Lightning Performance Improvement of 115 kV and 24 kV Circuits by External Ground in MEA's Distribution System

A. Phayomhom and S. Sirisumrannukul

Abstract— *This paper presents the guidelines for preparing a paper for GMSARN International Journal. This document can be used as a template if you are using Microsoft Word 6.0 or later. The abstract should contain not more than 200 words. It should outlining the aims, scope and conclusions of the paper. Do not cite references in the abstract. Do not delete the space before Introduction. It sets the footnote.*

Keywords— **About four key words or phrases in alphabetical order, separated by commas.**

1. INTRODUCTION

Metropolitan Electricity Authority (MEA) is responsible for power distribution covering an area of 3,192 square kilometers in Bangkok, Nonthaburi, and Samutprakarn provinces of Thailand. MEA serves approximately 37 % of the whole country power demand. MEA's networks consist of transmissions, subtransmissions, and distribution systems. The voltage level in transmission systems is 230 kV, in subtransmission systems 69 kV and 115 kV, and in distribution systems 12 kV and 24 kV.

Due to the right of way and obstruction in some service areas, a 24 kV circuit have to be installed under a 115 kV circuit on the same concrete pole. In this configuration, the 24 kV and 115 kV circuits share the same lightning protection that uses a ground wire embedded in the pole to provide a grounding path between an overhead ground wire (OHGW) on the top of the pole and a ground rod located in earth under the pole.

The number of thunderstorm days in Bangkok, averaged over the period from 1993 to 1997, is 68 days [1]. Direct or indirect lightning stokes on OHGWs could lead to power interruption as a result of insulation flashover caused by the high energy of the strokes.

When a lightning stroke hits at the OHGW of a 115 kV subtransmission system, an overvoltage is induced on both the phase conductors of the 115 kV and 24 kV systems. This overvoltage can damage insulators by back flashover if the voltage across the insulators exceeds the critical flashover voltage (CFO) of the insulators. This problem can be solved by the method of external ground.

An external ground is attached along the concrete pole connected between the OHGW and a ground rod. It can help reduce the resistance of the ground rod and the surge impedance of the pole. This method gives a reduction in voltage across the insulator units as well as back flashover rate (BFOR). The benefit of an external ground depends on pole span, line configuration, surge impedance of the pole, and resistance of the ground rod. In this paper, the Alternative Transient Program-Electromagnetic Transient Program (ATP-EMTP) is employed to model and analyze a lightning performance improvement of 115 kV and 24 kV circuits by external grounds. The performances are considered in terms of top pole voltage, critical current and BFOR. Simulation results with and without external grounds for different values of lightning front time and impulse resistance of ground rod are presented.

2. DATA OF SYSTEM STUDIED

Detail of 115 kV and 24 kV circuits

The configuration and grounding system of a 115 kV subtransmission system with underbuilt 24 kV distribution feeders in MEA is shown in Figure 1. The reinforced concrete pole is 20 m high. The 115 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 [2].

Insulator

A suspension porcelain insulator type 52-3 (see Figure 2) and a pin post porcelain insulator type 56/57-2 (see Figure 3) are commonly seen 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 115 kV subtransmission system, a string of 7 suspension insulator units are installed to support a phase conductor, while in the 24 kV circuit, the pin post insulators support the phase conductor. The critical-impulse flashover values of these two insulators are listed in Table 1 [2].

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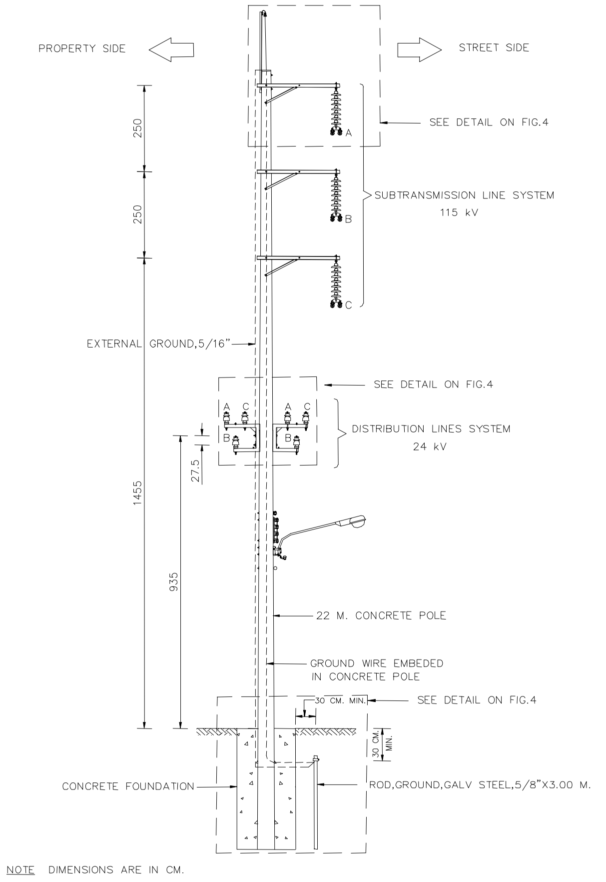

Fig.1. Installation of 115 and 24 kV Circuits in MEA's Network.

Table 1. Critical Flashover Voltage of Insulators [3], [4]

Insulator type	Critical Flashover Voltage	
	Positive (kV)	Negative (kV)
52-3 (7unit)	695	670
56/57-2 (1unit)	180	205

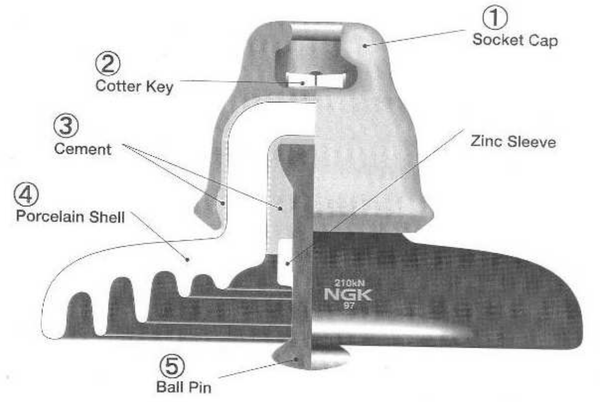

Fig.2. Typical Suspension Insulator Type 52-3.

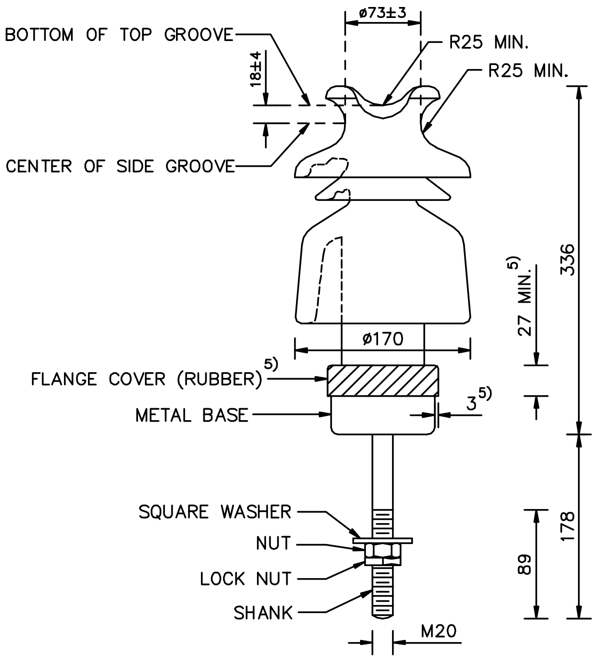

Fig.3. Typical Pin Post Insulator Type 52/57-2.

3. INSTALLATION OF EXTERNAL GROUND

The interruption data in the 115 kV circuits in the year 2006 collected by the Power System Control Department of MEA reveal that lightning strokes resulted in 2 sustained interruptions (interruption duration is greater than or equal to one minute) and 9 momentary interruptions (interruption duration is less than 1 minute). The total length of the 115 kV circuits in MEA's system is 480.30 circuit-kilometers. With these data, the BFOR, calculated from the number of interruptions and the total length, is 2.29 flashes/100 km/year.

In this paper, the method of external ground is applied to the MEA network in order to reduce the back flashover rate (BFOR) value. The method of external ground is implemented by attaching a 1×38.32 mm^2 of zinc-coated steel wire along the concrete pole connected between an overhead ground wire (OHGW) and an existing ground rod. The typical detail of external ground installation and its schematic diagram are provided in Figures 4 and 5.

4. ATP-EMTP MODEL

The proposed ATP-EMTP model used to analyze lightning performance is shown in Figure 6. The 115 kV and 24 kV circuits are represented by AC three-phase voltage sources. The OHGW, subtransmission, 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 6 and needs following parameters:

- Frequency for line modeling
- Lightning current model (Block A)
- Surge impedance of concrete pole (Block B)
- Impulse impedance of the ground rod (Block C)
- Surge impedance of external ground (Block D)

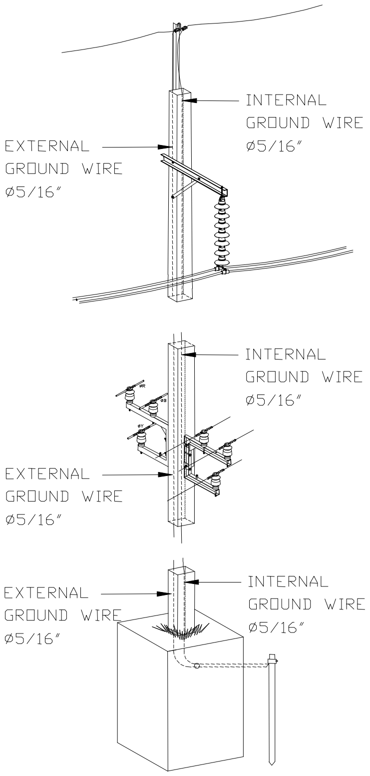

Fig.4. External Ground Installation.

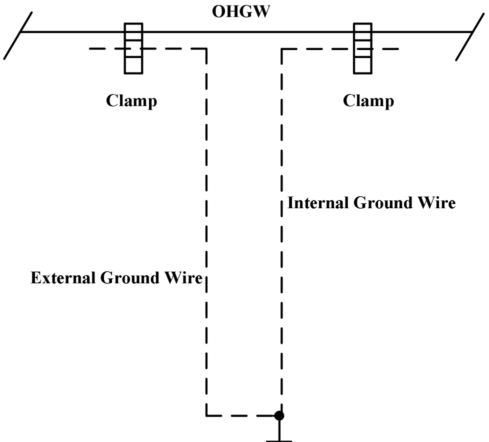

Fig.5. Schematic Diagram of External Ground Installation

Frequency for line modeling

Line parameters (resistance, inductance, and capacitance) are represented by a frequency dependent model of the transient phenomenon of lightning [5]. This frequency varies with the length of line segment. The frequency is calculated by

$$f = \frac{3 \times 10^8}{4 l_{line}} \tag{1}$$

where f = frequency for line modeling (Hz)

l_{line} = line segment of length (m)

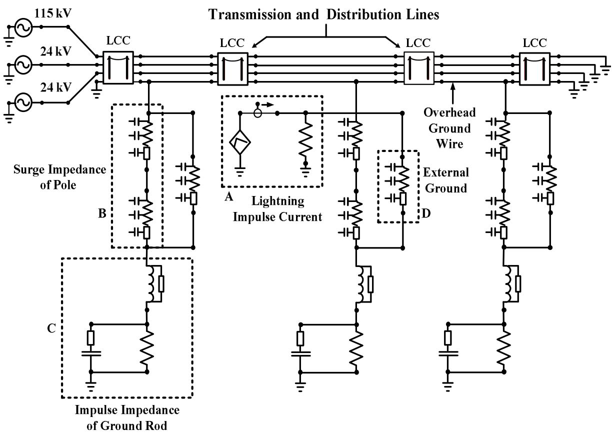

Fig.6. Diagram of ATP-EMTP Model.

Lightning current source model

Lightning is represented by the slope ramp model shown in Figure 7. Three important parameters that identify the characteristic of lightning current waveforms are peak current I_p, front time t_1, and tail time t_2. The peak current is the maximum value of current found in the waveform. The front time is a time interval when the current increases from zero to its peak. The tail time is the sum of the front time and the time that the current falls to 50% of its peak value.

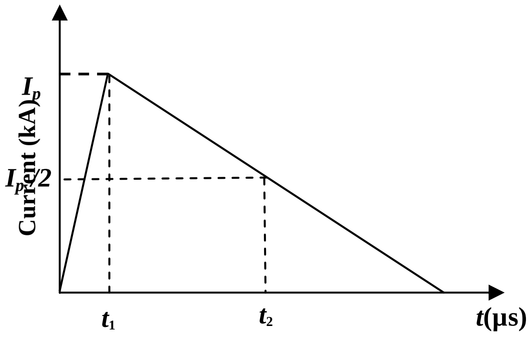

Fig. 7. Lightning Current Waveform.

Surge impedance of 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 [6]:

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

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

Impulse impedance of the ground rod

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

$$R_i = \alpha R_0 \tag{3}$$

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

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

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

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 (Ω-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

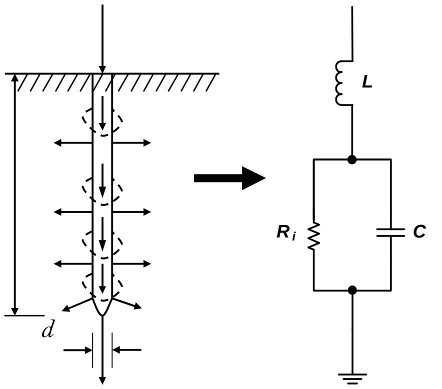

Fig.8. Equivalent Circuit for Ground Rod under Impulse Condition.

Surge impedance of external ground

A good approximation for the surge impedance of an external ground is given in (7) [9], whose parameters are based on those of the MEA standard as presented in Table 2.

Table 2. Parameters in ATP-EMTP Modeling

Detail	Values	Model
1. Lightning current		
- Amplitude (kA)	34.4	Ramp
- Front time/tail time (μs) [10],[11]	0.25/100, 10/350	
2. OHGW		J.Marti
- Diameter (mm)	7.94	
- DC resistance (Ω)	3.60	
3. Phase conductor of 115 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. Pole		Distributed Parameter
- Height (m)	20	
- Span (m)	80	
- Surge impedance (Ω)	451.4	
- Wave velocity (m/μs) [12]	123	
6. External ground		
- Diameter (mm)		
- Length (m)	20	
- Surge impedance (Ω)	411.27	
- Wave velocity (m/μs) [12]	300	
7. Ground rod		
- Diameter (mm)	16	
- Length (m)	3	
- Impulse resistance (Ω)	5-100	

$$Z_{gc} = 60\ln\left(\frac{h}{er}\right) - k\ln\left(1+\left(\frac{r_c}{D}\right)\right) \tag{7}$$

$$k = 0.096\times r_c + 13.95 \tag{8}$$

where Z_{gc} = surge impedance external ground (Ω)
h = conductor height (mm)
r = conductor radius (mm)
e = base of natural logarithm
k = constant
r_c = radius of pole (mm)
D = separate distance between skill of reinforced concrete pole and grounding conductor (mm)

5. LIGHTNING PERFORMANCE INDICES

Three lightning performance indices are considered: 1) top pole voltage, 2) critical current and 3) BFOR. The top pole voltage in a 115 kV circuit is a voltage-to-ground of the OHGW. For the underbuilt 24 kV circuit, the top pole voltage is a voltage-to-ground of the bonding point connected to the grounding system of the 115 kV. The critical current is defined as lightning stroke current when injected into the conductor causing flashover. When the critical current is known, BFOR, expressed in flashovers per length of line per year, can be calculated by: [1], [13], [14].

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

$$P(I) = \frac{1}{\left(1+\left(\frac{I}{A}\right)^{B}\right)} \tag{10}$$

$$N_l = N_g\left(\frac{28h^{0.6}+b}{10}\right) \tag{11}$$

$$Ng = 0.0133T_d^{1.25} \tag{12}$$

where

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

$P(I)$ = probability distribution of stroke current peak magnitude

I = first stroke peak current magnitude (kA)

A = median of stroke peak current magnitude (kA)

B = constant (2.6 for Thailand power system) [1]

N_l = number of lightning strikes (flashes/100 km/yr)

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

h = average conductor height (m)

b = separation distance of overhead ground wire (m)

T_d = number of thunderstorms (days/yr)

6. CASE STUDY

The system in Figure 1 is simulated by the ATP-EMTP program. The lightning performance of this system is analyzed by two lightning current waveforms, 0.25/100 µs and 10/350 µs, with and without an external ground for different impulse resistances of the ground rod. The test results are derived from a lightning current magnitude of 34.4 kA, which is the median of stroke peak current magnitude over the period from 1993 to 1997 in Thailand [1]. Simulation results are shown in Tables 3-8.

The numerical results under the 0.25/100 µs waveform in Tables 3 reveal that without an external ground in the 115 kV circuit, the top pole voltage remains unchanged for different impulse resistances. The reason is that the top pole voltage cannot be attenuated by the reflected wave generated by the impulse resistance of the ground rod. But this is not the case for the 10/350 µs waveform (Table 4) because its font time is 40 times longer than that of the other and for the 24 kV circuit because the reflected wave travels shorter to the bonding point.

An external ground helps reduce the top pole voltage particularly for the 0.25/100 µs waveform since the reflected wave can travel through the grounding path faster and therefore reducing the top pole voltage. However, for the 10/350 µs waveform if the impulse resistance is greater than 50 Ω for 115 kV and 10 Ω for 24 kV, the top pole voltage will stay constant owning to reduction in the reflected coefficient magnitude.

Table 3. Top Pole Voltage for 0.25/ 100 µs Waveform (kV)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	with
5	5,678.60	3,368.20	4,010.20	2,844.40
10	5,678.60	3,385.40	4,042.20	2,872.50
25	5,678.60	3,430.20	4,138.70	2,945.90
50	5,678.60	3,488.50	4,256.80	3,099.20
75	5,678.60	3,532.60	4,339.80	3,340.10
100	5,678.60	3,566.80	4,421.90	3,531.70

Table 4. Top Pole Voltage for 10/ 350 µs Waveform (kV)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	with
5	250.63	161.24	167.70	140.97
10	276.01	225.18	214.39	214.39
25	363.75	359.94	335.55	335.55
50	457.33	457.33	447.42	447.42
75	504.67	504.67	499.70	499.70
100	528.07	528.07	525.58	525.58

Table 5 shows that with an external ground, the system is able to withstand more critical current, for example under the 0.25/ 100 µs waveform, as much as 56% - 70% for 115 kV and 20% - 40% for 24 kV. But under the 10/350 µs waveform in Table 6, the increase of critical current becomes less obvious when the impulse resistance is increased for the same reason used to explain the top pole voltage of Table 4.

The mathematical relation between critical current and BFOR, as expressed in (9) and (10), indicates that increasing the critical current decreases $P(I)$ and hence BFOR. It is shown from Tables 7 and 8 that BFORs under the 0.25/100 µs waveform for both 115 kV and 24 kV circuits are slightly different. An external ground does not much affect BFOR in the 115 kV and 24 kV circuits. With the 10/350 µs waveform, the maximum reductions of BFOR in both circuits are only achieved by the 5 Ω impulse resistance.

Table 5. Critical Current for 0.25/ 100 µs Waveform (kA)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	With
5	4.60	7.80	2.00	2.80
10	4.60	7.60	1.98	2.70
25	4.60	7.60	1.95	2.70
50	4.60	7.40	1.85	2.50
75	4.60	7.30	1.83	2.30
100	4.60	7.20	1.80	2.15

Table 6. Critical Current for 10/350 µs Waveform (kA)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	with
5	103.30	170.00	54.00	60.00
10	100.00	120.00	40.00	40.00
25	74.00	75.00	24.50	24.50
50	60.00	60.00	18.00	18.00
75	55.00	55.00	15.00	15.00
100	53.00	53.00	14.00	14.00

Table 7. BFOR for 0.25/100 µs Waveform (flashes/100 km/yr)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	with
5	43.59	42.83	43.80	43.80
10	43.59	42.90	43.80	43.80
25	43.59	42.90	43.80	43.80
50	43.59	42.96	43.82	43.82
75	43.59	42.99	43.83	43.83
100	43.59	43.02	43.84	43.84

As seen in Tables 7 and 8, the 5 Ω of impulse resistance (R_i) is optimal for the installation of external ground. Thereby, the economic analysis of external ground is performed only in this value of R_i. The net present value (NPV), which is defined as the total present value (PV) of a time series of cash flows [15], is applied to demonstrate the economic merit.

The breakdown of investment cost for the installation of external ground depicted in Figure 4 is listed in Table 9. From this table, the total investment cost for 100 km subtransmission lines can be calculated as 502,038.81 Baht. It was reported in [16] 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 712,037.08 Baht/100 km and 258,016 Baht/event with a discount rate of 7.24%. The total outage cost can be estimated by the product of 258,016 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 in case of with and without external ground are shown in Tables 10 and 11. Note that the cash flows for the investment cost are considered as positive. The total NPV for each lightning waveform is the summation of NVP from 115 kV and 24 kV circuits whereas the total expected NPV is calculated by assuming that both waveforms are equally likely to occur (i.e., 50% chance). The lower expected value in case of the system with external ground indicates the economic merit to implement this proposed technique to MEA'system.

Table 8. BFOR for 10/350 µs Waveform (flashes/100 km/yr)

R_i (Ω)	115 kV		24 kV	
	External ground		External ground	
	without	with	without	with
5	2.64	0.79	10.74	8.47
10	2.85	1.85	17.85	17.85
25	5.63	5.47	30.73	30.73
50	8.74	8.74	36.63	36.63
75	10.37	10.37	38.98	38.98
100	11.12	11.12	39.69	39.69

Table 9. Breakdown of Investment Cost (Baht/pole)

Item	Investment Cost (Baht/pole)
Material	425.65
Labor	54.25
Work Control	16.28
Transportation	21.28
Operation	25.87
Miscellaneous	25.87
Total	569.20

Table 10. Net Present Value with External Ground (Million Baht/100 km)

Description	Waveform	
	0.25/100 (µs)	10/350 (µs)
NPV of 115 kV Circuit	126.29	3.28
NPV of 24 kV Circuit	129.85	3.28
Total Circuit	256.14	6.56
Total expected NPV	131.35	

Table 11. Net Present Value without External Ground (Million Baht/100 km)

Description	Waveform	
	0.25/100 (μs)	10/350 (μs)
NPV of 115 kV Circuit	128.28	7.77
NPV of 24 kV Circuit	128.90	7.77
Total Circuit	257.18	15.54
Total expected NPV	136.36	

From the economic and reliability advantages of external ground installation, this proposed technique can be served as a guideline to develop the performance of MEA's distribution system because this proposed technique can increase the reliability of system and is able to reduce the electricity failure due to back flashover.

7. CONCLUSION

This paper has presented the lightning performance improvement of 115 and 24 kV circuits installed on the same pole by an external ground in MEA's distribution network. The lightning performance is evaluated by 0.25/100 μs and 10/350 μs lightning current wavefoms and different impulse resistances. The test results obtained from the ATP-EMTP indicate that top pole voltage, critical current, and BFOR can be improved when an external ground is installed. The advantages of external ground depend on lightning current waveform and impulse resistance of ground rod. In addition, the test results also reveal that low impulse impedance is suitable for external ground.

ACKNOWLEDGMENT

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