercept the lightning strikes to 24 kV MEA’s distribution line system. The OHGW is grounded for every pole or every 40 meters resulting in voltage across insulator is lower than the CFO of 205 kV in condition that the ground resistance is not more than 4 ohms, the ground resistance and grounding distance of OHGW plays an important role for the voltage across insulator and the critical lightning current as well as the back-flashover rate. In some areas that do not keep the ground resistance within 4 ohms. In that case, increasing the CFO will be required, for example, ground resistance up to 10 ohms, CFO shall be increased from 205 kV to 268 kV that can withstand the lightning current strikes to OHGW. The optimum design of the grounding distance of OHGW depends on the ground resistance and lightning current magnitude in each area. All the results in this paper could be served as a guideline for grounding system design and modification of grounding standard in MEA’s 24 kV distribution lines in the future.

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