Transient Current Behaviour during Multiple Lightning strokes on Multiple Unit Trains

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ABSTRACT

This paper studies transient current behavior during multiple lightning strokes on multiple unit trains of catenary contact system in airport rail link (Bangkok). Since lightning flashover across insulators is a source of power network failure, the protection against overvoltage disturbances in the overhead catenary system has been recently taken into consideration as its parameters. In this study, the impact in lightning strokes current magnitude with IEC 62305 waveforms of the first and subsequent stroke were evaluated. Moreover, in invariant elevated pole and grounding resistance, lightning strikes on multi-car trains' pantographs at the mast and mid-range of the masts were the interested locations for investigation. The modeled elements of the necessary system have been effectuated in ATP-EMTP software. The flashover was shown to occur for lightning current from -34 kA and above at targeted positions. Also, the mast induced voltage was recognized to increase with lightning magnitude. The striking on three-car trains resulted in high consequences compared to the four-car trains. However, the overcritical mast induced voltage often occurred in the catenary line once it strikes on three-car trains' pantograph across the mast unlike at mid-range. Therefore, protection against lightning multiplicity into multi-car trains and striking points should be highly considered.

Keywords: Electrified Multiple Unit Trains, Catenary, Multiple Lightning Strokes, Transient Current, Mast Induced Voltage, ATP-EMTP.

1. INTRODUCTION

Improvement on electrification of railway line due to the advantage of electric traction over diesel-electric traction and hybrid traction has become more important for everyday life. Also, for energy dependent, a human, desired environment, and economic growth have been demanded electric train services since the second half of 19^{th} century, due to technology innovation improvement to increase speed, safety, efficiency, and reliability of economic enhancement [1-2]. Typically, electricity in electrified railway transmission system must be stably secured with effectively track system and control system. Power is injected into the system which is in the form of overhead catenary transmission line without disturbance. Although the hardship of transmission line that injects power into a system along distance when lightning strikes on multiple unit trains as a natural disturbance, may likely cause the electrical breakdown. Actually, this disruption leads various electrical elements failure, power losses, and other unreliable condition on catenary contact system.

Induced over-voltages in a mast is a most exist issue which causes flashover across insulators due to lightning strikes on multiple unit trains of catenary contact system. Lightning strokes disturbances have influenced the overhead lines on double-track elevated railway system in an existing environment without any prevention. Flashover occurs when the induced voltage in a mast exceeds lightning withstand voltage level of insulators. This incidence makes the study of lightning to be more important in reliability, protection, and durable insulation design to prevent power losses in 2×25 kV AC, 50 Hz electrified railway power system. The significances of this system over 1×25 kV AC, 50 Hz electrified railway system have been stated in [3].

The experience of thunderstorm days and lightning activities per year in Thailand has led to the study of transient current behavior during multiple lightning strokes on multiple unit train's pantographs of the overhead catenary system on the elevated railway system. It uses catenary for the most traction power supply system to deliver power to electric locomotive by pantograph which is exposed to the lightning activities. The report of lightning statistics in Thailand from [4] showed that the Lightning often occurs in April-May but severely in June. The magnitude ranges 11-171 kA with positive polarity and -10 to -139 kA with negative polarity. Positive lightning strokes account for 5% while negative is 95% with the magnitude of -10 to -50 kA. In [5-8] showed that negative polarity lightning stroke could associate with multiple strokes per flash and [5,7-8] reported that the multiple strokes are averaging 3 to 4 strokes per flash with intervals of tens of milliseconds. The negative polarity of multiple lightning strokes was taken as much concern in the study, especially for 2×25 kV

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AC, 50 Hz catenary contact system on the double-track elevated railway system. The overhead catenary system connects Phayathai BTS station in the center and Suvarnabhumi airport in the East of Bangkok in Thailand. In addition, airport rail link covers three lines which are city line, Makkasan express line and Phayathai express line at 28.6 km track length. Currently, city line has 5 three-car trains, and express lines have 4 four-car trains (1 for baggage) [9]. For the purpose of the study, seven masts on elevated poles at the line of 480 m length with 60 m spacing in case 1 and six masts on elevated poles at the line of 420 m length with 60 m spacing in case 2 were considered. Case 1 was preferred when multiple unit trains' pantographs are at 4^{th} Mast and case 2 between 3^{rd} and 4^{th} Masts. The negative multiple lightning strokes on three-car and four-car trains' pantograph were analyzed for city and express line respectively.

2. THE ANALYSIS OF ELEVATED STRUCTURE AND CATENARY LIGHTNING RANGE

Thai catenary contact system consists of auto-transformer (AT), booster transformer (BT) and tracks circuit which includes relay and rectifier units. There are also interconnections between the overhead catenary conductors on the double-track elevated railway system. In the double-track electrified railway system with I-rail (R1), S-rail (R2), catenary line (contact line (R3) and messenger line (R4)), return line (R5) and auxiliary line (R6) that are interconnected as a circuit shown in Fig. 1 and cross-sectional view in Fig. 2 [9]. The return conductors are also interconnected to the booster transformer (BT) systems, and it's also connected to the S-rail at the midpoint between two consecutive transformers at every 5 km. At every pole position, the S-rail (R2) is shorted to the elevated pole footing.

Due to the unpredictability of lightning strike point on multiple unit train's pantographs which touches the catenary wire, it better to study the parts which are exposed to lightning according to the IEEE STD. 1234-1997, by using the formula (1) in [10].

$$\begin{cases} r_c = 1.34h^{0.6}I^{0.65} \\ r_c = r_g \end{cases} \quad (1)$$

where r_c is lightning strike distance of catenary which touches on pantograph of multiple unit trains, its UI is m; h is the average height of hanging wire, its UI is m; I is the lightning current amplitude, its IU is kA; r_g is lightning strike distance of earth on top of elevated pole, its UI is m.

The range of triggered lightning of catenary shown in Fig. 3 as in [10] but in this study, was considered when it is on top of the elevated pole. AB arc line is triggered a lightning range of auxiliary line (R6), CD arc is triggered a lightning range of catenary line (contact line and messenger line) (CA). The lightning current reaches first to the line which has a higher range of lightning strike distance compared to other wires. Auxiliary line (R6) and return line (R5) are on the same side on top of the mast. Lightning strike distance of auxiliary line (R6) is greater than return line (R5) which lead R6 to shield R5, but there is no any shield for the catenary line that touch pantograph, and lead great possibilities to be attacked by lightning strikes on it. In this study, we focus when multiple lightning strokes on multiple unit train's pantographs because pantograph touches catenary line. It is casual that catenary on high ground like on top of an elevated pole experience more lightning strike than that on low ground as in [11].

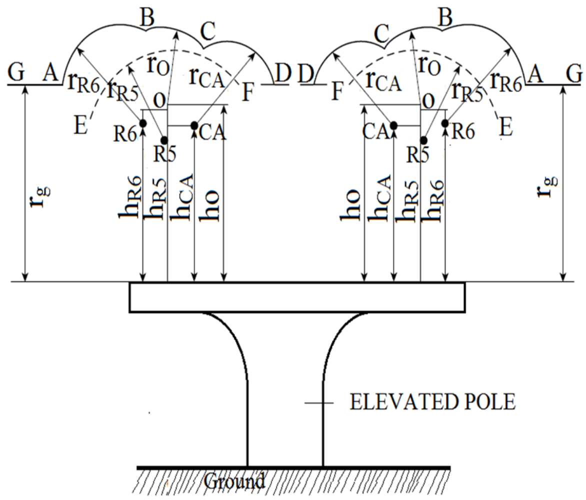

Fig.3: *The range of triggered lightning of Catenary on the double-track elevated railway system.*

3. MODELLING

The proposed ATP-EMTP software which recognized as standard procedure in power system used to investigate transient current behavior during multiple lightning strokes on multiple unit train's pantographs. Modeling of multiple lightning sources, mast, multiple unit trains, overhead catenary transmission line, insulator, elevated pole, and the ground was guided to represent catenary contact system on the double-track elevated railway system for analyzing the problem.

3.1 Multiple Lightning Source Model

Since negative lightning strokes may associate with subsequent strokes, only the first and second strokes are highly considered due to the effects of their current magnitudes in insulation [6]. But the behavior of tower grounding electrode and surrounding soil at higher frequencies of up to 10 MHz is not yet explicitly represented [12]. Frequently, both triangular and

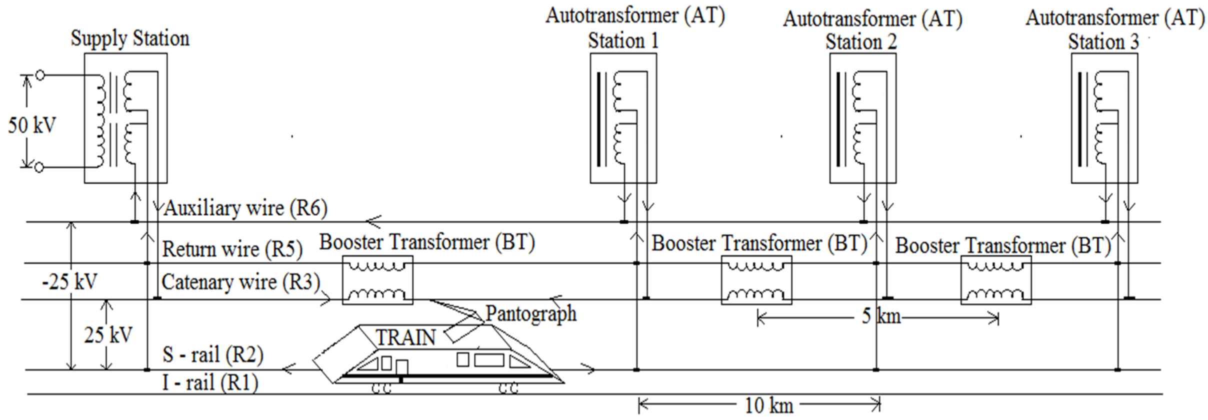

Fig.1: *Power Supply Circuit of 2×25 kV AC, 50 Hz Catenary Contact System.*

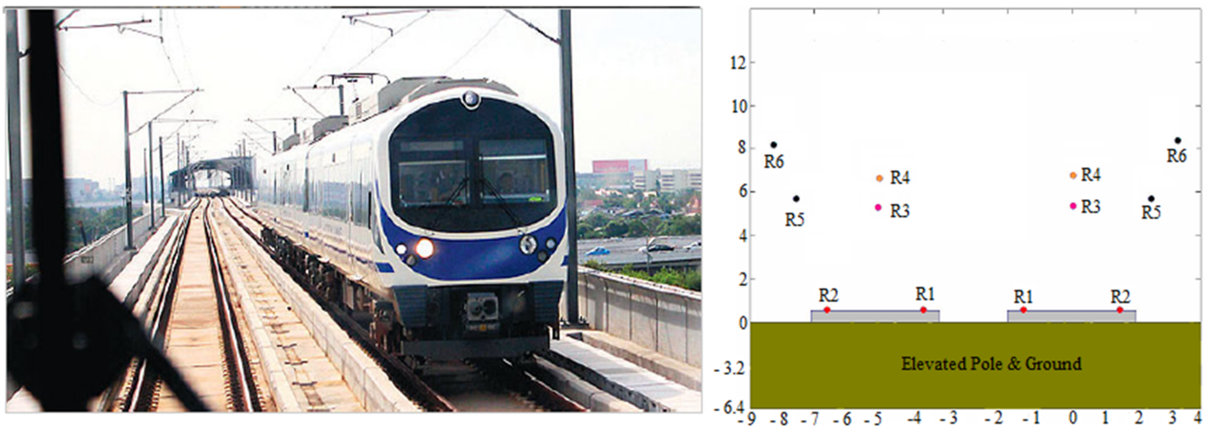

Fig.2: *Double track Railway Electrification system on elevated railway system and same cross-section view axis [9].*

exponential waveforms have been utilized to represent return strokes currents of lightning. Presently, it is deduced that a concave waveform can be better representation since it could not show a discontinuity at the initial stage. Several expressions have been suggested for such waveforms [13-15]. Therefore, the Heidler current function model in ATP-EMTP was used to represent the lightning current as one of the most widely used as shown in (2) [16-17].

$$i(t) = \frac{I_P}{k} \cdot \frac{\left({}^{t}/_{\tau_1} \right)^n}{1 + \left({}^{t}/_{\tau_1} \right)^n} \cdot \exp\left(-{}^{t}/_{\tau_2} \right) \tag{2}$$

where I_P is the peak value of the lightning stroke; k is the adjustment constant; n is a factor influencing the rate of rise; t is the time instant of the maximum rate of rise; τ_1 and τ_2 are the coefficients of the decay time and front time respectively.

The calculation of variables τ_1,τ_2 and n are explained in [18]. The correction factor of Amplitude, which regularly appears in the mathematic expression of Heidler function [14], is automatically modified and does not materialize in ATP-EMTP. Heidler-type is suitable throughout the concave lightning current front of the wave, regarding the natural lightning, is modeled.

Parameters of lightning sources are given in Table 1. Fig. 4 depicts the lightning waveforms of -34 kA normalized the first stroke with 1.0/100 Îijs and subsequent stroke with 0.2/50 Îijs as recommended by IEC 62305 [19]. The allocation of the lightning sources in selected railway transmission line for the city and express line in case 1 and 2 are shown in Figs. 5-8.

3.2 Mast Model

The mast is modeled by cylindrical geometrical steel column in single wave impedance model as recommended by IEEE and CIGRE by expression from surge impedance equation (3) in [10,20] and modeled

Table 1: *Multiple lightning sources Parameters [4,19]*

Parameter	First strokes	Subsequent Strokes
Type	Heidler 15	Heidler 15
Amp. (kA)	-34	-34
	-50	-50
	-100	-100
Front time (μs)	1	0.2
Tail time (μs)	100	50

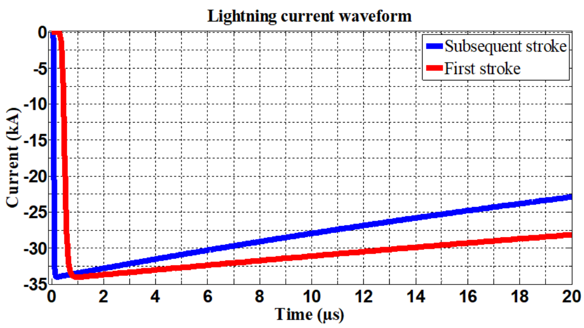

Fig.4: *Lightning current waveforms of the -34 kA first stroke-(1.0/100 μs), subsequent stroke -(0.2/50 μs) designed in ATP-EMTP.*

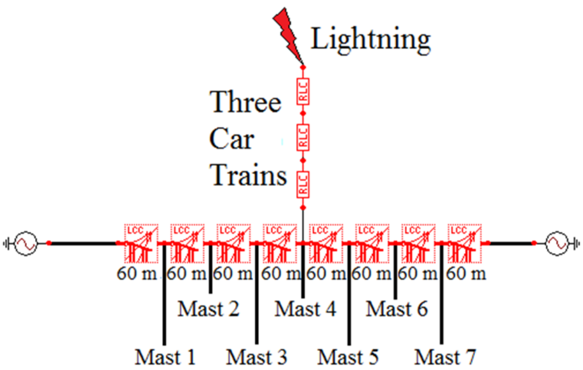

Fig.5: *City line with lightning source (Case 1).*

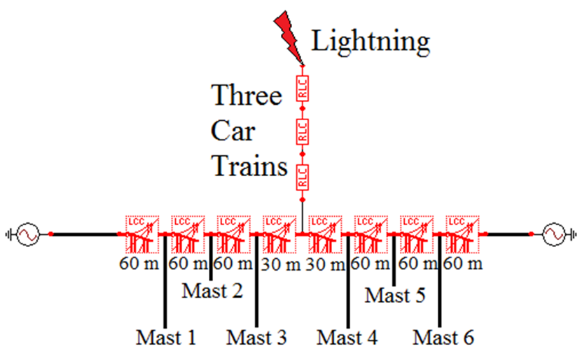

Fig.6: *City line with lightning source (Case 2).*

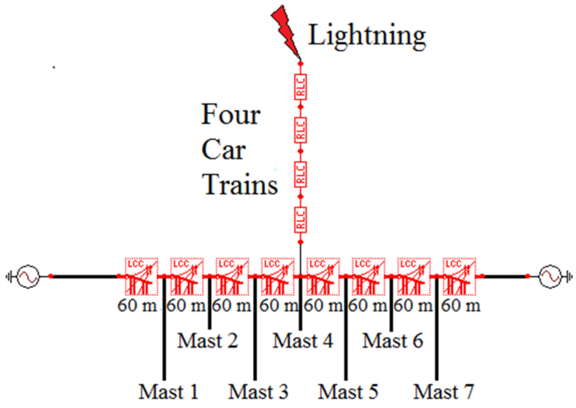

Fig.7: *Express line with lightning source (Case 1).*

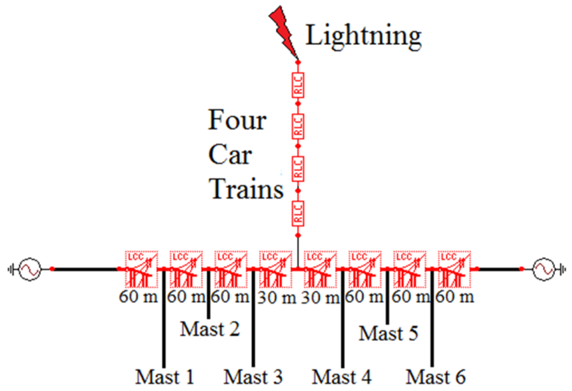

Fig.8: *Express line with lightning source (Case 2).*

parameters are shown in Table 2.

$$Z = 60In\cot\left[0.5\arctan\left(\frac{R}{H}\right)\right] \quad (3)$$

where Z is the surge impedance, its IU is Ω; R is the equivalent radius of the mast, its IU is m; H is the height of the mast, its IU is m.

Table 2: *Modelled Parameters of Mast Model*

Location	Parameters
Auxiliary	Z_{aux}= 176.35 Ω, L_1= 3.3 m
Return	Z_{return}=275.1 Ω, L_2= 0.2 m
Catenary	$Z_{catenary}$= 126.88 Ω, L_3= 6.3 m

3.3 Insulator Model

Generally, insulator resists the flow of current from phase conductor to the ground during normal operating condition. Since the capability of an insulator to withstand stress depends on its voltage withstand level, this behavior can be represented as a voltage controlled switch [21]. Moreover, the effects of coupling conductors to mast structure can also be represented by the capacitor. If the voltage across insulator terminals is greater than control voltage of the switch, the switch closes which indicates flashover. Otherwise, if the voltage stress is less than control voltage, the switch remains open to show no flow of current across the insulator. In the simulation, the voltage controlled switch was designed by Switchvc.sup model. The voltage withstands capabilities for the rod/composite, spool and pin as given in Table 3 [22] were set as the control voltage of the switch. The values of capacitance for suspension insulators are 80 pF/unit while for pin insulators are around 100pF/unit [21].

Table 3: *Impulse withstands level of Insulators [22]*

Insulators	Impulse Withstand level
Rod/Composite (R3/R4)	225 kV
Spool (R5)	60 kV
Pin (R6)	140 kV

3.4 Grounding Resistance Model

Once the lightning current discharges to earth through the mast, the ionization process occurs around soil surrounding the grounding rod. This situation makes surrounding soil as non-linear and the frequency dependent. A non-linear frequency-dependent representation is required to obtain an accurate simulation [6,12,23-24]. Due to difficulties of information to representing this behavior not always available, the reasonable model approximation of grounding resistance as recommended by IEC and IEEE standards is given in (4) [10,21,25-27].

$$R_g = \frac{R_0}{\sqrt{1 + \frac{2\pi R_0^2 I}{E_0 \rho}}} \quad (4)$$

From expression, R_g is grounding resistance, its IU is Ω; R_0 is the striking impendence value in low-frequency power flow, its IU is Ω; I is the striking lightning current passing through the grounding system, its IU is kA; ρ is the soil resistivity, its IU is Ω·m; E_0 is the soil ionization intensity, usually take a value of 400 kV/m [24].

3.5 Multiple Unit Trains Model

The electric train was modeled as electric locomotive which contains pantograph, locomotive transformer, diode rectifier bridge and DC motors as stated in [28-29]. The rectifier bridge is represented by the parallel RC elements and the series resistance of the diodes. A series reactor is connected between the motor and the rectifier bridge in order to smooth the direct current [28]. Three-car trains in city line consisted 6 DC motors while four-car trains in express line carried 8 DC motors. The network of an electric vehicle with elements listed above and one DC motor are indicated in Figs. 9-10. In the case of positions, Fig. 9 and 10 show when the pantograph is at the mast and mid-span of the masts respectively. Railway transmission line with 60 m spacing, elevated pole resistance and grounding resistance, and Insulators are shown in Fig. 9.

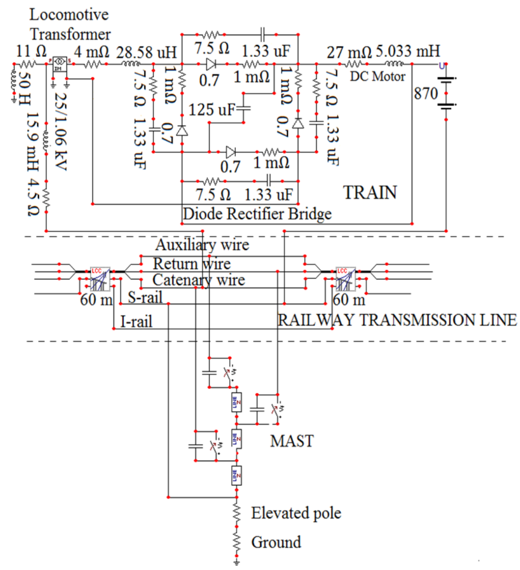

Fig.9: *Mast with Train, Railway Transmission line, Pole, Ground, and Insulators at elevated pole in ATP EMTP.*

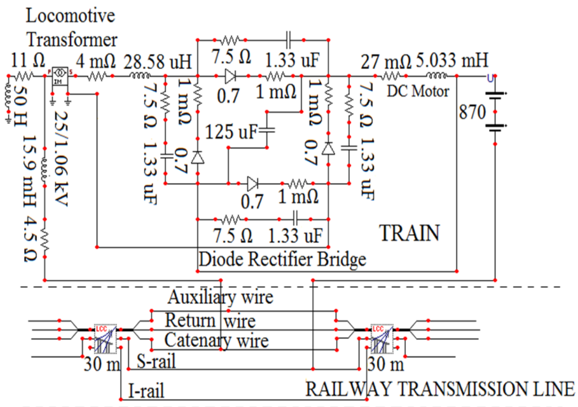

Fig.10: *Train with Railway Transmission line between elevated poles in ATP EMTP.*

3.6 Overhead Catenary Transmission Line Model

The overhead catenary transmission line was modeled by LCC_8 with JMARTI model in ATP EMTP as shown in Fig. 11 and it consists of a catenary line, return line, auxiliary line, S-rail and I-rail on elevated poles at every 60 m along overhead catenary system as in [22,30] with autotransformer and booster transformer. Autotransformer and booster transformer were modeled as 1:1 ideal transformers in ATP EMTP as shown in [10]. This type of transformer used to force the traction current to return through designated return conductors to traction supply in order to reduce stray current which may cause electromagnetic interference with electrical systems in the vicinity of the railway system and to ensure the return of transmission energy to the substation from the train. Mast cross section view of 25 kV electrified railway line have been shown in Fig. 3.

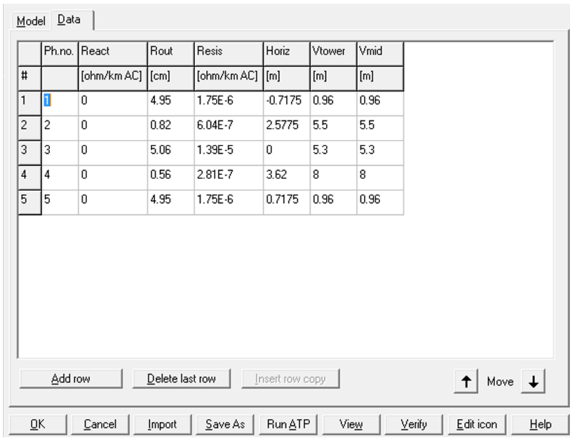

Fig.11: *Railway Transmission line data in ATP EMTP.*

4. SIMULATION ANALYSIS

As a version part of the electromagnetic transients program, ATP-EMPT is the powerful tool for steady state and transient analysis of power systems [31]. It has been recognized as per international standard as IEEE and CIGRE in arithmetic circuits [32]. In this task, ATP-EMTP is utilized as time domain computation in overvoltage protection against lightning as indicating from Figs. 9-10.

The traction voltage of the system is 25 kV AC, 50 Hz as stated by IEC standard [33]. A nominal voltage was inserted to both sides of the termination of the line. A 25 kV railway transmission line with arrangements of masts as in Figs. 5-8 were simulated in ATP-EMTP. Multiple lightning sources were inserted on train's pantograph. The elevated poles and grounding resistance were set to 50 âĎę and 5 âĎę unchanged respectively. The magnitude, front time and tail time of negative multiple lightning strokes were studied as factors that cause a transient current which leads flashover across insulators. As the impulse voltage withstand capability of insulation depends on the front time of lightning stroke current, the different multiple lightning stroke currents were initiated. The present magnitude of -34 kA was started to be simulated and followed by -50 kA and -100 kA as specified in Table 1. First strokes-(1.0/100 μs) and subsequent stroke-(0.2/50 μs) waveforms were used in the simulation for both city line and express line.

4.1 Simulation Results

Figs. 12-17 and Figs. 18-23 contain the outcome of mast induced voltage waveforms stressed insulators of the auxiliary, return and catenary line for city line and express line respectively. For instance, Figs. 12-14 and Figs. 18-20 are represented case 1 while Figs. 15-17 and Figs. 21-23 are evinced case 2. Figs. 12-23 differ in the magnitude of mast induced voltages across insulators. Table 4 and 6 show the magnitude of mast induced voltages and Table 5 and 7 show flashovers across insulators.

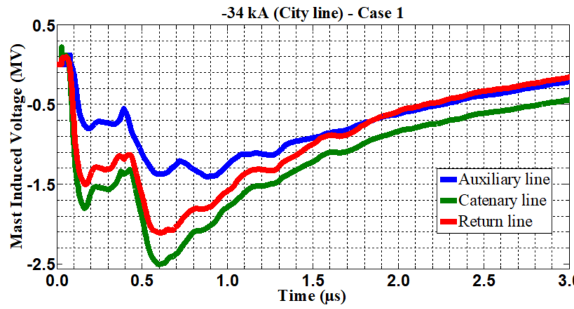

Fig.12: *Mast induced voltage waveform of the -34 kA first stroke-(1.0/100 μs), subsequent stroke-(0.2/50 μs).*

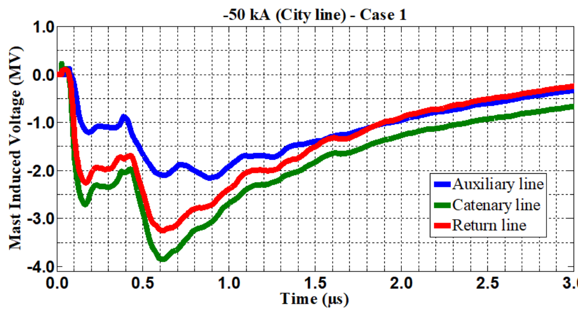

Fig.13: *Mast induced voltage waveform of the -50 kA first stroke-(1.0/100 μs), subsequent stroke-(0.2/50 μs) .*

Table 4: *Magnitude of mast induced voltages (MV)*

City line								
Case 1								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
1.41	2.11	2.51	2.15	3.25	3.85	4.41	6.72	8.0
Case 2								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
1.52	2.18	2.32	2.26	3.30	3.51	4.62	6.72	7.15

Key:

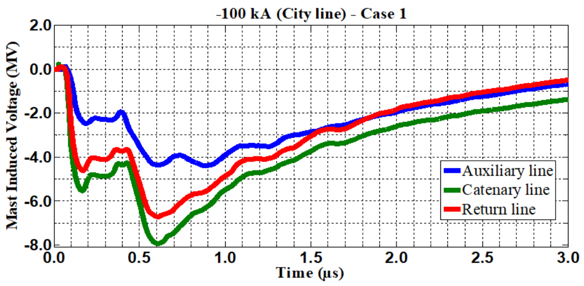

Fig.14: *Mast induced voltage waveform of the -100 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs).*

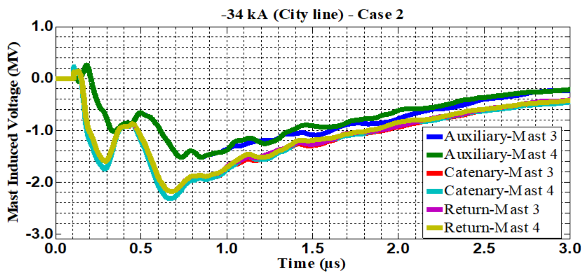

Fig.15: *Mast induced voltage waveform of the -34 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs).*

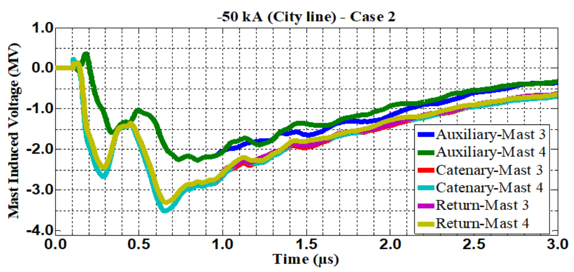

Fig.16: *Mast induced voltage waveform of the -50 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs) .*

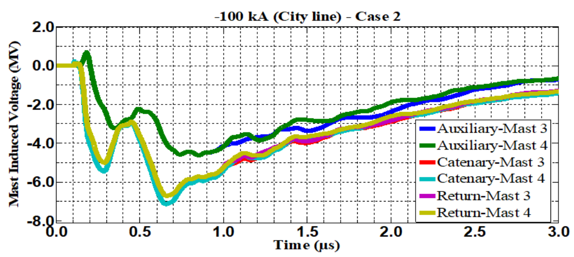

Fig.17: *Mast induced voltage waveform of the -100 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs) .*

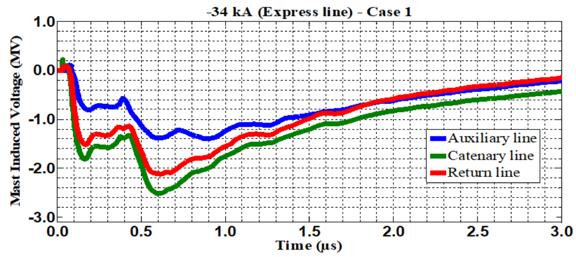

Fig.18: *Mast induced voltage waveforms of the -34 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs).*

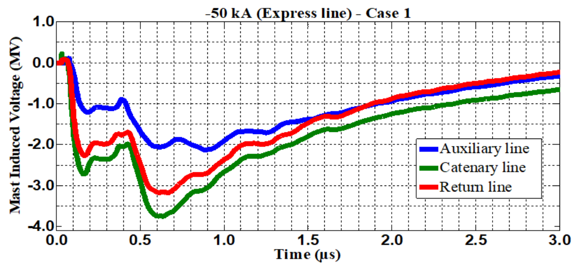

Fig.19: *Mast induced voltage waveforms of the -50 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs) .*

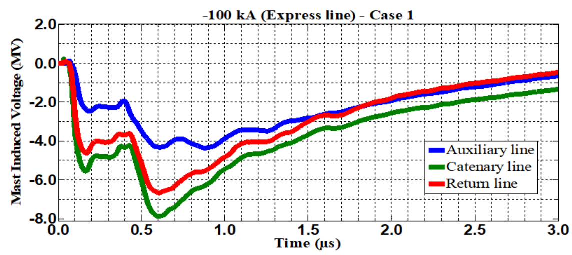

Fig.20: *Mast induced voltage waveform of the -100 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs) .*

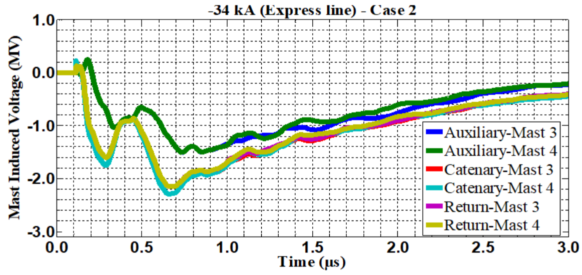

Fig.21: *Mast induced voltage waveform of the -34 kA first stroke-(1.0/100 µs), subsequent stroke-(0.2/50 µs) .*

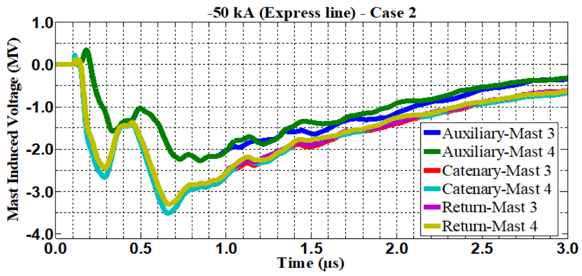

Fig.22: *Mast induced voltage waveform of the -50 kA first stroke-(1.0/100 μs), subsequent stroke-(0.2/50 μs).*

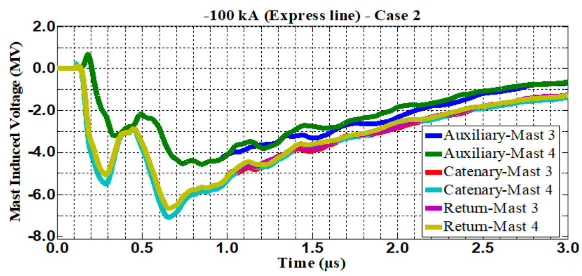

Fig.23: *Mast induced voltage waveform of the -100 kA first stroke-(1.0/100 μs), subsequent stroke-(0.2/50 μs) .*

Table 5: *Flashover across insulators*

City line								
Case 1								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
S	S	S	S	S	S	S	S	S
Case 2								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
S	S	S	S	S	S	S	S	S

Table 6: *Magnitude of mast induced voltages (MV)*

Express line								
Case 1								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
1.40	2.12	2.52	2.12	3.18	3.75	4.37	6.66	7.88
Case 2								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
1.51	2.15	2.30	2.27	3.30	3.51	4.56	6.66	7.08

Table 7: *Flashover across insulators*

Express line								
Case 1								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
S	S	S	S	S	S	S	S	S
Case 2								
-34kA			-50kA			-100kA		
Aux	Ret	Cat	Aux	Ret	Cat	Aux	Ret	Cat
S	S	S	S	S	S	S	S	S

S-Flashover, Aux-Auxiliary line, Ret-Return line, Cat- Catenary line

5. DISCUSSION

According to the simulation results, two different sections are discussed. The first and second parts are described when three-car and four-car train's pantograph struck by multiple lightning strokes with negative polarity respectively.

5.1 Effect of Negative Multiple Lightning Strokes on Three-Car Train's Pantograph

As shown in Figs. 12-17, the mast induced voltages in the auxiliary, return, and catenary lines are above the lightning withstand levels of their respective insulators. The amounts of mast induced voltages are shown in Table 4. However, the flashover was observed to occur from -34 kA and above in both case 1 and case 2 (see Table 5). Also, the mast induced voltages were seen to increase with lightning magnitudes from -34 kA to -100 kA. The catenary line in case 1 and case 2 was seemed to be the most affected line from -34 kA to -100 kA. The worst case for the catenary line was occurred in -100 kA for case 1.

5.2 Effect of Negative Multiple Lightning Strokes on Four-Car Train's Pantograph

From the illustrations of Figs. 18-23, the lightning withstands levels of the auxiliary, return, and catenary lines are below the mast induced voltages across their respective insulators. The quantities of mast induced voltages are exhibited in Table 6. Moreover, in both case 1 and case 2, lightning magnitude from -34 kA and above caused the flashover (see Table 7). Additionally, the mast induced voltages were noticed to increase with lightning magnitudes from -34 kA to -100 kA. The catenary line in case 1 and case 2 was discerned to be the most pretentious line from -34 kA to -100 kA. The worst case for the catenary line was appeared in -100 kA for case 1.

6. CONCLUSION

In this paper, the transient current behavior when multiple lightning strokes on three-car and four-car trains' pantographs have been studied. The investigation of flashover voltage across auxiliary, return, and catenary lines insulators on the elevated railway system were analyzed. The occurrence of flashover was observed for any the lightning magnitude from -34 kA to -100 kA for case 1 and case 2 of both three-car and four-car train. Moreover, the mast induced voltage was seen to increase with the magnitude of lightning strokes current. The effect of lightning current was observed more in three-car train compared to the four-car train. The catenary line of the three-car train was the most stressed line in contrast to auxiliary and return line. The maximum value of the mast induced voltage in the catenary line of the three-car train was seen to occur when the pantograph was across the mast. Since the mast induced voltage across insulator of the catenary line was seemed to decrease from three-car train (8.0 MV) to four-car train (7.88 MV), it was suggested to study the behavior of lightning current for other multi-car trains.

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