Lightning Flashover Rates of Overhead Distribution Lines Applying EMTP and IEEE Std.1410

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ABSTRACT

This paper calculates the lightning flashover rates of 22 kV overhead distribution line. In order to calculate the backflashover rate (BFOR), the performance of line which related to the insulator backflashover has been modeled and analyzed using Electromagnetic Transient Program (EMTP). The flashover models, volt time curve (VT), disruptive effect model (DE) and leader progression model (LPM) have been compared. The shielding failure flashover rate (SFFOR) and induced voltage flashover rate (IVFOR) have been calculated follow equations given in IEEE std 1410-2010. Finally the total numbers of flashovers of line have been determined. The lightning flashovers rates of BFOR, SFFOR and IVFOR have also been compared with the data taken from the line outages recorder. From the system being studied shown that, the total numbers of flashovers from simulation and calculation is closed to the data from the line outage recorder.

1. INTRODUCTION

Lightning continues to be the main cause of line outages on overhead distribution lines, especially for lines without overhead ground wire. The direct strokes occur when lightning hits shield wire (or pole) or phase conductors. The indirect strokes occur when lightning hits ground or nearby objects. Those lightning when occurred may cause insulation flashovers which can leads to line outages.

If the voltage build up as a result of a lightning strike, terminated on shield wires or pole, is a function of the grounding resistance. A high resistance may result in a voltage level that exceed the basic impulse insulation level (BIL) of the insulators, and a flashover will occur. This type of flashover when occurred call backflashover. The methods used for calculating backflashover may applied : CIGRE method, simplified CIGRE method, IEEE volt-time curve model (VT), disruptive effect model (DE) and leader progression model (LPM) [1].

For shielding failure flashover, lightning strikes directly on a phase conductor instead of a shield wires

resulting in a flashover. Because the shielding angle for overhead lines is normally less than 30°, the shielding failure flashover can be neglected.

Instead of direct strike, lightning strikes on trees or nearby objects and voltage are induced in the phase conductors. If induced voltages are greater than BIL of insulators it will result in a flashover call induced voltage flashover.

Induced voltage flashover in distribution lines can affects more the total lightning performances because an assumption for CFO (critical flashover voltage) used for distribution lines is that if the CFO is 300 kV or greater, there will be no induced flashovers. The distribution lines indirect lightning performance estimation considering the soil resistivity shows the EGM (electrogeometric model) can affects the results of indirect lightning performance [2]. Besides the EGM, the peak value of lightning induced voltages considering the soil resistivity, line height, return stroke velocity and distance from the lightning point have been considered [3]. The effects of soil resistivity applying Rusck's formula for maximum lightning induced voltages have been reviewed [4]. The procedure for the assessment of indirect lightning performance proposed by [5] takes into account more realistic line configurations and the effect of the finite soil resistivity (ground conductivity) using the LIOV (lightning-induced overvoltage code) leading to the revisions of IEEE std 1410-2004 to be IEEE std 1410-2010 finally.

The lightning flashover rates of 22 kV overhead distribution line by means of flashover rates of BFOR, SFFOR and IVFOR have been determined. In order to calculate the BFOR, the performance of line which related to the insulator backflashover has been modeled and analyzed using EMTP. For backflashover, the comparative studies of flashover models of VT, DE and LPM models have been analyzed. The SFFOR and IVFOR have been calculated follow equations given in IEEE std 1410-2010 [6]. The IVFOR have been analyzed taken into account the effects of imperfect soil at high frequency applying Rusck's formula for maximum lightning induced voltages. The total numbers of lightning flashovers of BFOR, SFFOR and IVFOR have been compared with the data taken from the line outages recorder [7].

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2. SYSTEM MODELING

System models for lightning overvoltage calculations must include parts of the line that get involved when a lightning hits a shield wire or a phase conductor or a pole, and have some influence on the voltages across insulator. A section of a typical 22 kV overhead distribution line has been modeled using ATP-Draw [8], a royalty free version using world-wide of EMTP.

A typical 22 kV overhead distribution line was modeled to analyze the lightning overvoltage and also flashover rates. The overhead distribution line has been represented using the JMARTI frequency dependent model [9]. Conductor sizes for phase conductors of 22 kV circuit is 185 mm2 and 25 mm2 for shield wire. The line configuration has been studied are in horizontal with one overhead ground wire.

A. Pole and Footing Resistance Models
For pole without external ground lead [10], only one ground lead is inside the pole, the surge impedance is given in (1).

$$Z_T = 60 \ln \left(\frac{2h}{r} \right) \tag{1}$$

For pole with external ground lead (every 200 m) [11], the surge impedance of circular-shaped grounding conductor is given in (2).

$$Z_{gc} = 60 \cdot \ln \left(\frac{h}{e \cdot r} \right) - k \cdot \ln \left(1 + \left(\frac{r_e}{D} \right) \right) \tag{2}$$

where h is the pole height, D is the distance between the concrete pole and the ground lead conductor, e is the natural logarithm, r is the conductor radius of the ground conductor, r_c is the reinforced concrete pole radius and the constant k is evaluated by the linear function against the conductor radius and is given in (3).

$$k = 0.096 \cdot r_c + 13.95 \tag{3}$$

The pole and footing resistance models of 22 kV circuit is shown in Fig. 1.

Footing resistance is represented using Weck's model [10]. The footing resistance is determined by using the current dependence of the pole footing resistance, R_i, as shown in (4).

$$R_i = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \tag{4}$$

where R_0 is grounding or footing resistance at low current and low frequency in Ω (The measured footing resistance of the line are quite varies and the average of 25 Ω has been used.), I is the lightning current
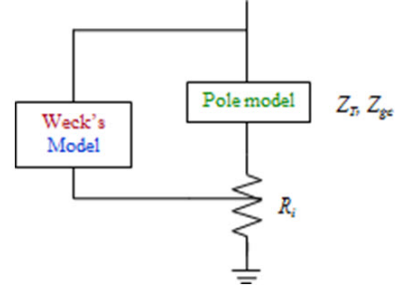

Fig.1: Pole and footing resistance models in ATP-Draw.

through the footing resistance in A and I_g is the limiting current through the footing resistance in A, as shown in (5).

$$I_g = \frac{1}{2\pi} \left(\frac{E_0 \rho_0}{R_0^2} \right) \tag{5}$$

where ρ_0 is the soil resistivity in Ω-m, E_0 is the soil breakdown gradient, typically 400 kV/m.
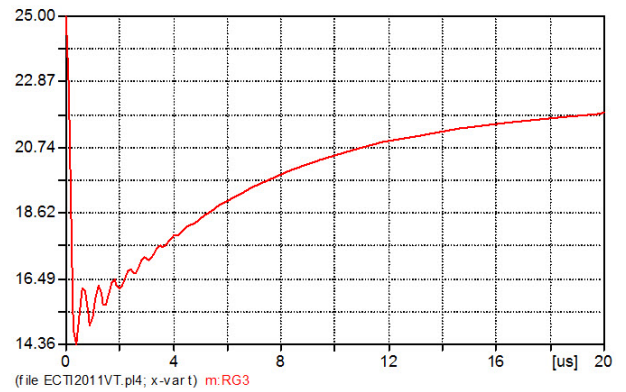

Fig.2: Footing resistance when the lightning current flowing through.

Using the MODELS simulation language in ATP. ATPDraw supports only a simplified usage of MODELS [8]. The user writes a model-file and ATPDraw takes care of the INPUT/OUTPUT section of MODELS along with the USE of each model. Fig. 2 shows the footing resistance when the lightning current flow through footing resistance for the 50 Hz resistance of 25 Ω.

B. Flashover Models
To compare the results, three flashover models, IEEE volt-time curve model (VT), disruptive effect model (DE) and leader progression model (LPM), have been implemented. The volt time curve from testing has been used for simulation. The simulated VT [11] can be expressed as shown in (6).

$$V_{v-t} = K_1 + \frac{K_2}{t^{0.75}} \tag{6}$$

V_{v-t}=Flashover voltage, kV.
K_1=400*L
K_2=710*L
L=Insulator length, m.
t=Elapsed time after lightning stroke, μs.

Fig. 3 compares the volt time curve from IEEE model and from testing.
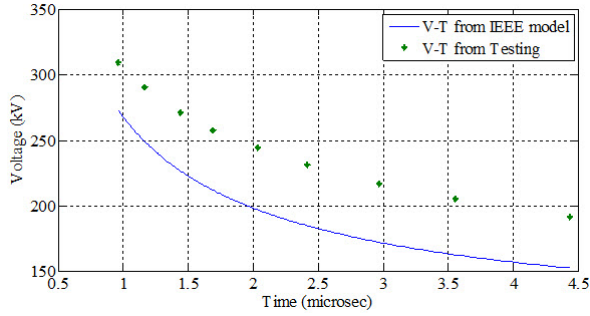

Fig.3: *Comparison of volt time curve from simulation and from testing.*

A general form for disruptive effect model [11] has been given in (7).

$$DE = \int_{t_0}^{T} (V(t) - E_0)^n dt \qquad (7)$$

where $V(t)$ = magnitude of voltage across insulator, V
E_0 = minimum breakdown voltage, V
n = exponent
When DE exceeds a critical level, the insulator flashover.
The expression for leader progression model [11] is given in (8).

$$\frac{dg}{dt} = kV(t)\left[\frac{V(t)}{l-g} - E_0\right] \qquad (8)$$

where dg/dt = the leader velocity, m/s.
  k = constant
  g = leader length, m.
  l = air gap length, m.
  V(t) = voltage across gap, kV.
  E_0 = breakdown gradient, kV/m.

When the leader velocity reaches zero, the insulator flashover.

The three flashover models have been implemented using Model in ATPDraw, for the insulators that are likely to flashover at each pole. These insulators have a controlled switch across the capacitor in their ATPDraw models which is closed automatically when the conditions exceed the values which have been specified. Fig. 4 shows model of flashovers in ATPDraw.
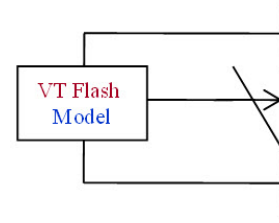

Fig.4: *Flashover model with controlled switch.*

C. Ground Flash Density (GFD)
From IEEE Std. 1410-2010, GFD is estimated from (9).

$$N_g = 0.04T_d^{1.25} \qquad (9)$$

N_g = ground flash density, flashes/km^2/yr.
T_d = number of thunderstorm days per year (the keraunic level). With the uncertainty in the choice of appropriate expression, the poor statistical quality of observations in regions with limited lightning and the ready availability of better alternatives, the use of thunder data to predict distribution line lightning performance should be discontinued [6].

For areas without ground-based lightning location systems or lightning flash counters, the recommended estimate of ground flash density is shown in (10).

$$N_g = N_t/3 \qquad (10)$$

N_t = total (cloud + ground) density of optical flashes/km^2/ yr. (varied from 0.6-20 flashes/km^2/yr for Thailand, approximately 15-20 for line being considered).

Estimates of average GFD may also be obtained directly from lightning detection network. The GFD may be estimated from the keraunic level collected in Thailand as shown in (11) proposed by [12] and (12) proposed by [13].

$$N_g = 0.0133T_d^{1.25} \qquad (11)$$

$$N_g = 6.5 \times 10^{-5}T_d^{2.277} \qquad (12)$$

From Thailand's isokeraunic map of the line route has been studied, the keraunic level considered is 80. The GFD at keraunic level and the density of optical flashes have been used for this paper shown in Fig. 5.

3. RESULTS

D. Backflashover Rates (BFOR)
Lightning overvoltage which occur on overhead distribution lines can damaged the insulation at the striking location which lightning hit and can travel toward

the terminal or substation and cause damage, particularly to expensive equipment such as substation transformers and surge arrester protecting transformers. So the voltage developed across insulator are the major concerned when studies lightning overvoltage. The voltage across insulator in system configuration described earlier with flashover model applied using volt time curve from testing at critical current causing flashover shown in Fig. 5. The voltage across insulator for DE and LPM at critical current causing flashover also shown in Fig. 6 and Fig. 7 respectively.
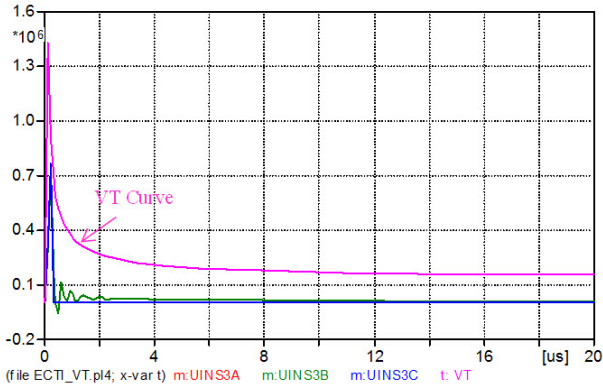

Fig.5: *Voltage across insulator phase A, B and C with flashover occurred on phase A and C using volt time curve from testing.*
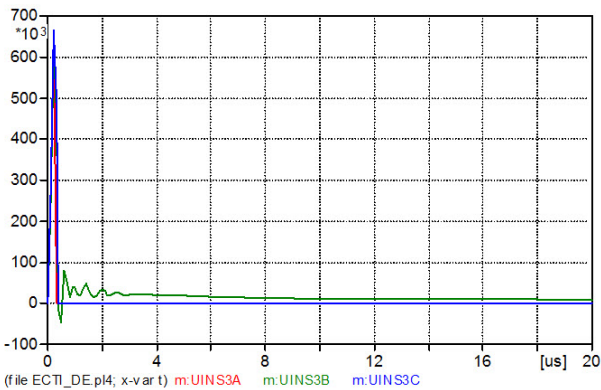

Fig.6: *Voltage across insulator phase A, B and C with flashover occurred on phase A and C using DE.*

Table 1: *Critical current causing flashover*

Critical Current (kA)		
Volt time curve (VT)	Disruptive effect (DE)	Leader progression (LPM)
15	13	13.5

Table I shows critical current causing flashover for VT, DE and LPM flashover models from EMTP simulations. The lightning flashover rates from backflash can be calculated using simplified method given in
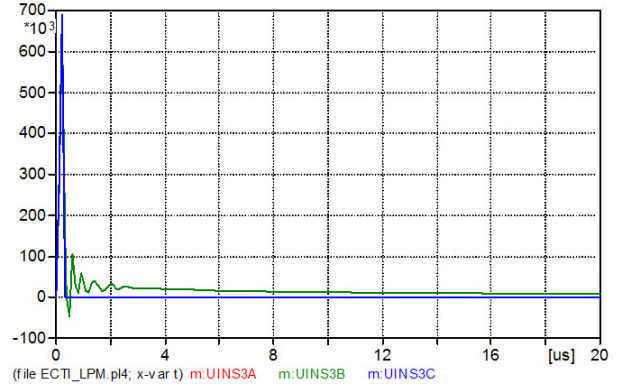

Fig.7: *Voltage across insulator phase A, B and C with flashover occurred on phase A and C using LPM.*

[11]. The number of flashovers on insulators due to backflashover can be calculated as shown in (13).

$$BEPR = 0.6N \cdot p(I_c) \qquad (13)$$

where $p(I_c)$ is the probability of the current exceeding the current i_0 and N is the flash collection rate. The probabilistic distribution of current peak values as shown in (14).

$$p(I \geq i_0) = \frac{1}{1 + \left(\frac{i_0}{A}\right)^b} \qquad (14)$$

For the probabilistic distribution of current peak values from IEEE std. 1410-2010 [1], A=31 kA, b=2.6 and data collected in Thailand, A=34.4 kA, b=2.5. The probabilistic distribution of current peak values from IEEE std. 1410-2010 and data collected in Thailand are close.

The flash collection rate in open ground is estimated by Eriksson's equation [6] as in (15).

$$N = N_g \left(\frac{28h^{0.6} + b}{10}\right) \qquad (15)$$

where $h = $ the pole height, m.
$b = $ the structure width, m
$N = $ the flash collection rate, flashes/100 km/yr

Estimates of average ground flash density (GFD) may also be obtained directly from lightning detection network. The GFD may be estimated from the keraunic level collected in Thailand as shown in (10) proposed by [9]. Base on eq. (12), therefore the BFOR is approximately 8.22 (VT), 8.59 (DE) and 8.48 (LPM) flashes/100 km/yr respectively. (keraunic level considered is 80).

E. Shielding Failure Flashover Rates (SFFOR)
The number of flashovers on insulators due to shielding failure flashover [6] can be calculated as shown in (16).

$$SFFOR = 2N_gL\int_{I=I_c}^{I=I_{max}} D_c(I)f_1(I)d_I \qquad (16)$$

where L is the line length (km), D_c is the horizontal exposed distance of phase conductor (m), and f_i is the probability density of the first stroke current. Therefore the SFFOR is approximately 0.08 flashes/100 km/yr.

F. Induced Voltage Flashover Rates (IVFOR)

The induced voltage flashover can be accomplished with computer program using electrogeometric models and electromagnetic field theory or by using EMTP, however this paper used equations given in IEEE std 1410-2010. The induced voltage flashover model is shown in Fig. 8.
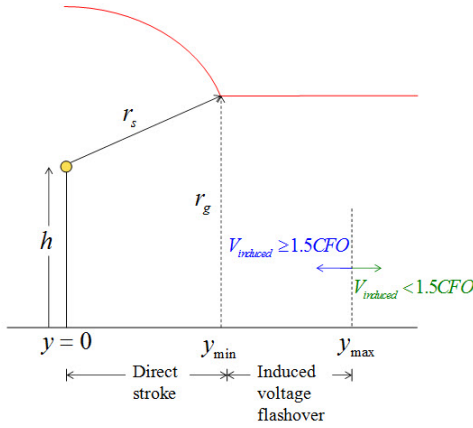

Fig.8: *Induced voltage flashover model.*

The striking distances, r_s and r_g equations taken from IEEE std 1410-2010 [6]. For induced voltage flashover rate, the number of induced voltage flashovers can be calculated as shown in (17).

$$F_p = 2 \cdot N_g \cdot 0.1 \cdot \sum_{i=1}^{200} P_i \cdot (y_{imax} - y_{imin}) \qquad (17)$$

F_p = the number of insulation flashovers per 100 km of line and per year.

y_{imax} = the maximum distance for every peak current interval at which lightning may produce an insulation flashover.

y_{imin} = the minimum distance for which lightning will not divert to the line.

P_i = the difference between the probability for current to be equal or larger than the lower limit and the probability for current to reach or exceed the higher limit, $P(i) - P(i + \Delta i)$.

Fig. 9 presents the frequency of flashover as a function of the critical flashover voltage (CFO) of the line taken into account the effect of soil resistivity (imperfect soil at high frequency). The effect of finite
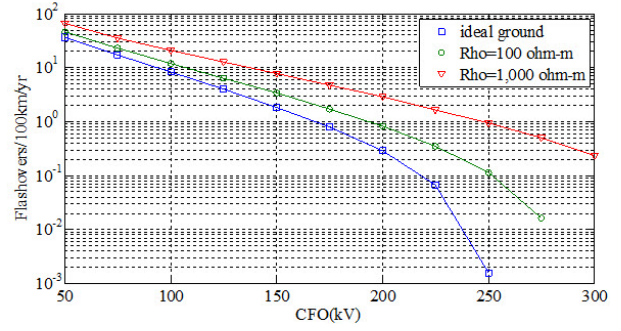

Fig.9: *Number of induced voltage flashovers for different line insulation level.*

soil conductivity on surge impedance can be modeled with acceptable accuracy in lightning calculations [4, 6] by replacing the real height of the line h in (1) with a real value of effective height as shown in (18).

$$h_{eff} = h + \frac{4.7}{\sqrt{\sigma}} \qquad (18)$$

where h = the height of conductor above ground, m.

$\quad$ h_{eff} = the effective height, m.

$\quad$ σ = the conductivity of the uniform, lossy ground beneath the conductor, mS/m.

The ground resistivity of 100 Ω-m is equivalent to conductivity of 10 mS/m and 1,000 Ω-m is equivalent to 1 mS/m. As mentioned in IEEE Std 1410-2004 the Rusck's model for a distribution line shielded by nearby objects gives unrealistic estimates of distribution line performance, as shown in the top curve of Fig. 8. Because much of the distribution line is shielded, larger magnitude strokes can terminate close to the line, without striking the distribution line directly. This will cause more induced voltage flashovers. The number of induced voltage flashovers should be somewhere between the number of induced voltage flashovers in open ground and the number of direct lightning hits in open ground [6]. From Fig. 7 the number of induced voltage flashovers are 0.66 flashes/100 km/yr (CFO=180 kV) and the number of direct hits in open ground are 15.8 flashes/100 km/yr. As an estimate, IEEE Std.1410-2010 assumes that the induced voltage flashovers are two times the induced flashovers in open ground. Therefore for ideal ground, the IVFOR is approximately 1.32 flashes/100 km/yr, 1.48 at soil resistivity of 100 Ω-m and 4.28 at soil resistivity of 1,000 Ω-m. Consider IVFOR at soil resistivity of 100 ohm-m,

For the distance of line route being studied of approximately 20 km. The number of flashovers are approximately 1.956 flashes/yr. The report of line outages from the recorder for the past three years have shown that the number of outages from lightning has the average value of 2.7 flashes/yr as shown in Table II which means the GFD from Eq. (12) seems
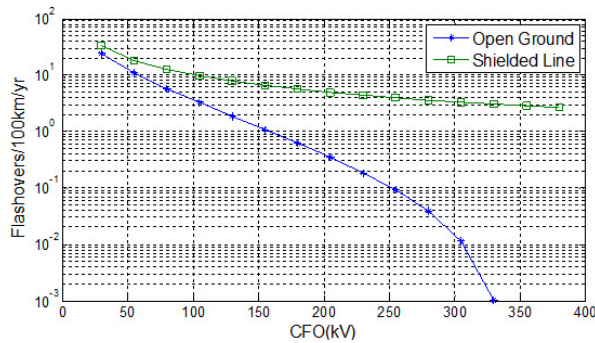
Fig.10: *Number of induced voltage flashovers for open ground and shielded line.*

Table 2: *Total number of line outages from recorder*

Causes of line outage								
Fog			Normal events			Rain and Thunderstorm		
'08	'09	'10	'08	'09	'10	'08	'09	'10
3	2	5	13	5	9	2	3	3

to match with the data from the recorder much more than equation given in IEEE std 1410-2010. The total numbers of lightning flashovers rates from simulation using EMTP and calculation using equations given in IEEE std 1410-2010 is close to the data from the line outage recorder.

4. CONCLUSIONS

The lightning overvoltage of 22 kV overhead distribution line by means of BFOR, SFFOR and IVFOR of line have been determined. For BFOR, the flashover model of volt time curve from testing has been implemented. Because of the line configuration has been studied are in horizontal with one overhead ground wire that can almost protect the three phase conductors so SFFOR is very small when compared to BFOR. IVFOR can increase for low insulation level, however CFO for system being studied is 180 kV so IVFOR will contribute the number of flashovers in some level.

In order to calculate the BFOR, the performance of line which related to the insulator backflashover has been modeled and analyzed using EMTP. The critical current causing flashing from VT, DE and LPM are closed. The SFFOR and IVFOR have been calculated follow equations given in IEEE std 1410-2010. Finally BFOR, SFFOR and IVFOR of line have been determined. The numbers of lightning flashovers rates of BFOR, SFFOR and IVFOR have been compared with the data taken from the line outages recorder. From the system being studied shown that, the total number of flashovers from simulation and calculation is close to the data from the line outage recorder.

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