Improving The Lightning Performance of Overhead Distribution and Sub-transmission Lines Applying Additional Underbuilt Shield Wire

Thanaphong Thanasaksiri, Non-member

ABSTRACT

This paper analyzes the lightning performance of 22 kV single and double circuit overhead distribution lines and 115 kV sub-transmission line with 22 kV circuit underbuilt by means of installation the additional underbuilt shield wire. The three different shield wire sizes of 25, 35 and 50 mm2 and the placement locations from ground which is taken into account the clearances from the phase conductors and ground have been considered. Evaluating were performed using ATPDraw and calculations by applying the equations from IEEE std. 1243-1997 and 1410-2010 to determine the best placement location and size. For the systems being studied, both for overhead distribution and sub-transmission lines, the additional underbuilt shield wire can be used to gain better lightning performance besides the overhead shield wire.

Keywords: Lightning Performance, Underbuilt Shield Wire, Distribution Line, Sub-Transmission Line, ATPDraw.

1. INTRODUCTION

Lightning continues to be the main cause of line outages not even on overhead distribution lines but also on sub-transmission and transmission lines, especially on overhead distribution lines without shield wire. Line outages occurred when insulation flashovers. There are two types of flashover, direct stroke flashover and indirect stroke or induced voltage flashover. The direct stroke occurs when lightning hits shield wire (or pole/tower) or phase conductors which can leads to backflashover and shielding failure flashover respectively. The indirect stroke occurs when lightning hits ground or nearby objects leading to induced voltage flashovers. Those flashovers when occurred may cause line outages as a sequence.

Options for improving the lightning performance of overhead distribution lines could be improved ground, increasing insulator critical flashover voltage (CFO), add surge arresters, move shield wire and add shield wire [1]. Mostly when utilities would like to improving the lightning performance, they are mainly focus on the most effective way (both technical and economical points of view) which is improving the footing resistance much more than other options. However when reducing the footing resistance is limited, the other options may be selected.

Equipment and support hardware on structures may severely reduce insulator CFO [3]. By increasing the insulation level (CFO) of the line, the chances of a flashover are reduced. Especially induced voltage flashovers should not be a problem for distribution lines where the Critical Flashover Voltage (CFO) is at least 300 kV. But, unless the insulating level is that of a transmission line, there will still be flashovers [2], [3]. However increasing the insulator CFO may need to review the potential impact on the line lightning performance [1] and line uprating if need, could improve the lightning performance.

Surge arresters protect against both direct lightning strikes and from induced voltages which can reduce the occurrence of flashovers and circuit interruptions. Arresters act to limit the surge voltages to a level less than that of the breakdown, or flashover, voltage of the insulation. The closer the arresters locations are to each other, the better the flashover performance. The closer the arresters are to each other, the more that they can share the lightning current and a chance of causing an arrester failure [3], [4]. The lightning discharge energy duty may cause some distribution arrester failures, especially on unshielded lines in open areas [2]. In theory, for protecting against direct stroke, arresters may provide protection against direct strokes, but they must be installed with very close spacing, at every pole or every other pole depends on CFO and footing resistance [3], [5] which the cost for adding surge arresters are very expensive. On the other hand, if arresters are widely spaced, greater than every 5 to 6 poles, then there is very little flashover protection [3], [4]. For protecting against indirect stroke, a significant improvement of the lightning performance of the considered distribution line can be obtained only when the arrester stations spacing is about 300 m or lower [3], [5].

Overhead shield or ground wire (OHGW) is a wire

Manuscript received on May 28, 2014 ; revised on June 9, 2014.
The authors is with Department of Electrical Engineering, Chiang Mai University, Chiang Mai, Thailand, E-mail : tthana@ee.eng.cmu.ac.th

that is installed above the phase conductors and tied to ground through ground lead at each pole. The only drawback to shield wire protection is the lack of protection from induced overvoltages if the lightning strike is close enough to the line to induce a voltage that is greater than the insulating level of the line [4]. To be effective, shield wire requires very good grounding. The lower the ground resistance, the better the lightning performance [3], [6]. Also to be effective, the shielding angle should be as small as possible. The shielding angle of 45° for distribution lines and 30° for transmission lines were usually employed and recommended [3], [6]. Most of the time, moving shield wire (up/down or left/right) or repositioning may not gained any benefit when compared to other options.

Adding shield wire above phase conductors can intercept a lightning strike which prevent the shielding failure especially for transmission line with the negative shielding angle [6]. Adding shield wire, one or more shield wires under the phase conductors or underbuilt shield wires can reduce the outage rate at some degree. IEEE Std. 1243-1997 [6] mentions the special methods of improving lightning performance using additional shield wires on 345 kV double circuits line. By applying three or four shield wires, the outage rate can be reduced lower than 0.63 per 100 km/yr depends on the location of additional shield wires.

Adding underbuilt shield wire is of interested for this paper. In order to investigate the lightning performance of a particular 22 kV overhead distribution line design and also 115 kV sub-transmission line with 22 kV circuit underbuilt. It was thought technically that installing additional underbuilt shield wire of single and double circuits of 22 kV overhead distribution line and 115 kV sub-transmission line was one choice of the most effective improving the lightning performance which can be possible. Evaluating were performed using ATPDraw [7] and some calculations by applying equations from IEEE std. 1243-1997 and 1410-2010 [3] to verify this assumption and determine the best placement location and size.

2. SYSTEM MODELLING

The single circuit overhead distribution line configurations have been analyzed : Configuration 1 : P1 (No shield wire), Configuration 2 : P2 (Line protected by shield wire on pole top), Configuration 3 : P2-G0 (Line protected by shield wire on pole top and additional underbuilt shield wire, 8.85 m height from ground) Configuration 4 : P2-G1 (Line protected by shield wire on pole top and additional underbuilt shield wire, 8.50 m height from ground) and Configuration 5 : P2-G6 (Line protected by shield wire on pole top and additional underbuilt shield wire, 7.80 m height from ground).

The double circuit overhead distribution line configurations : Configuration 6 : P1920 (No shield wire), Configuration 7 : P3435 (Line protected by shield wire on pole top), Configuration 8 : P3435-G0 (Line protected by shield wire on pole top and additional underbuilt shield wire, 8.85 m height from ground) Configuration 9 : P3435-G1 (Line protected by shield wire on pole top and additional underbuilt shield wire, 8.50 m height from ground) and Configuration 10 : P3435-G6 (Line protected by shield wire on pole top and additional underbuilt shield wire, 7.80 m height from ground).

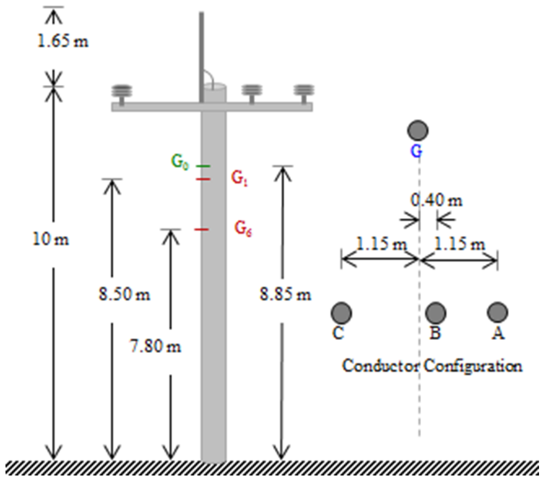

Fig.1: *Typical 22 kV single circuit overhead distribution line section (P2, P2-G1, P2-G6).*

The configurations studied for distribution lines are shown in Fig. 1 for single circuit and in Fig. 2 for double circuits. The overhead distribution line conditions were as follows, **Line length:** 100 km, **Span length:** 40 m, **Footing resistance:** 10, 25, 50, 100, 500 and 1,000 Ω, **GFD (Ground flash density):** 1 flash/km^2/yr, **Phase conductors:** PIC (Partial Insulated Cable), 185 mm^2, **Shield wire:** Steel wire, 25 mm^2, **Additional underbuilt shield wire sizes:** 25, 35 and 50 mm^2, **Line insulation:** Pin type (56-2), **Structure type:** Concrete pole, **Placement locations of underbuilt shield wire:** 7.80 (G_6), 8.00, 8.23, 8.35, 8.50 (G_1), 8.70 and 8.85 (G_0) m height from ground. Due to the clearance of 1.2 m between the phase conductors of 22 kV (phase B) and the neutral wire of low voltage system (380/220 V), the highest placement location of underbuilt shield wire from ground being studied is 8.85 (G_0) m. The clearance from ground allows the lowest placement location of underbuilt shield wire to be 7.80 (G_6) m.

The sub-transmission line configurations : Configuration 1 : U115-22 (Shield wire on pole top), Configuration 2 : U115-22-G0 (Line protected by one shield wire on pole top and additional underbuilt shield wire, 8.85 m height from ground) Configuration 3 : U115-22-G1 (Line protected by one shield wire on pole top and additional underbuilt shield wire, 8.50 m height from ground) and Configuration 4 : U115-

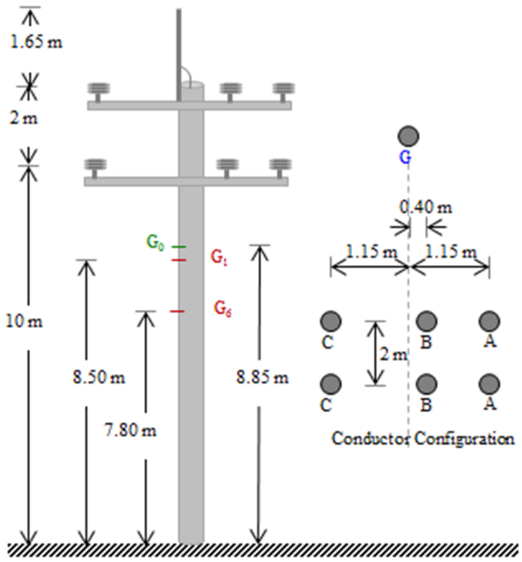

Fig.2: *Typical 22 kV double circuit overhead distribution line section (P3435, P3435-G1, P3435-G6).*

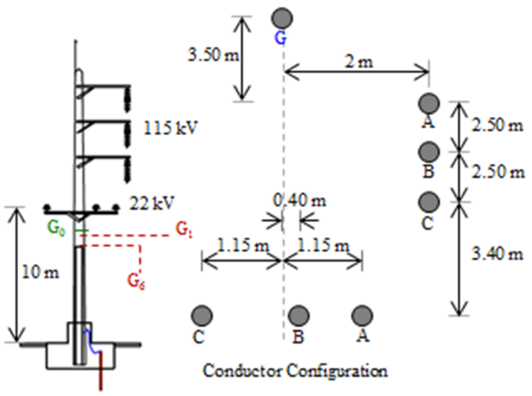

Fig.3: *Typical 115 kV sub-transmission line with 22 kV distribution line underbuilt (U115-22, U115-22-G1, U115-22-G6).*

22-G6 (Line protected by one shield wire on pole top and additional underbuilt shield wire, 7.80 m height from ground).

The configurations studied for sub-transmission line (115 kV on top and 22 kV circuit underbuilt) is shown in Fig. 3. The overhead sub-transmission line conditions were as follows, **Line length:** 100 km, **Span length:** 80 m, **Footing resistance:** 10, 25, 50, 100, 500 and 1,000 Ω, **GFD (Ground flash density):** 1 flash/km^2/yr, **Phase conductors:** AAC (All Aluminium Conductor), 400 mm^2, **Shield wire:** Steel wire, 35 mm^2, **Additional underbuilt shield wire sizes:** 25, 35 and 50 mm^2, **Line insulation:** I-string for 115 kV and Pin type (56-2) for 22 kV circuit underbuilt, **Structure type:** Concrete pole, **Placement locations of underbuilt shield wire:** 7.80 (G_6), 8.00, 8.23, 8.35, 8.50 (G_1), 8.70 and 8.85 (G_0) m height from ground.

Therefore the parameters of phase conductor and shield wires of 22 kV overhead distribution line are shown in Table 1. The parameters of phase conductor and shield wires of 115 kV sub-transmission line are also shown in Table 1.

The same clearance of 1.2 m between the phase conductors of 22 kV (phase B) underbuilt circuit gives the same highest placement location of underbuilt shield wire from ground is 8.85 (G_0) m and the lowest placement location of underbuilt shield wire from ground is also 7.80 (G_6) m. Models of system studied have been presented as follow.

A. Pole and Footing Resistance Models

For pole without external ground lead [8], 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, the surge impedance of circular-shaped grounding conductor is given in (2).

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

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).

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

Footing resistance is represented using Weck's model [3]. [6] and [9].

B. Lightning Source Model

Using Heidler model for lightning source [10]. The functional form of current is given in (4).

$$I(t) = \frac{I_{pk}}{\eta} \times \frac{\left(\frac{t}{\tau_1}\right)^n}{\left(\frac{t}{\tau_1}\right)^n + 1} e^{(-t/\tau_2)} \tag{4}$$

where I_{pk} is the peak current, τ_1 is rise time constant, τ_2 is tail time constant, n is concave factor (=5) and η is the peak correction factor.

From ATPDraw, the HEIDLER surge function TYPE 15 [7] has been used. Stroke front time = 2 μs, tail time = 100 μs with lightning channel impedance equal to 400 Ω. The example of Heidler waveshape is shown in Fig. 4.

Table 1: *Parameters of 22 kV Distribution Lines and 115 kV Sub-transmission Line.*

Conductor type	Conductor size	Overall diameter (mm)	Resistance (ohms/km)	Resistance ohms/km
PIC	185 mm^2	19.4	0.2107	0.3192
AAC	400 mm^2	27.0	0.0874	0.3062
Steel	25 mm^2	6.3	11.4950	1.2430
Steel	35 mm^2	7.5	9.4420	1.0940
Steel	50 mm^2	9.0	7.6910	0.9613

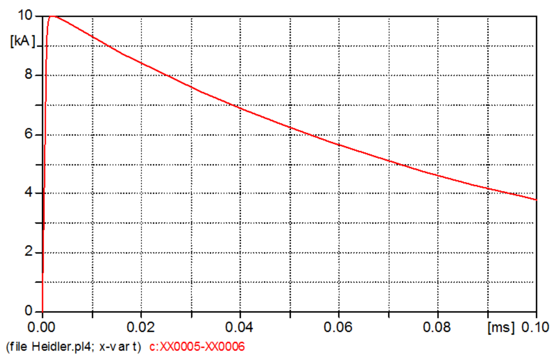

Fig.4: *Heidler waveshape with peak current of 10 kA, 2/100 μs.*

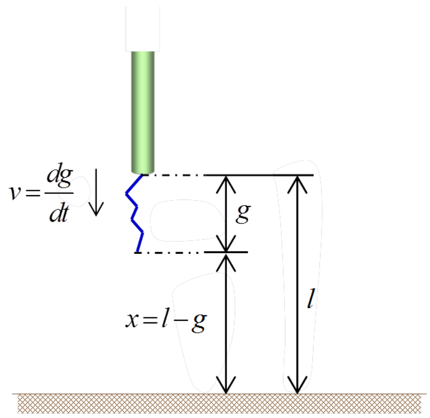

Fig.5: *Leader progression model (LPM).*

C. Flashover Model

The flashover model for the simulation has been applied using leader progression model (LPM). The expression for leader progression model [9] is given in (5) and the process model is shown in Fig.5.

$$\frac{dg}{dt} = kV(t)\left[\frac{V(t)}{l-g} - E_0\right] \tag{5}$$

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 equals zero, the insulator flashover. The LPM has been implemented in ATP-Draw by using MODELS programming language.

D. BackFlashover Rates

The lightning flashover rates from backflash can be calculated using simplified method given in [11]. The number of flashovers on insulators due to back-flashover can be calculated as shown in (6).

$$BFOR = 0.6N \cdot p(I_c) \tag{6}$$

where N is the flash collection rate, flashes/100 km/yr.

The flash collection rate in open ground is estimated by Eriksson's equation [3], [6] as in (7).

$$N = N_g\left(\frac{28h^{0.6}+b}{10}\right) \tag{7}$$

where h = the pole height, m., b = the structure width, m., N_g = the ground flash density (GFD), flashes/km^2/yr.

$p(I_c)$ is the probability of the current exceeding the current i0. The probabilistic distribution of current peak values as shown in (8).

$$p(I \geq i_0) = \frac{1}{1+\left(\frac{i_0}{A}\right)^b} \tag{8}$$

For the probabilistic distribution of current peak values from IEEE std. 1410-2010 [3], [6], A=31 kA and b=2.6.

E. Shielding Failure Flashover Rates

The number of flashovers on insulators due to shielding failure flashover [3], [6] can be calculated as shown in (9).

$$SFFOR = 2N_gL\int_{I=I_c}^{I=I_{max}} D_c(I)f_1(I)dI \tag{9}$$

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 (subsequent strokes have not be considered).

F. Induced Voltage Flashover Rates

The induced voltage flashover used equations given in IEEE std 1410-2010. The induced voltage flashover

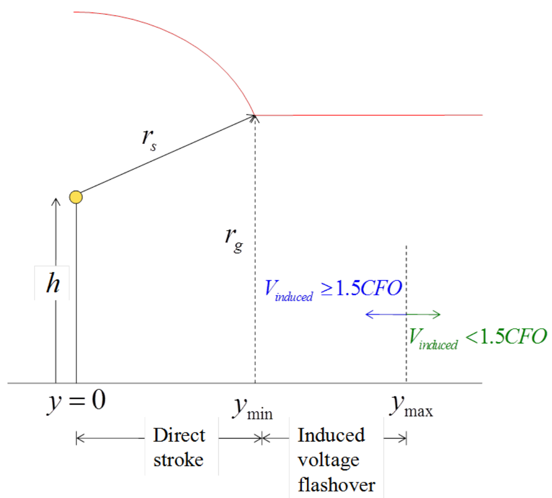

Fig. 6: *Induced voltage flashover model.*

model is shown in Fig. 6. The striking distances, r_s and r_g equations taken from IEEE std 1410-2010. For induced voltage flashover rate, the number of induced voltage flashovers can be calculated as shown in (10).

$$F_p = 2 \times \sum_{i=1}^{200} (y_{i\,\max} - y_{i\,\min}) \times N_g \times P_i \times 0.001 \qquad (10)$$

Where F_p is the number of insulation flashovers per km of distribution line and per year, y_{max} is the maximum distance for every peak current interval at which lightning may produce an insulation flashover, y_{min} is the minimum distance for which lightning will not divert to the line and P_i is 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.

3. RESULTS

For 22 kV overhead distribution lines, due to the clearance from the phase conductors and from the ground. Also the clearance of 1.2 m between the phase conductors of 22 kV (normally phase B) and the neutral wire of low voltage system (380/220 V). The placement locations at the height of 7.80 (G6), 8.00, 8.23, 8.35, 8.50 (G_1), 8.70 and 8.85 (G_0) m from ground have been considered. For 115 kV sub-transmission line with 22 kV circuit underbuilt, the same clearance and the placement locations have been applied. The lightning performance of lines which taken into account the footing resistance, the placement locations and shield wire sizes are as follow.

G. Shield Wire Performance on Single Circuit Distribution Lines

For single circuit distribution line, when compare to the unshielded circuit (P1), the shield wire (P2) and the additional underbuilt shield wires (P2-G1 and P2-G6) can reduce the number of direct stroke flashovers when footing resistance is less than approximately 25 Ω and 180 Ω respectively as shown in Fig. 7. The number of induced voltage flashovers is also reduced for any footing resistance as shown in Fig. 8.

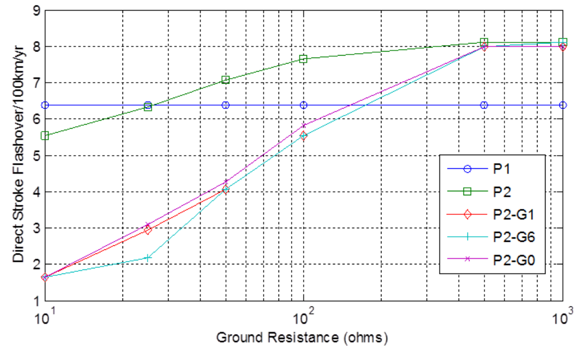

Fig. 7: *Shield wire performance of single circuit distribution line from direct stroke flashovers.*

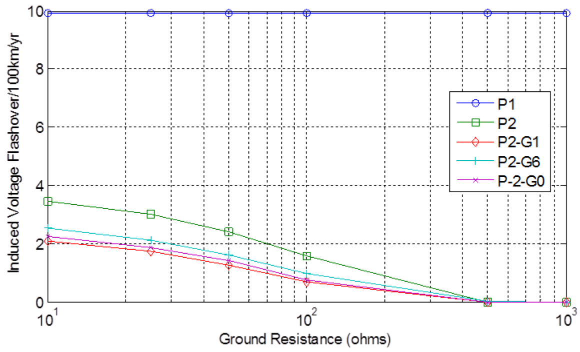

Fig. 8: *Shield wire performance of single circuit distribution line from induced voltage flashovers.*

H. Shield Wire Performance on Double Circuits Distribution Lines

For double circuits distribution line, when compare to the unshielded circuit (P1920), the shield wire (P3435) and the additional underbuilt shield wires (P3435-G1 and P3435-G6) can reduce the number of direct stroke flashovers when footing resistance is less than approximately 55 Ω, 225 and 300 Ω respectively as shown in Fig. 9. The number of induced voltage flashovers is also reduced for any footing resistance as shown in Fig. 10.

From the simulation, both for single and double circuits overhead distribution lines, the additional underbuilt shield wire will reduce the number of direct stroke and induced voltage flashovers which means the line lightning performance would be improved.

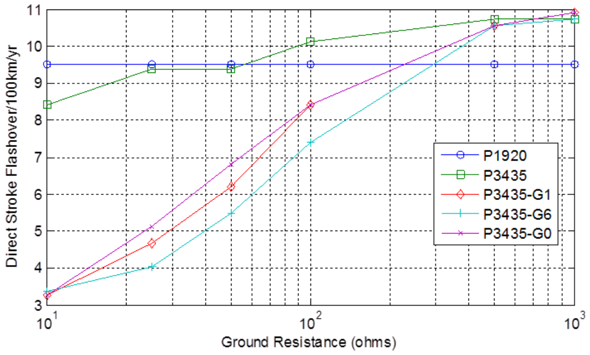

Fig.9: *Shield wire performance of double circuit distribution line from direct stroke flashovers.*

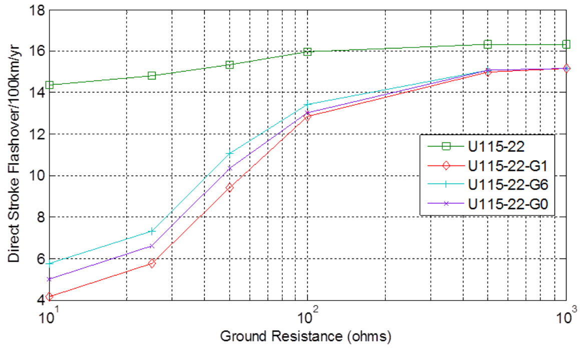

Fig.11: *Shield wire performance of sub-transmission line from direct stroke flashovers.*

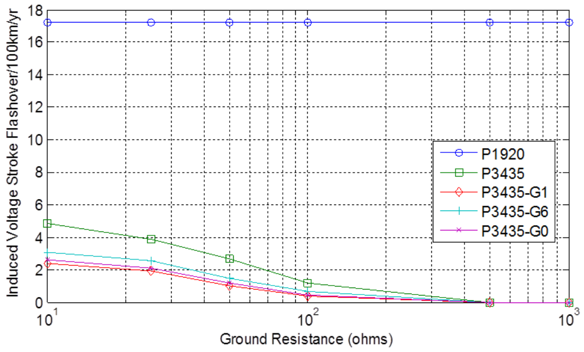

Fig.10: *Shield wire performance of double circuit distribution line from induced voltage flashovers.*

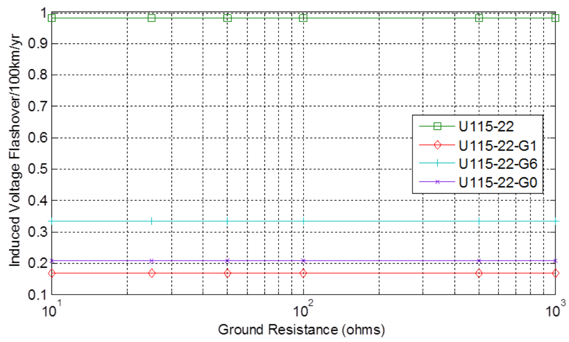

Fig.12: *Shield wire performance of sub-transmission line from induced voltage flashovers.*

I. Shield Wire Performance on Sub-transmission Lines

For sub-transmission line (115 kV sub-transmission line with 22 kV circuit underbuilt), when compare to the line installs shield wire on pole top only (U115-22), the additional underbuilt shield wires (U115-22-G1 and U115-22-G6) can reduce the number of direct stroke flashovers for any footing resistance as shown in Fig. 11. The number of induced voltage flashovers is also reduced for any footing resistance as well which is shown in Fig. 12. Again, from the simulation, the additional underbuilt shield wire will reduce the number of direct stroke and induced voltage flashovers which means the line lightning performance would be improved.

J. Effect of Placement Location of Underbuilt Shield Wire

For single circuit distribution lines being studied (P2-G1, P2-G6) and double circuits distribution lines being studied (P3435-G1, P3435-G6), to reduce the direct stroke flashovers, the placement location of additional underbuilt shield wire at the height of 7.80 m is recommended as shown in Fig. 7 and 9. To reduce the induced voltage flashovers, the placement location of additional underbuilt shield wire at the height of 8.50 m is recommended as shown in Fig. 8 and 10. For better lightning performance on overhead distribution lines, the simulations have shown that the placement location at the height of 7.80 for direct stroke flashovers and 8.50 for induced voltage flashovers are preferred.

For sub-transmission line being studied (U115-22-G1, U115-22-G6), to reduce the direct stroke flashovers and induced voltage flashovers, the placement location of additional underbuilt shield wire at the height of 8.50 m is recommended as shown in Fig. 11-12. For better lightning performance on sub-transmission lines, the simulations have shown that the same placement locations at the height of 8.50 both for direct stroke flashovers and induced voltage flashovers are preferred.

The reason for better lightning performance of distribution and sub-transmission lines are the additional underbuilt shield wire will improve the coupling and reduce voltages across the insulators which leads to reduce the numbers of flashovers or improving the lightning performance [6].

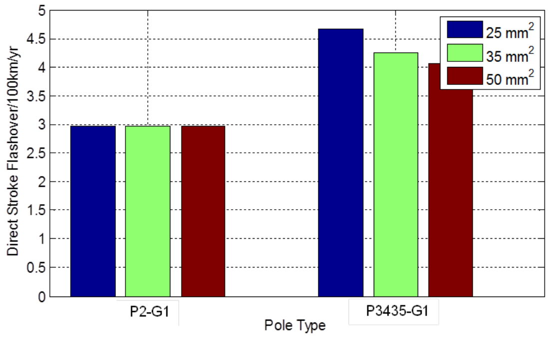

Fig.13: *Effect of shield wire size from direct stroke flashovers on distribution line at position* G_1.

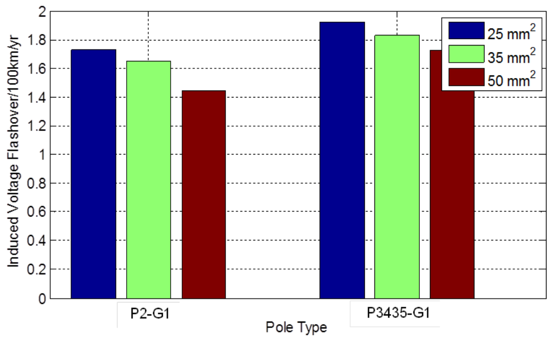

Fig.14: *Effect of shield wire size from induced voltage flashovers on distribution line at position* G_1.

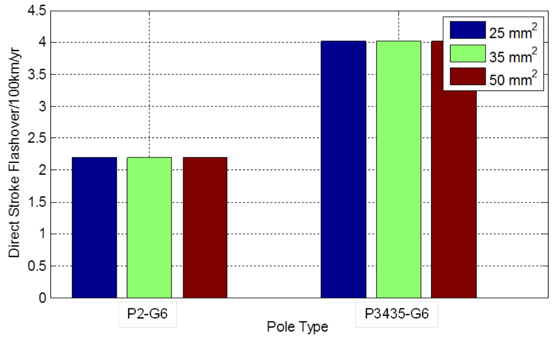

Fig.15: *Effect of shield wire size from direct stroke flashovers on distribution line at position* G_6.

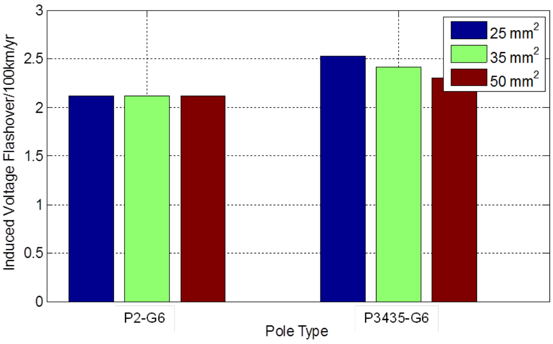

Fig.16: *Effect of shield wire size from induced voltage flashovers on distribution line at position* G_6.

K. Effect of Shield Wire Sizes

The shield wire sizes of 25 mm^2, 35 mm^2 and 50 mm^2 have been evaluated which may affect the distribution and sub-transmission lines lightning performance. Fig. 13 and 14 show the effect of additional underbuilt shield wire sizes at the height of 8.50 m from ground on direct stroke and induced voltage flashovers for single (P2-G1) and double circuits (P3435-G1) overhead distribution lines respectively. The direct stroke and induced voltage flashovers will be affected by the different shield wire sizes except for direct stroke flashover on P2-G1.

Fig. 15 and 16 show the effect of additional underbuilt shield wire sizes at the height of 7.80 m from ground on direct stroke and induced voltage flashovers for single (P2-G6) and double circuits (P34-35G6) overhead distribution lines respectively. The direct stroke and induced voltage flashovers will not be affected by the different shield wire sizes except for induced voltage flashover on P3435-G6.

The lightning performance shows in Fig. 13-16 have been simulated at the footing resistance of 25 Ω. The reason is Provincial Electricity Authority (PEA) tries to keep the footing resistance as low as possible and most of the time the footing resistance which lower than or equal the value of 25 Ω is preferred. When compared the number of flashovers (both direct stroke and induced voltage) on single and double circuits for the different shield wire sizes of 25, 35 and 50 mm^2. If there is any effect from the different shield wire sizes contribute to the line lightning performance as shown in Fig. 13-16, they will affect significantly when the GFD is getting higher. The bigger shield wire sizes, the better lightning performance. From the simulation, the underbuilt shield wire size of 50 mm^2 give the best lightning performance.

For sub-transmission line, the line with the different additional shield wire sizes of 25 mm^2, 35 mm^2 and 50 mm^2 at the placement location of 8.50 m (U115-22-G1) and 7.80 m (U115-22-G6) from ground give better lightning performance when compared to the line which installs only one shield wire on pole top (U115-22) but all of them have be given the same results. Which means that for the line configurations being studied, the different shield wire sizes will not affect the degree of improving the lightning performance as shown in Fig. 17-18 (As before, the lightning performance is shown at the footing resistance of 25 Ω).

4. CONCLUSIONS

The lightning performance of 22 kV single and double circuits overhead distribution lines and 115 kV sub-transmission line with 22 kV circuit underbuilt by

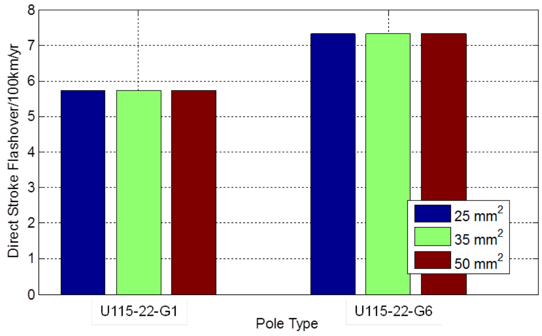

Fig.17: *Effect of shield wire size from direct stroke flashovers on sub-transmission line at position* G_1 *and* G_6*.*

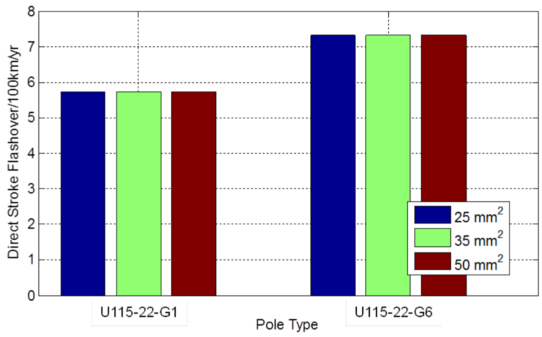

Fig.18: *Effect of shield wire size from direct stroke flashovers on sub-transmission line at position* G_1 *and* G_6*.*

means of installation the additional underbuilt shield wire have been analyzed. The three different shield wire sizes of 25, 35 and 50 mm^2 and the placement locations of 7.80, 8.00, 8.23, 8.35, 8.50, 8.70 and 8.85 m from ground have been considered.

For single and double circuit overhead distribution lines being studied, to reduce the direct stroke flashovers, the best placement location of additional underbuilt shield wire is 7.80 m. To reduce the induced voltage flashovers, the best placement location of additional underbuilt shield wire is 8.50 m. For the sub-transmission line being studied, to reduce the direct stroke and induced voltage flashovers, the best placement location of additional underbuilt shield wire is 8.50 m.

When compared the different shield wire sizes of 25, 35 and 50 mm^2, the different shield wire sizes will affect the lightning performance of overhead distribution lines significantly when the ground flash density is getting higher. The bigger shield wire sizes, the better lightning performance and the size of 50 mm^2 give the best lightning performance. For the sub-transmission lines, the different shield wire sizes will not affect the line lightning performance.

References

[1] Electric Power Research Institute, "Handbook for Improving Overhead Transmission Line Lightning Performance", Technical Report, 2004.

[2] T.E. McDermott, T. A. Short, and J. G. Anderson, "Lightning protection of distribution lines", *IEEE Trans. Power Del.*, vol. 9, no. 1, pp. 138-152, Jan. 1994.

[3] *IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines*, IEEE Std. 1410-2010, 2011.

[4] J. McDaniel, "Lightning protection of distribution lines : things to consider for a reliable design", *Proc. IEEE PES Transmission Distrib. Conf. Exhibition*, 2006, pp. 1229-1232.

[5] A. Borghetti, C.A. Nucci, M. Paolone, and F. Rachidi, "Indirect-lightning performance of distribution lines: influence of protection devices", *Proc. IEEE PES Transmission Distrib. Conf. Exhibition*, 2006, pp. 455-458.

[6] *IEEE Guide for Improving the Lightning Performance of Transmission Lines.*, IEEE Std. 1243-1997,1997.

[7] ATPDraw version 5.8 : www.atpdraw.net.

[8] T. Mozumi, N. Nagaoka, A. Ametani, and S. Sekioka, "An empirical formula for the surge impedance of a grounding conductor along a concrete pole in distribution line," *Proc. Int. Conf. Power Syst. Transients*, 2001, pp. 603-608.

[9] IEEE Modeling and Analysis of System Transients Working Group, "Modeling guidelines for fast front transients," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 493-506, Jan. 1996.

[10] *EPRI AC Transmission Line Reference Book-200 kV and above*, 3rd ed., Electric Power Research Institute, 2005.

[11] A. R. Hileman, *Insulation Coordination for Power Systems*, Marcel Dekker, 1999.

Thanaphong Thanasaksiri received the bachelor degree in electrical engineering from King's Mongkut Institute of Technology Ladkrabang, Thailand, in 1994 and master of science in electrical engineering from Clemson University, USA, in 1997. His current research interests include, power system analysis, transient overvoltages in power and communication systems, modeling of system transients using EMTP and analysis of power system protection under system transients.