Computation of Total Flashover Rate in MEA’s Overhead Transmission Circuit due to Shielding Failure

A. Phayomhom and S. Sirisumrannukul

Abstract— *Flashovers due to shielding failures caused by lightning strokes on 69 kV overhead transmission lines are one of the main causes of electricity interruption in Metropolitan Electricity Authority (MEA)’s service areas. With a geometrical configuration of the tower, a geometrical arrangement of the phase and overhead ground conductors, and a ground flash density, a system performance of a 69 kV circuit can be computed by Alternative Transients Program-Electromagnetic Transients Program (ATP-EMTP). The performance indices are described in terms of shielding failure rate, back flashover rate and total flashover rate. The analysis is conducted on a 69-kV circuit in an area of MEA to determine the effects of a 69 kV circuit placed under the 69-kV circuit and to evaluate the degree to which the number of 24 kV circuits is sensitive to these three indices. The study results reveal that the total flashover rate is significantly decreased with the presence of an under built 24-kV circuit and is sensitive to overhead ground wires with shielding failure. Therefore, this type of transmission configuration not only reduces the failure rate of the transmission line circuit but also provide an attractive solution to right-of-way problems for the transmission and distribution systems in MEA.*

Keywords— **Back flashover rate, Lightning performance, Shielding failure, Total flashover rate.**

1. INTRODUCTION

Metropolitan Electricity Authority (MEA) is an electric power utility that is responsible for power distribution covering an area of 3,192 square kilometers in Bangkok, Nonthaburi, and Samutprakarn provinces of Thailand. MEA serves approximately 35.32 % of the whole country power demand in 2010 .About 90% of MEA’s distribution networks consist of overhead lines classified as transmission lines (230 kV), sub-transmission lines (69 kV and 115 kV) and distribution lines (12 kV and 24 kV). In many cases, due to the restriction of the right of way, transmission and distribution lines have to be installed at the same poles. As a result, transmission lines are placed at the upper part of the pole with an overhead ground wire (OHGW) as shield wire on the top and the distribution lines are placed under the transmission lines.

The electricity interruptions from lightning are categorized into three major types depending upon its striking position. First, lightning directly strikes to the overhead ground wire. If the lightning current is within a designed standard limit for protection system, then the insulator is able to withstand it. However, if the tower footing resistance is high, it will cause a high different voltage between the phase conductor and the OHGW. If this different voltage is higher than the critical flashover voltage (CFO) of insulators, a flashover will occur to the insulators. This event is called “backflash over”. Second, lightning directly strikes to a distribution line. If the voltage across the insulators exceeds the CFO of the insulators, a flashover will occur to the insulators. This event originates from shielding failure and is occasionally found. In this case, the lightning-hit conductor may be broken. Finally, lightning strikes near distribution lines or on the ground. In this case, a voltage will be induced on the phase conductors. If this induced voltage exceeds the CFO of insulator, the flashover will occur to the insulators. This type of overvoltage is more often found than the other two but with low lightning current and therefore in many cases, its contribution to electricity interruption can be neglected [1]-[3].

As briefly described, construction of overhead ground wire for 24 kV distribution feeders in MEA’s system has been facing the right of way problem. This issue can be effectively avoided by installing a 24 kV circuit under a 69 kV circuit. Both circuits then share the same towers and hence this configuration, of course, reduces the construction costs. However, the effects arising from the installation of the integrated systems of 24 kV and 69 kV need to be investigated in detail in terms of distribution, transmission and overall delivery performances.

This paper presents the computation of lightning performances of a sub-transmission system of 69 kV where there is a 24 kV circuit under built. With a geometrical configuration of the tower, a geometrical arrangement of the phase and overhead ground conductors, and a ground flash density, a system performance of a 69 kV circuit can be computed by Alternative Transients Program-Electromagnetic Transients Program (ATP-EMTP). The performance indices are described in terms of shielding failure

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flashover rate *(SFFOR)*, back flashover rate*(BFOR)* and total flashover rate *(TFOR)*. The developed methodology is tested with an existing pole configuration of 69 kV and 24 kV circuits in MEA. Extensions from the existing configuration are also purposed to include an added number of overhead ground wires and 24 kV circuits.

2. CONFIGURATION OF EXISTING 24 kV AND 69 KV SYSTEMS IN MEA

Detail of 69 kV and 24 kV Circuits

The configuration and grounding system of a 69 kV subtransmission system with underbuilt 24 kV distribution feeders in MEA is shown in Figure 1. The reinforced concrete pole is 22 m high. The 69 kV circuit consists of 2×400 mm^2 all-aluminium conductor (AAC) per phase, while the double circuit of the 24 kV circuit consists of 1×185 mm^2 spaced arial cable (ASC) per phase. A 1×38.32 mm^2 OHGW is directly connected to a ground wire embedded in the concrete pole. The ground wire is connected to a 3-m-long ground rod with a diameter of 15.875 mm [4].

Detail of 24 kV Circuits

The reinforced concrete pole of a 24 kV circuit is 12 m high. The 24 kV circuit consists conductors and an OHGW (see Figure 1) but ground wire is external ground wire by attach the pole which connected to a 2.4 m-long and ground rod with a same diameter of 69 kV. Therefore the induced voltage from the lightning has a traveling velocity to ground of 300 $\text{m}/\mu s$ while that of 69 kV is 123 $\text{m}/\mu s$ since the ground wire of the latter case is embedded in the concrete [4].

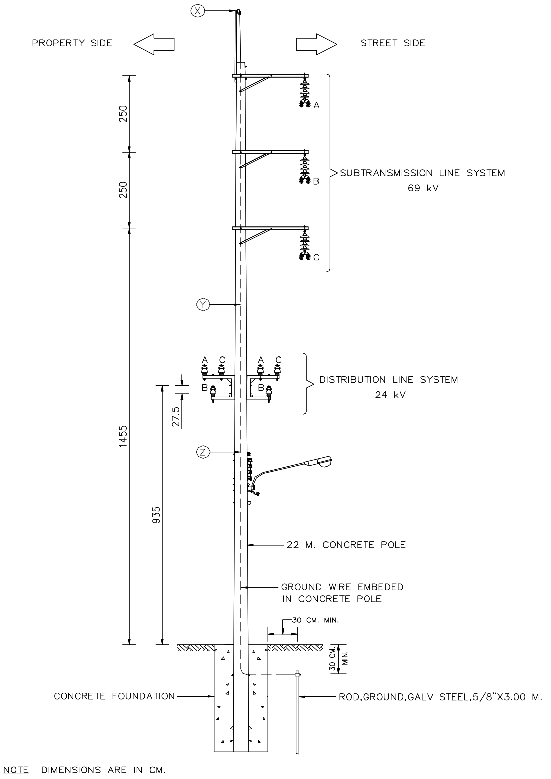


Fig.1. Installation of 69 and 24 kV Circuits in MEA's Network

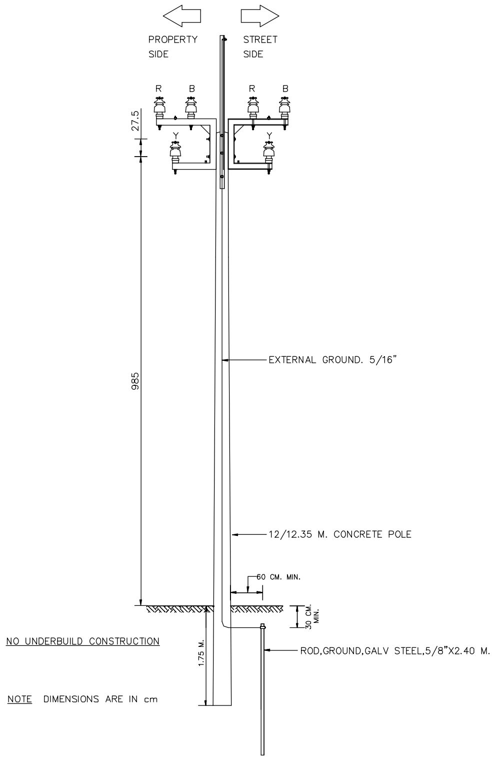


Fig.2. Typical main Line Construction Space Aerial Cable (ASC) 2 Circuit (No Suburbs)

Insulator

A suspension porcelain insulator type 52-3 and a pin post porcelain insulator type 56/57-2 are commonly used in MEA's system. The suspension insulator is complied with Thai Industrial Standard: TIS.354-1985 and the pin post insulator with TIS.1251-1994 standard. In a 69 kV subtransmission system, a string of 4 suspension insulator units are installed to support a phase conductor, while in the 24 kV feeder, the pin post insulators support the phase conductor. The critical flashover voltage of these two insulators is listed in Table 1 [5], [6]. An approximate figure for the coefficient of variation (*CV*) of self restoring insulation is 3% [7] as shown in Eq. (1).

$$CFO_{NEW} = CFO_{OLD}\left(1 - CV\right) \tag{1}$$

where CFO_{NEW} = new critical flashover voltage

CFO_{OLD} = old critical flashover voltage

CV = coefficient of variation

Table 1. Critical Flashover of Insulators

Insulator Type	CFO (kV)		Coefficient of Variation	
	Positive	Negative	Positive	Negative
52-3(4 unit)	440	415	426.80	402.55
56/57-2 (1unit)	180	205	174.60	198.85

3. ATP-EMTP MODEL

The proposed ATP-EMTP model used to analyze lightning performance is shown in Figure 3. The 69 kV and 24 kV circuits are represented by AC three-phase voltage sources. The OHGW, sub-transmission, and distribution lines are modeled by line constants or cable parameters/cable constants of J. Marti's line model. The ATP-EMTP model is proposed in Figure 3 and needs following parameters:

Frequency for line modeling (see Table 2)
Lightning current model (see Table 2)
Surge impedance of concrete pole
Impulse impedance of ground rod

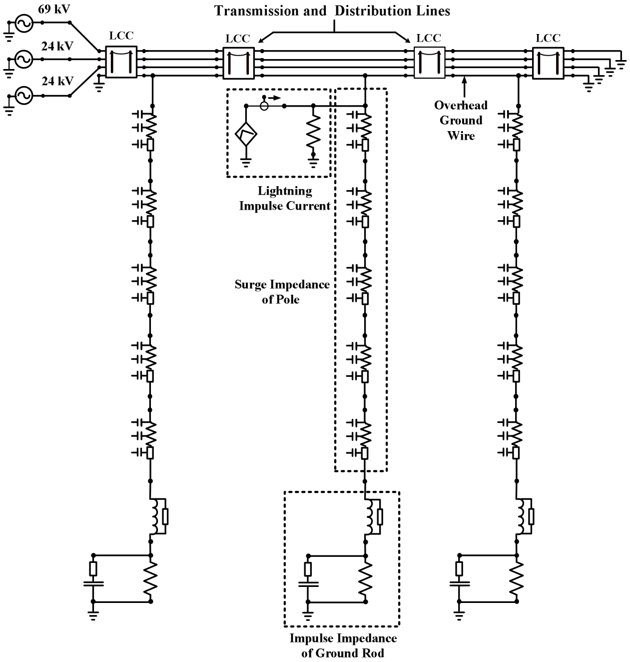


Fig. 3. Typical Diagram of ATP-EMTP

Surge Impedance of Concrete Pole

Surge impedance of pole (Z_T) is the impedance of the grounding path. Its value depends on the height of the pole and the size of the ground wire. Z_T can be expressed as [9]:

$$Z_T = 60\ln\left(\frac{H}{r}\right) + 90\left(\frac{r}{H}\right) - 60 \qquad (2)$$

where Z_T = surge impedance pole (Ω)
H = pole height (m)
r = radius of ground wire (m)

Impulse Impedance of Ground Rod

An equivalent circuit of the ground rod is shown in Figure 4. The resistance, inductance, and capacitance of the under transient phenomenon are calculated by [7], [8]:

$$R_i = \alpha R_0 \qquad (3)$$

$$R_0 = \frac{\rho}{2\pi l}\left(\ln\frac{8l}{d} - 1\right) \qquad (4)$$

$$L = 2l\ln\frac{4l}{d}\times 10^{-7} \qquad (5)$$

$$C = \frac{\varepsilon_r l}{18\ln\left(\frac{4l}{d}\right)}\times 10^{-9} \qquad (6)$$

where R_i = impulse resistance of ground rod (Ω)
α = impulse coefficient
R_0 = resistance of ground rod at power frequency (Ω)
ρ = soild resistivity $(\Omega\cdot\mathrm{m})$
l = total length of ground rod (m)
d = diameter of ground rod (m)
L = inductance of ground rod (H)
C = capacitance of ground rod (F)
ε_r = relative permittivity of solid

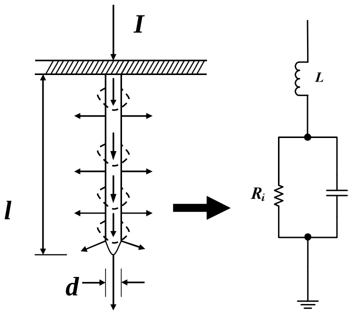


Fig. 4. Equivalent Circuit for Ground Rod under Impulse Condition

4. LIGHTNING PERFORMANCE INDICES

Lightning Statistical Record in MEA's service Area

The number of thunderstorm days in Bangkok, averaged over the period from 1993 to 1997, is 68 days [12]. This number of thunderstorm days are used to calculate the ground flash density (GFD) given by

$$Ng = 0.0133T_d^{\,1.25} \qquad (7)$$

where Ng = ground flash density (flashes/km^2/yr)

The probability of stroke peak current exceeding a given first stroke peak current magnitude can be estimated by

Table 2. Parameters in ATP-EMTP Modeling

Detail	Values	Model
1. Lightning current		Ramp
- Amplitude (kA)	34.4	
- Front time/tail time (μs) [9],[10]	10/350	
2. OHGW of 69 kV and 24 kV		J.Marti
- Diameter (mm)	7.94	
- DC resistance (Ω)	3.60	
3. Phase conductor of 69 kV		
- Diameter (mm)	25.65	
- DC resistance (Ω)	0.0778	
4. Phase conductor of 24 kV		
- Diameter (mm)	15.35	
- DC resistance (Ω)	0.164	
5.Frequency for line modeling		
- Transmission line (Hz)	937,500	
- Distribution line (Hz)	187,5000	
6. Pole of 69 kV		Distributed Parameter
- Height (m)	20	
- Span (m)	80	
- Surge impedance (Ω)	451.4	
- Wave velocity (m/μs) [11]	123	
7. Pole of 24 kV (external ground wire)		
- Height (m)	10.25	
- Span (m)	40	
- Surge impedance (Ω)	378.25	
- Wave velocity (m/μs) [11]	300	
8. Ground rod of 69 kV		
- Diameter (mm)	16	
- Length (m)	3	
- Impulse resistance (Ω)	5	
9. Ground rod of 24 kV		
- Diameter (mm)	16	
- Length (m)	2.4	
- Impulse resistance (Ω)	5	

$$P(I) = \frac{1}{\left(1+\left(\frac{I}{M}\right)^{B}\right)} \tag{8}$$

where T_d = number of thunderstorms (days/yr)
$P(I)$ = probability distribution of stroke current peak magnitude
I = first stroke peak current magnitude (kA)
M = median of stroke peak current magnitude (kA)
B = constant (2.5 for Thailand power system) [12]

A plot of Eq. (8) is shown in Figure 5, where the median is 34.4 kA as of the year 1997.

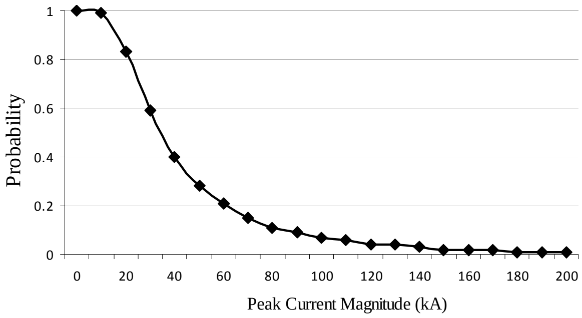


Fig. 5. Probability distribution function for stroke peak current in Thailand

Total Flashover Rate due to Lightning Overvoltage

The occurrence of lightning in different striking positions is an important factor for the calculation of a rate of power failure. The transmission and distribution lines can effectively be protected from lightning by installing an OHGW over the phase conductors to reduce the induced voltages. In practice, this method works well if the maximum vertical angle between the OHGW and each of the phase conductors is narrow, e.g. 30° for towers up to 30 meters high [13]. This angle is known as the shielding angle. Although insulation design for transmission and distribution overhead lines in MEA's service areas complies with the MEA standard, the insulators can withstand overvoltage from lightning only to a certain extent. The maximum current that an insulator can withstand before the occurrence of a backflash is defined as the critical current. For a given critical current, *BFOR* [3], [14] is calculated from (9) and *SFFOR* from (11)

$$BFOR = P(I \geq I_c) \times N_l \tag{9}$$

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

where $BFOR$ = back flashover rate (flashes/100 km/yr)

h = average conductor height (m)
b = separation distance of overhead ground wire (m) [15],[16]
$P(I \geq I_c)$ = cumulative probability of I exceeding or equal to I_c

$$SFFOR = N_l \cdot P(I \leq I_p) \times P(I \geq I_c) \tag{11}$$

where $SFFOR$ = shielding failure flashover rate (flashes/100 km/yr)
$P(I \leq I_p)$ = cumulative probability of I less than or equal to I_p

With a geometrical configuration of the tower, a geometrical arrangement of the phase and overhead ground conductors, the striking distance and the horizontal distance between the OHGW and a rolling sphere centered at point C in Figure 6 are calculated from

$$S = \frac{1}{2}\left[H_G + H_P + A\left(\frac{2W - A}{H_G - H_P}\right)\right] \tag{12}$$

$$W = \frac{H_G A + \sqrt{H_G H_P\left(A^2 + \left(H_G - H_P\right)^2\right)}}{H_G - H_P} \tag{13}$$

where S = striking distance to phase conductor (m)
W = horizontal distance between the OHGW and a sphere centered at point C in Figure 6 (m).
H_G = height of OHGW above the ground (m)
H_P = Height of phase conductor above the ground (m)
A = distance between the phase conductors and the centre of the OHGW (m)

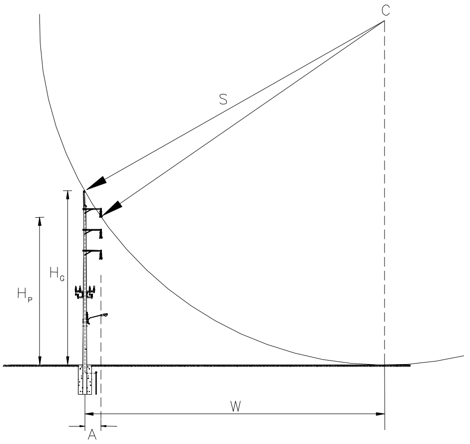


Fig. 6. Striking distance and horizontal distance between the OHGW and a sphere centered at point C

A typical value of striking distance is between 20 and 200 m. The striking distance varies with a lightning current, given by the following relationship.

$$S = F \cdot I_P{}^b \tag{14}$$

where S = striking distance (m)
I_P = lightning current (A)
F = constant from field test
b = constant from field test

The striking distance in (14) is used to calculate the maximum lightning current that the OHGW can protect the phase conductors. A number of methods are proposed to calculate this current as shown in Table 3. In this article, we use the equation of Mousa and IEEE-1995, which will give a maximum current of 14.82 kA whereas the critical current is obtained from ATP-EMTP.

Table 3. Expressions for Striking Distance

Source	Striking Distance to Phase Conductor and Ground Wires		I_P (kA)
Wagner	14.2	0.42	16.55
Armstrong and Whitehead	6.7	0.8	11.16
Brown and Whitehead	7.1	0.75	12.13
IEEE-1992 T&D Committee	10	0.65	10.51
Mousa and IEEE-1995	8	0.65	14.82

5. CASE STUDY

The system in Figure 1 is simulated by a program developed on the ATP-EMTP platform. The lightning performance of this system is analyzed by a lightning current 10/350 μs waveform, and a lightning current magnitude of 34.40 kA, which is the median of the stroke peak current magnitude in Figure 5. The value of R_i is 5 ohm. Ten cases are of interest as follows:

Case 1: This case represents the existing configuration in MEA as shown in Figure 1. There is only one circuit of 69 kV.

Case 2: This case represents the existing configuration in MEA as shown in Figure 2. There is only one circuit of 24 kV.

Case 3: This case represents the existing configuration in MEA as shown in Figure 1. There are one 69 kV and two 24 kV circuits installed on the same pole.

Case 4: This case is an extension of case 3. One additional overhead ground wire is added at point X of Figure 1.

Case 5: This case is an extension of case 3. One additional overhead ground wire is added at point Y, shown in Figure 1. This point is located between the crossarm of phase C of the 69 kV circuit and the upper part of 24 kV circuits.

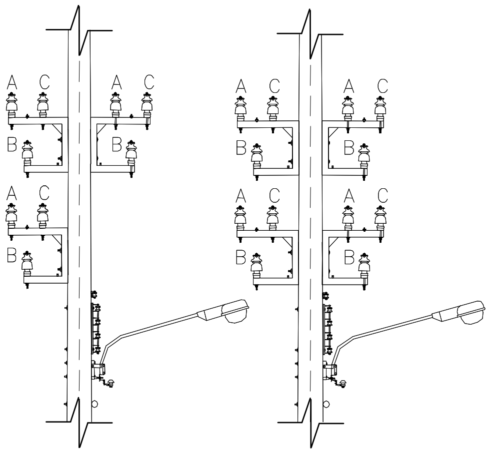
Case 6: This case is is an extension of case 3. One additional overhead ground wire is added at point Z of Figure 1. It is installed at the lower part of the 24 kV circuits

Case 7: This case is an extension of case 3. One 24 kV circuit is added to Figure 1, totaling three 24 kV circuits under the 69 kV circuit shown in Figure 7a.

Case 8: This case is an extension of case 3. Two 24 kV circuit is added to Figure 1, totaling four 24 kV circuits under the 69 kV circuit shown in Figure 7b.

Case 9: This case is an extension of case 3. An OHGW conductor is added to Figure 1. The bundled OHGWs are 40 cm apart and have a shielding angle of 30° respect to one of the phase conductors.

Case 10: This case is an extension of case 8. An OHGW conductor is added to Figure 1. The bundled OHGWs are 40 cm apart and have a shielding angle of 30° respect to one of the phase conductors.



a) Three 24 kV circuits b) Four 24 kV circuits

Fig. 7. Geometrical arrangement of 24 kV circuits under 69 kV circuit

Table 4. Critical for 10/350 μs Waveform (kA) for Calculation of *BFOR*

Case	Critical Current (kA)	
	69 kV	24 kV
1	60.20	-
2	-	78.50
3	62.60	45.90
4	65.60	46.60
5	70.00	29.10
6	66.60	31.60
7	62.80	45.00
8	62.80	45.00
9	77.40	55.50
10	77.00	53.50

Table 5. Critical for 10/350 μs Waveform (kA) for Calculation of *SFFOR*

Case	I_P (kA)		Critical current (kA)	
	69 kV	24 kV	69 kV	24 kV
1	14.82	-	20.70	-
2	-	47.97	-	9.25
3	14.82	14.82	20.70	87.50
4	14.82	14.82	24.40	55.90
5	14.82	14.82	28.20	77.40
6	14.82	14.82	21.80	73.70
7	14.82	14.82	20.70	58.80
8	14.82	14.82	20.70	58.20
9	12.94	12.94	24.90	32.00
10	12.94	12.94	24.80	64.00

Table 6. *BFOR, SFFOR* and *TFOR* for Each Case

Case	Voltage (kV)	*BFOR*	*SFFOR*	*TFOR*	*TFOR* of 69 &24 (kV)
1	69	9.12	3.90	13.02	49.14
2	24	5.19	30.92	36.12	
3	69	8.42	3.90	12.33	27.84
	24	15.07	0.44	15.51	
4	69	7.65	3.51	11.16	26.99
	24	14.69	1.15	15.83	
5	69	6.67	3.11	9.78	38.13
	24	27.77	0.58	28.36	
6	69	7.41	3.79	11.20	37.31
	24	25.46	0.65	26.11	
7	69	8.37	3.90	12.27	28.89
	24	15.57	1.04	16.61	
8	69	8.37	3.90	12.27	28.91
	24	15.57	1.06	16.63	
9	69	5.36	2.54	7.90	20.62
	24	10.70	2.02	12.71	
10	69	5.42	2.55	7.97	20.08
	24	11.47	0.64	12.11	

The critical current of each case for calculation of BFOR is shown in Table 4. The results from Table 4 reveal that the critical currents of the 69 kV circuit in case 3 to case10 are greater than in case 1. The increased critical current for cases 4, 5, 6, 9 and 10 are due to the parallel surge impedances of the added OHGW and for cases 3, 7 and 8 due to the voltage coupling between the 24 kV feeder and the 69 kV phase conductors. For these reasons, the top pole voltage and the voltage across the 69 kV insulators are reduced. In case 2, where only one 24 kV circuit is installed on a 12-m pole, its critical current is lowest as the traveling wave of the induced overvoltage is able to travel faster through the external ground and therefore able to cancel the top pole voltage faster.

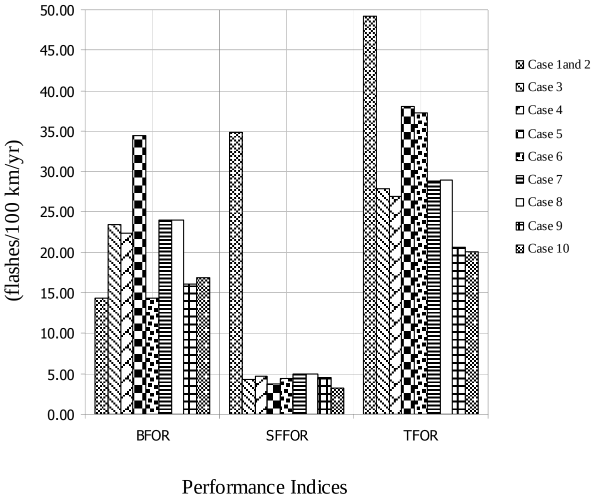


Fig. 8. Lightning Performance Indices for 69 and 24 kV Circuits

Table 7. Statistical Interruption Data

Item	ID. of Sub.Line	Interruption Duration (minutes)		Length of Circuit (km)	*TFOR* (flashes/ 100 km/yr)
		Sustained	Temporary		
1	BOT695		< 1 minute	17.26	5.79
2	BOT698		< 1 minute	12.29	8.14
3	BPT693B		< 1 minute	9.3	10.75
4	LPT693B		< 1 minute	2.22	45.09
5	SKT691	5		26.31	3.80
6	SKT691	4		26.31	3.80
7	SKT691		< 1 minute	26.31	3.80
8	SKT693		< 1 minute	8.97	11.38
9	SKT694	4		6.04	16.57
10	SKT695		< 1 minute	7.70	12.99
11	SKT697	344		9.54	10.49
12	SKT699		< 1 minute	6.25	16.01
13	STT696		< 1 minute	12.03	8.31
14	STT697		< 1 minute	27.93	3.58
15	TTT691		< 1 minute	2.22	6.71
TFOR average 13 subtransmission lines					12.28

The critical current of each case for calculation of SFFOR is shown in Table 5. When a lightning stoke hits a phase conductor, there will be a voltage coupling between the phase conductor and the OHGW. This coupling will reduce the voltage across the 69 kV insulators and therefore increase the critical current. Cases 3 to 10 confirm this explanation. However, the critical current of the 24 kV circuit in cases 3-10 is lower because the external ground is able to help reduce the voltage across the insulator. In addition, cases 3 to 10 have an influence of the voltage coupling from the added OHGW.

The *BFOR*, *SFFOR* and *TFOR* for each case are listed in Table 6 and graphically shown in Figure 8. As shown in Table 6, the *TFORs* for cases 3 to 10 are less than the combined *TFOR* between cases 1 and 2. Such a reduction demonstrates the benefit of OHGW. Case 10 has the lowest *TFOR* for both voltage levels. Compared with case 3, case 10 has a reliability improvement by 27.87%. Although the *TFORs* of cases 9 and 10 are comparable, case 10 would be more attractive particularly in areas of high energy consumption because more power can be transferred. However, as far as safety clearance for field operation and maintenance is concerned, the number of 24 kV circuits may be constrained by these factors. Figure 8 indicates that *BFOR* is contributed more toward electricity outage than *SFFOR*.

As detailed in Table 6, 10 different configurations were investigated for the evaluation of lightning performance. Among these, the configuration in case 3 is extensively used in the subtransmission and distribution systems of MEA. Table 7 shows statistical interruption data due to lightning strike of 13 subtransmission lines of 69 subtransmission systems, collected between January and December of the year 2007. During this period, there were 15 interruptions, classified as 4 sustained interruptions (duration is longer than or equal to one minute) and 11 momentary interruptions (duration is less than 1 minute). The average *TFOR* obtained from the data of this table is 12.28 flashes/100km/yr, which is comparable to the average TFOR of 12.33 flashes/100km/yr simulated by ATP-EMTP.

6. ECONOMIC ANALYSIS

Case 9 is used to evaluate its economic merit described in terms of net present value (NPV). The NPV, which is defined as the total present value (PV) of a time series of cash flows [17], is applied to demonstrate the economic merit. The breakdown of investment cost for the installation of the bundled OHGWs are 40 cm apart and have a shielding angle of 30° respect to one of the phase conductors depicted in Figure 9 is listed in Table 8. From this table, the total investment cost for 100 km sub-transmission lines is calculated as 18,076,285.33 Baht. It was reported in [18] that the interruption cost per event in MEA's service area was 147,500 Baht/event in the year 2000. The total investment cost and the interruption cost are respectively equivalent to 18,076,285.33 Baht/100 km and 296,729.05 Baht/event with a discount rate of 7.24%. The total outage cost can be estimated by the product of 296,729.05 Baht/event and *BFOR*. The total investment cost and total outage cost are then used in the calculation of NPV with the same discount rate (7.24 %) over a period of 25 years. The NPV of the existing system with a shielding angle of 30° is shown in Table 9. Note that the cash flows for the investment cost are considered as positive. The total NPV for each configuration is the summation of NVP from 69 kV and 24 kV circuits whereas the total expected NPV is calculated with the 10/350 µs waveforms. The lower expected value indicates an economic merit to implement this proposed configuration to MEA’s system.

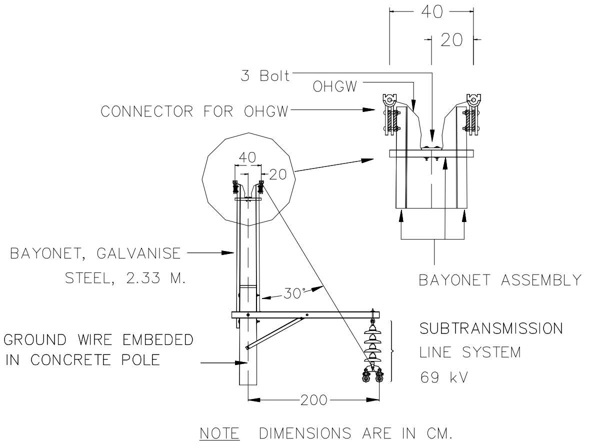


Fig. 9. Bundled OHGWs with shielding angle of 30°

Table 8. Statistical Interruption Data

Item	Investment Cost (Million Baht/100 km)
Material	4.66
Labor	14.29
Work Control	0.19
Transportation	0.23
Operation	0.28
Miscellaneous	0.28
Total	18.95

Table 9. Net Present Value with (Million Baht/100 km)

Description	Configuration	
	Existing system	Existing system with shielding angle of 30°
NPV of 69 kV Circuit	41.73	52.17
NPV of 24 kV Circuit	52.49	26.74
Total Circuit expected NPV	94.22	78.91
Difference of NPV	15.31	

7. APPLICABILITY

There are a number of ways in which the proposed method can be applicable to the practical cases of MEA. First, for example, as indicated in the paper, having both 24 kV and 69 kV circuits on the same pole, although economic, increases the overall *TFOR* and therefore more customer interruption costs can be expected. This existing configuration should be carefully reviewed, particularly in areas of high interruption costs. Second, in areas where lightning strokes have been frequently hit, installation of the bundled OHGW with a shielding angle of 30° helps reduce the *TFOR* of the 69 kV and 24 kV transmission circuits. As shown in case 9 of the case study, the average value *TFOR* is decreased and *SFFOR* of the 69 kV system is decreased by 34.82% (3.90 flashes/100km/yr to 2.54 flashes/100km/yr). Finally, a lower value of ground resistance at the pole foundation is more likely to have a complete cancellation between the lightning wave reflected from the footing and the impulse voltage generated at the top of the pole. Therefore, surveying and collecting the data of ground resistance in MEA's service areas play a crucial role for reliability improvement of the transmission and distribution systems.

The assessment of lightning performance depends on a number of factors, such as ground resistance, surge impedance of subtransmission lines and poles, geometrical arrangement of the phase conductors and the OHGW, lightning current, operating environment of the lines and the number of thunder storm days in the area. If these factors were considered in the proposed method, a good estimate of *TFOR* of the lines would be obtained.

8. CONCLUSION

Direct or indirect lightning stokes on OHGWs may cause power failure in a wide area and damage to electrical equipment in the delivery system as a result of insulation flashover caused by the high energy of the strokes. This paper has analyzed the lightning performance indices of the existing 69 kV and 24 kV circuits installed on the same tower. The computation of the indices consisting of *BFOR*, *SFFOR* and *TFOR* was performed by ATP-EMTP. The analysis was also extended to include the effect of adding one 24 kV circuit or more and adding an additional OHGW in different positions above and below the 24 kV system on the 69 kV subtransmission system. It is observed from the case study that adding feeder increases *TFOR* and that an added OHGW should be placed close to the existing one. In addition, if the constraint on a shielding angle of 30° is satisfied, the system reliability is improved. An optimal geometrical arrangement of the phase and overhead ground conductors of 69 kV and 24 kV circuits needs to be financially justified in conjunction with energy consumption, investment decisions and reliability requirement.

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