



The effect of lightning impulse characteristics and line arrester to the lightning protection performance on 150 kV overhead lines: ATP-EMTP computational approach

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Received 14 January 2019; accepted 15 November 2019

Abstract

This simulation study presents the effect of lightning strikes on the performance of arresters at 150 kV overhead lines. Lightning strikes have several parameters that affect the performance of line arresters (LA), namely lightning charge, and impulse energy. The simulation was attempted by the injection of a direct strike to the ground wire with the peak voltage of 10 MV. The peak voltage was varied in terms of wavefront time (Tf) and the duration of lightning impulses (τ). In order to calculate current, charge and impulse energy of LA from various variations of Tf and τ , the trapezoidal numerical integration method is used. The current and impulse energy arising due to direct strikes and various variations of Tf and τ will be compared for each phase so that the influence of Tf and τ can be obtained from the performance of the LA and the current charge and impulse energy values are still within the limits of the IEEE C62.11 standard. The installation of LA and the position of arresters affected the peak voltage of lightning on the phase line when lightning struck it. The line arresters provide a drop in the peak voltage of lightning in phase lines. By installing line arresters in each tower, it will reduce the peak voltage of lightning on the phase line more significantly than the standalone line arrester. It is shown that the line arresters have to install at least six towers to reduce the peak voltage in the phase lines.

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Keywords: lightning impulse; line arrester; peak voltage; impulse energy; placement of arrester.

I. Introduction

Overhead lines for 70 kV, 150 kV and 275 kV, which stretch along the island of Sumatra, are very susceptible to the disruption caused by lightning strike. This is proven by the lightning activity in Sumatra Island, which includes the high category. This happens because Indonesia is located in the humid tropics which results in very high thunderstorm days compared to other regions (100-200 days of thunder per year). Based on the calculation using IEEE flash software as shown in Figure 1, the back flashover rate (BFOR) and shielding failure flashover rate (SFFOR) are directly proportional to the ground flash density (GFD) for the 150 kV overhead lines in Sumatra. With GFD of 9-13 flash/km²/year, the 150 kV overhead lines in Sumatra

are often hit by the lightning strikes. The data show that from 2011 to 2014, the phase lines were struck by lightning as many as 305 times as shown in Figure 2.

The recorded failures of the 150 kV overhead lines in central Sumatra from 2011 to 2014 occurred throughout the year. This failure was recorded as a failure due to lightning. These data also show that the central Sumatra has a high lightning density which is a threat and disruption to the distribution of electricity. The data in Figure 1 and Figure 2 indicates that the 150 kV overhead lines in central Sumatra need to be protected according to the safety standard.

High-voltage transmission poles are tall objects and are subject to lightning strikes. It is not only the shielding failure caused by lightning struck that should be calculated, but the back flashover needs to also be estimated. The efforts that have been attempted by the Electric Company in Sumatra to reduce the outages caused by lightning strikes include checking and resetting the grounding rod at

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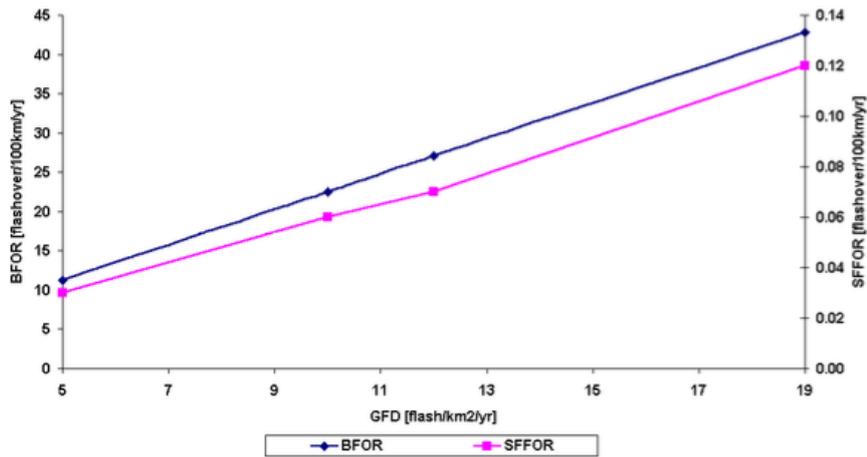
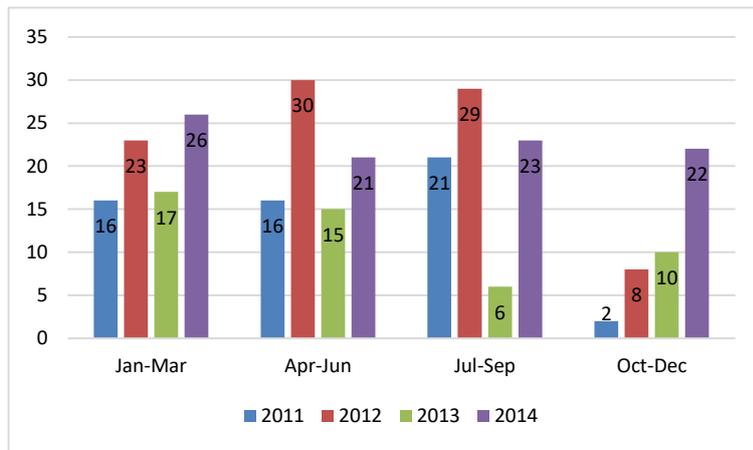


Figure 1. BFOR and SFFOR for 150 kV in Sumatra



Source: Electric Company in Sumatra

Figure 2. The number of the outage of the 150 kV overhead lines caused by lightning struck

least under 5 Ohms, checking and repairing the ground static wire clamps, as well as the installations of transmission lightning arrester (TLA), lightning protection termination early streamer emission (ESE), and static wire insulated ground (i-GSW) for areas that are often struck by lightning. Another effort was also carried out by installing jet stream arc-quenching lightning protection gap. External ground wires contribute to reduce flashover rate. Those efforts are done by [1][2][3][4][5][6][7][8]. The recommendation for back flashover rate improvement has been proposed by [9] using multi chamber insulator arresters (MCIA) to substitute the string insulators. From the improvement efforts carried out by the electric company in Sumatra, there are some interesting things to be evaluated further, such as whether, the installed TLA is related to the characteristics of the lightning impulses and their effects to decrease the lightning peak voltage hence improving the 150 kV lines performances. In this manuscript, the simulations were carried out by means of ATP-EMTP software. The impulse generator model uses the Heidler model which is an impulse current function model and is widely used as a model of lightning. Equation (1) and Equation (2) are momentary current equations that calculate lightning

currents in this model [10][11][12][13]. This Heidler model is given in Figure 3.

$$i(t) = \frac{I_0}{\eta} \cdot \frac{\left[\frac{t}{\tau_1}\right]^{\frac{1}{n}}}{\left[\frac{t}{\tau_1}\right]^{\frac{1}{n}} + 1} \cdot e^{\left[\frac{-t}{\tau_2}\right]} \tag{1}$$

$$\eta = e^{\left[-\left[\frac{\tau_1}{\tau_2}\right]\left[\frac{\eta\tau_2}{\tau_1}\right]^{\frac{1}{n}}\right]} \tag{2}$$

where I_0 is lightning peak current (kA), τ_1 is current rising time constant, τ_2 is current dropping time constant, and η is current crest factor.

The TLA model of 150 kV overhead lines is shown in Figure 4. This model has also been derived from IEEE standards [14][15][16]. This model will be used in the simulation with the ATP-EMTP software. The

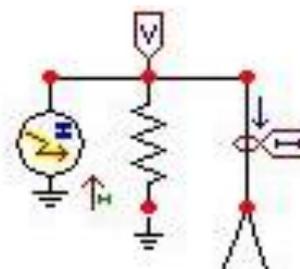


Figure 3. Lightning current model

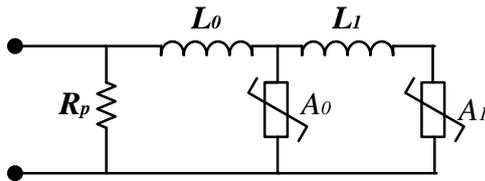


Figure 4. Pinceti and Giannettoni model

Table 1. Data of arrester MOV

I (A)	U (V)	
	A ₀	A ₁
10	271,250	0
100	298,530	238,390
1,000	325,500	263,500
2,000	337,280	277,140
4,000	348,750	286,750
6,000	352,780	290,780
8,000	362,390	296,360
10,000	368,280	300,390
12,000	373,860	302,250
14,000	381,610	306,280
16,000	387,500	308,140
18,000	397,110	310,000
20,000	407,030	311,860

Pinceti and Giannettoni model is a simplified model of the IEEE W.G 3.4.11 standard. This model eliminates the capacitance C because of its negligible effect. The two parallel resistances with inductance are replaced by one R resistance (about 1 MΩ) between the input terminals. The non-linear resistor characteristics A₀ and A₁ are identical to the IEEE W.G 3.4.11 model. The L₀ and L₁ parameters of this simplified surge arrester model are calculated from the following Equation (3) and Equation (4) [17][18].

$$L_1 = \frac{1}{4} \cdot \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \quad (3)$$

$$L_0 = \frac{1}{12} \cdot \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \quad (4)$$

where V_n is arrester rated voltage, V_{r1/T₂} is impulse voltage with a waveform of 1,2/5 μs, V_{r8/20} is impulse voltage with waveform 8/20 μs. The values of non-linear resistance A₀ and A₁ are taken from the data of ZnO arrester presented in Table 1. By using Equation (3) and Equation (4), the values of L₁ is 0.002448 mH and L₀ is 0.000816 mH. The values of A₀ and A₁, V_{ref} is twice of residual voltage for the current of 10 kA and

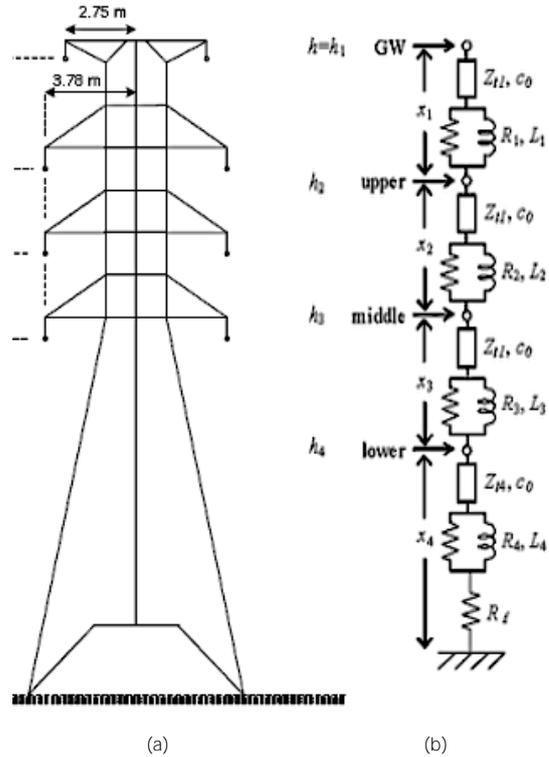


Figure 5. The well-known models: (a) 150 kV tower and (b) Multi-storey tower for ATP-EMTP model

waveform of 8/20 μs. The transmission tower is modelled for 150 kV with four parameters illustrated in Figure 5. One of the well-known models is the multistory model designed by Masaru Ishii. The multistory tower model consists of a line of parameters distributed with parallel RL circuits and has been recommended by Japanese standards for designing/coordinating insulation against lightning. This model is widely used for lightning wave analysis in Japan [13][19][20]. The velocity of propagation is 300 m/s. The recommended surge impedance value from the tower model above can be seen in Table 2. The values of R and L every section on the tower are defined as in Equation (5) and Equation (6) as follows:

$$R_i = \Delta R_i x_i \quad (5)$$

$$L_i = 2\tau R_i \quad (6)$$

where i = 1,2,3, and 4 for every section of the tower, tower height h, x₁ is the distance of ground wire (GW) to phase line 1, x₂ is the distance of phase line 2 to phase line 1, x₃ is the distance of phase line 3 to phase line 2, and x₄ is the distance of phase line 3 to ground. The formula of ΔR_i is determined by Equation (4) and

Table 2. Recommended value of lightning parameters

System voltage (kV)	Lighting current (kA)	Tower height/ geometry (m)				Surge Imp. (Ω)		Footing res. (Ω)
		H	x ₁	x ₂	x ₃	Z _{i1}	Z _{i4}	
1100	200	107	12.5	18.5	18.5	130	90	10
500	150	79.5	7.5	14.5	14.5	220	150	10
275	100	52.0	9.0	7.6	7.6	220	150	10
154 (110)	60	45.8	6.2	4.3	4.3	220	150	10
77 (66)	30, 40	28.0	3.5	4.0	3.5	220	150	10-20

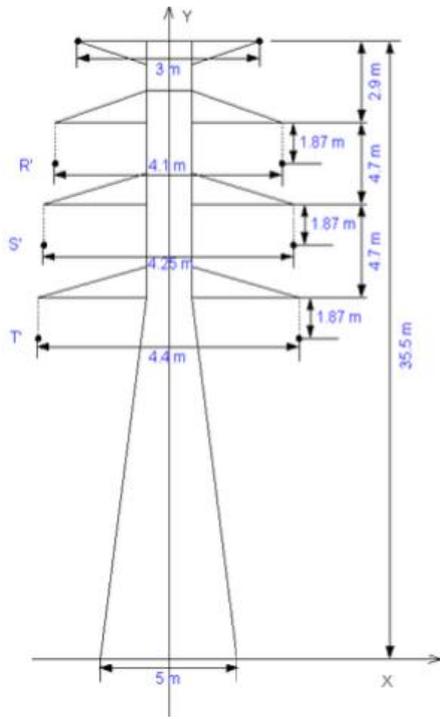


Figure 6. Tower configurations

Equation (5) where Z_{T1} and Z_{T4} are data from Table 1 for system voltage of 154 kV/110 kV and time of traveling wave on the tower: $\tau = h/c_0$, the attenuation constant: and propagation velocity: $c_0 = 300 \text{ m}/\mu\text{s}$.

$$\Delta R_1 = \Delta R_2 = \Delta R_3 = \frac{2Z_{T1}}{h-x_4} \ln\left(\frac{1}{\alpha_1}\right) \quad (7)$$

$$\Delta R_4 = \frac{2Z_{T4}}{h-x_4} \ln\left(\frac{1}{\alpha_1}\right) \quad (8)$$

Transmission lines in Japan use a vertical twincircuit configuration with two ground wires and 6 phase wires. This configuration model is used for the transmission line model on EMTP called the frequency-dependent line model of the EMTP. However, the influence of distributed-line models with a fixed propagation velocity, more attenuation, and surge impedance is explained in EMTP which is often used for transient overvoltage simulations [21]. The frequency-dependent effect of a tower used in the simulation is a combination of the frequency-

dependent tower impedance with the Semlyen or Marti line model in EMTP [22][23][24][25][26]. The current charge is the area of lightning or integral current with time. This current charge (Q) is formulated in Equation (9), where i is the lightning current strength in kA and t is a time in seconds.

$$Q = \int i dt \text{ (C)} \quad (9)$$

Integral Quadratic Current (E) is impulse energy which is a mechanical effect, and lightning heat can be formulated in Equation (10),

$$E = \int i^2 t dt \text{ (J)} \quad (10)$$

By following the simulation rules above, the effects of lightning impulse characteristics and transmission lines arrester (TLA) on the design of TLA laying in 150 kV overhead lines in Sumatra were carried out. The number of TLA used needs to be proven by simulations to determine the effectiveness of TLA installation on 150 kV overhead lines in Sumatra.

II. Research Methodology

Analysis of lightning strikes on arrester work at 150 kV overhead lines in this study was carried out using the ATP (Alternative Transient Program). The simulation process was carried out in several stages, namely: field data collection, transmission line parameter calculation, modelling all channel parameters into ATP-EMTP, analyzing current charge and impulse energy in arresters in each phase and analyzing the installation of arresters in each transmission tower.

The data retrieval was carried out by collecting equipment data, tower data, power transformer data, arrester data used at the substation and lines, and the components needed for the modelling process. The conductor data used in this study are divided into two: shield wires and phase wires. Shield wires are made of the galvanized steel wire with a cross-sectional area of 55 mm^2 , and the sag length is 4,576 m. Phase conductor is made of Zebra ACSR with a cross-sectional area of 428 mm^2 , R_{\max} resistance is 0.0397 Ohm/km, X_{\max} reactance is 0.272 Ohm/km, L_{\max} inductance is 0.433 mH/km and C_{\max} capacitance is 6.645 nF/km. Sag length is 5.4 m. The tower configuration is shown in Figure 6. Shield wires and phase wires are tabulated in Table 3.

Table 3.
The positions of shield wires and phase wires

Conductor No.	Operating Phase-Phase [kV]	Phase Angle [°]	Function	Phase Coordinates	
				X [m]	Y [m]
1	-	-	Shield	-1.5	35.5
2	-	-	Shield	1.5	35.5
3	150	0	R	-2.05	30.73
4	150	240	S	-2.125	26.03
5	150	120	T	-2.2	21.33
6	150	0	R'	2.05	30.73
7	150	240	S'	2.125	26.03
8	150	120	T'	2.2	21.33

Span (Average) = 300 m
Surge Impedance = 139 ohm

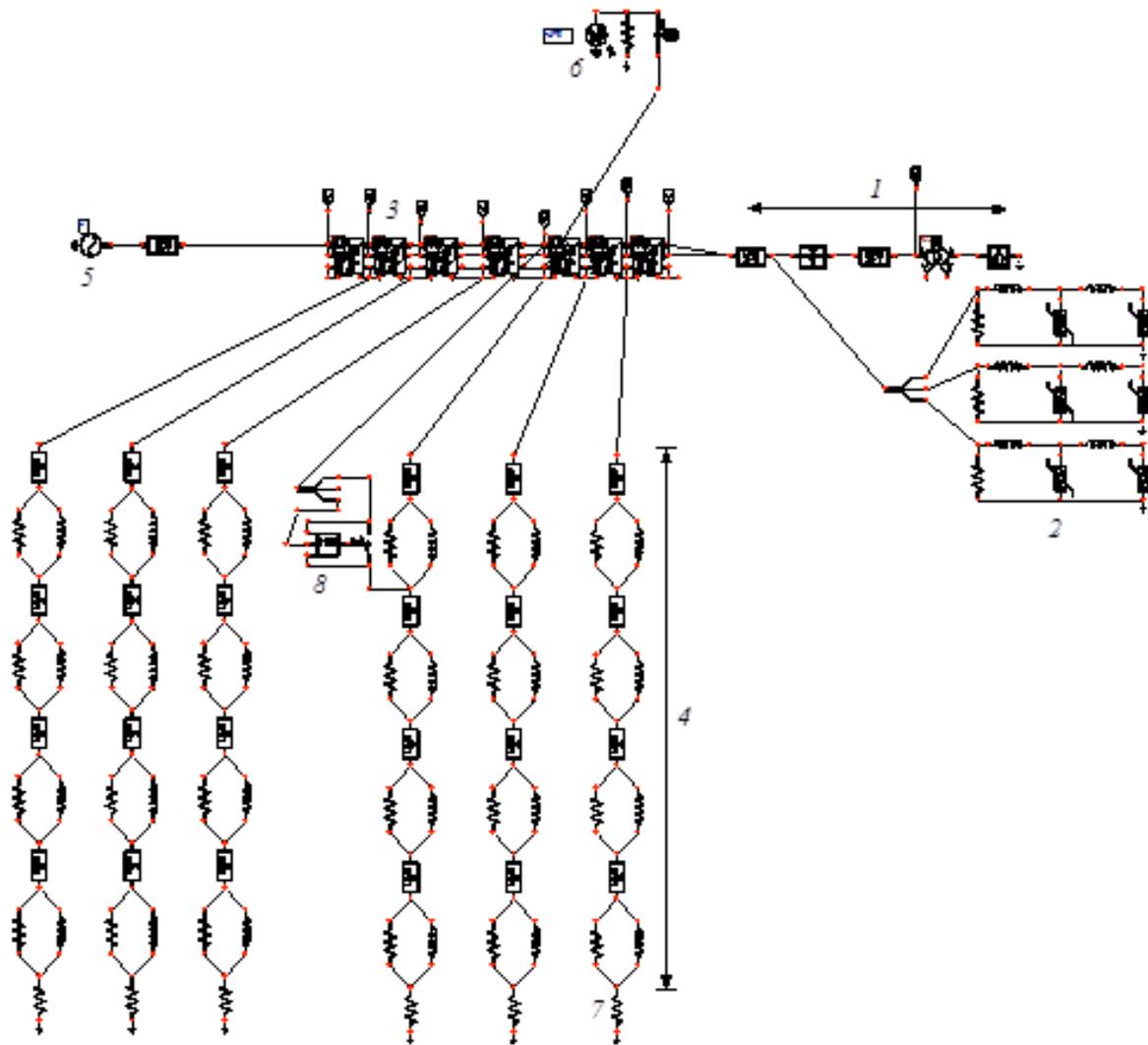


Figure 7. 150 kV overhead lines model: (1) Substation; (2) Lightning arrester; (3) LCC/Lines; (4) Multistory tower; (5) Power generator; 6. Impulse generator; (7) Footing resistance (R_f); (8) Switch for back flashover

By entering tower configuration data into Equations (5-8), the parameters for the tower replacement circuit were obtained in the ATP-EMTP software. Lines phases were modelled with LCC and the configuration of the circuit of sixline phases and two ground wires. The power transformer used was 150 kV rms with a frequency of 50 Hz. Arrester was used by the model in Figure 4.

The simulation method looked at the effect of lightning wave front (T_f) and lightning wave duration (τ) on lightning charge and lightning energy compared to the IEEE C62.11 standard. The peak voltage of the impulse generator (Heidler model) was 10 MV. After overvoltage on the tower, a simulation was carried out to see the effect of TLA installation on the 150 kV transmission line. The back flash over model was also created with an automatical switch in microsecond order, for example, number 6 in Figure 7. According to Table 2, the tower ground resistance is 10 Ohm. The number of TLA and TLA positions is the objective of this research. The model used in the simulation is given in Figure 7.

III. Results and Discussions

The variation of T_f of the lightning impulse modelled at ATM-EMTP is shown in Figure 8. The T_f value imputed on the Hiedler impulse generator model is 1.2, 2.4, 3.6, 4.8 μ s. Next, the wavefront start value and tau value are set at 0.1 and 50 μ s. After the T_f and data parameters are set, the impulse current flows through arresters in phase A because the isolator flashover process occurs in phase A. The characteristics of lightning impulse currents through arresters in phase A for variations of T_f are given in Figure 9. By using the trapezoidal numerical method, the current charge and impulse energy values can be solved by using current impulse data flowing in arrester A with a variation of T_f . For the comparison of the current charge, the change in T_f is still within the arrester resistance limit, which is in the range of 3.5 C. However, the impulse energy values that occur in arresters on phase A have exceeded the energy resistance limit of the arrester, which is 11 kJ. The value of the current charge and impulse energy with variations of T_f is given in Figure 10 and Figure 11. It

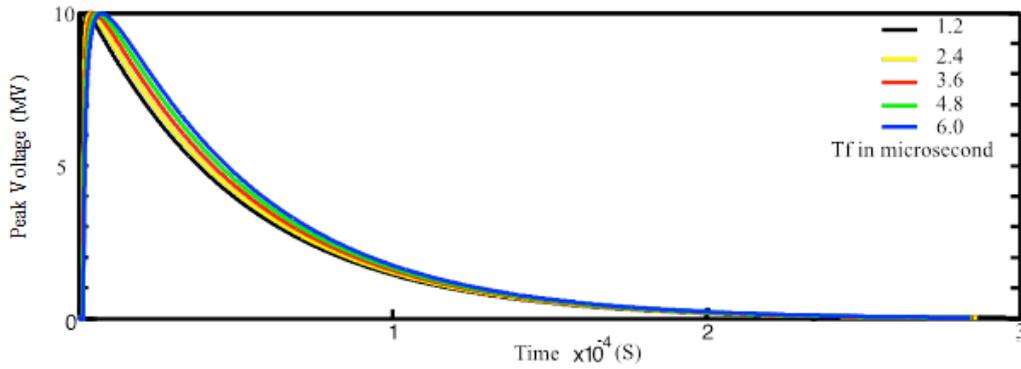


Figure 8. Lightning impulse with Tf variations

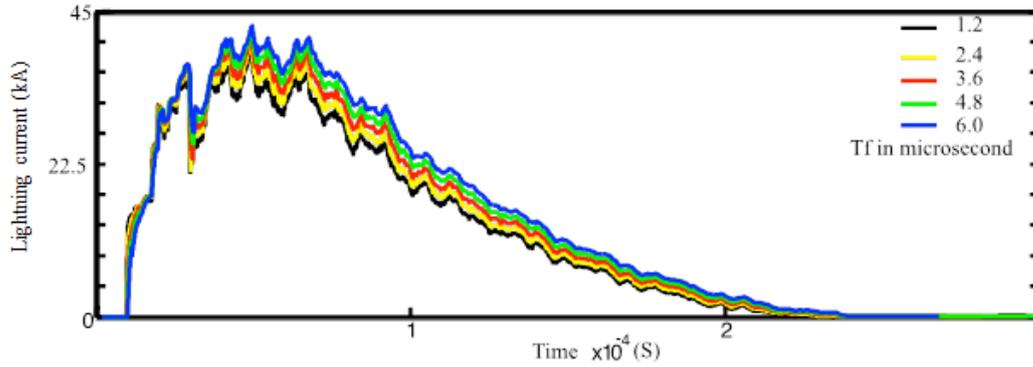


Figure 9. Current waves passing through arresters in phase A to variations of Tf

shows that the variation Tf of the lightning impulse influences the current charge and impulse energy values. Current and impulse energy values are proportional to Tf. By keeping the peak voltage of the impulse 10 MV and varying the Tf values, the impulse energy received by the arrester is greater than the standard value while the charge values are still below the standard. Impulse energy that exceeds this standard could result in a shorter lifetime of the arrester.

In order to find out the effect of changes in tau value, this simulation was carried out by varying the tau values of 50, 70, 90, 110 and 130 μs. As for the values of Tsta and Tf are fixed, which is 0.1 and 1.2 μs. The value of the variation of the lightning impulse is shown in Figure 12 and Figure 13. By injecting lightning impulses into a 150 kV overhead lines model, this will cause arresters in phase A to work because the arresters are passed by the current after

a flashover event of the insulator in phase A. The current charge and impulse energy can be solved using current data flowing in the arrester in phase A. These values are given in Figure 14 and Figure 15. It is shown that the tau value is proportional to the current charge. If the tau values exceed the 70 μs, the arrester will exceed the limit value (shown in yellow line). However, the value also affects the impulse energy value, which exceeds the standard value of arresters according to IEEE C62.11. The values of tau could affect the values of the charge and impulse energy that exceeds the standard. It is shown that tau can influence the arrester performance where the lifetime of arrester will be shorter than the variation of Tf.

In order to figure out the effect of arrester performance, the installation locations of arresters are varied in this study. Figure 16 shows a simulation of a series of a lightning strike that grabs the ground

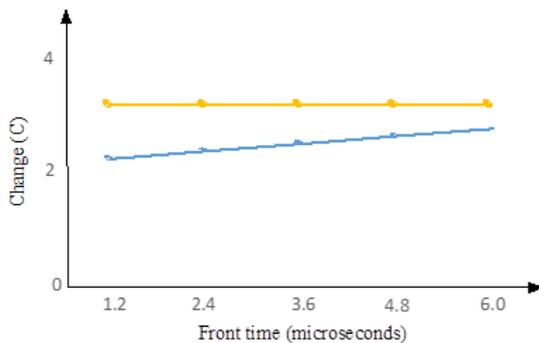
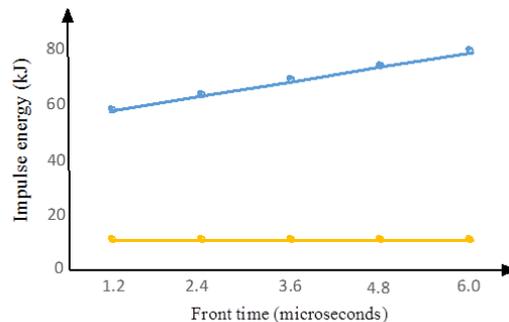


Figure 10. Comparison of current charge values to variations of Tf



*The yellow line is energy limit in the arrester

Figure 11. Comparison of impulse energy values with Tf variations

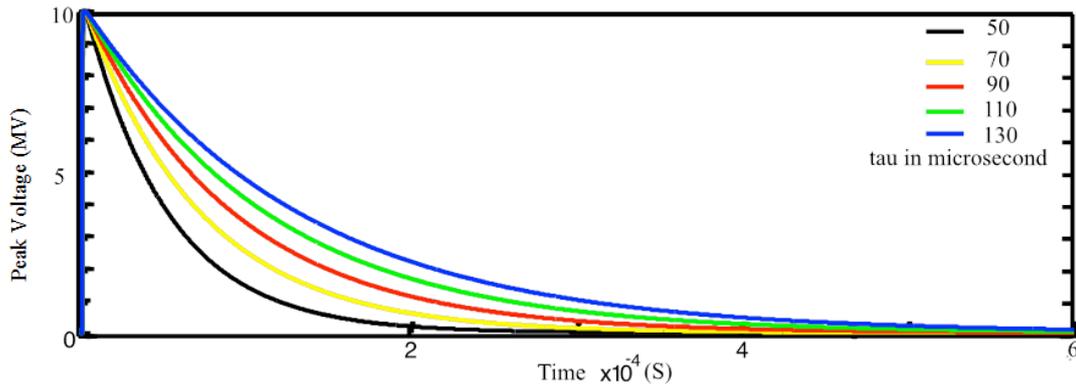


Figure 12. Lightning impulse with tau variations

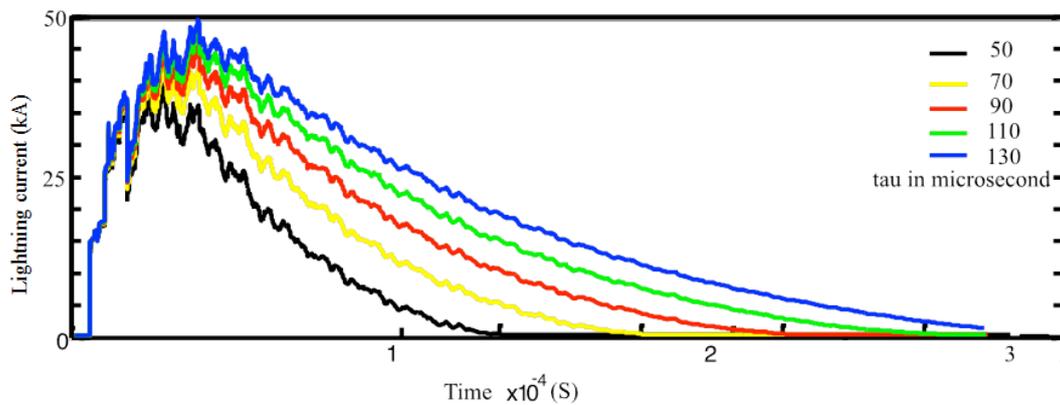
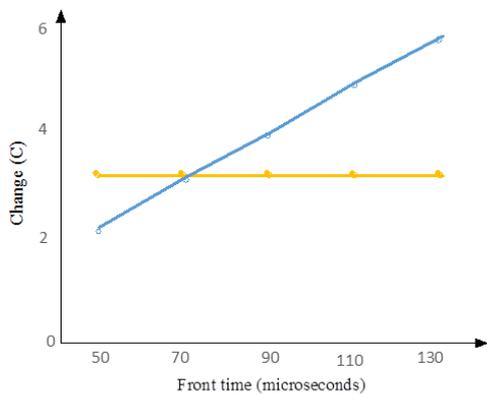


Figure 13. Current waves through arrester in phase A after lightning currents are injected with variations of tau

wire and propagates throughout the transmission lines. The carry out model is the insulator on tower number 4 during the flashover event and it causes an increase of voltage on the phase wire. The Tf, Tsta and tau values in this simulation are 1.2, 3, and 90 ms, respectively. The simulation results that were run on a series of a lightning strike on ground wires without mounting arresters can be seen in Figure 16. The values of the peak voltage of phase wire are 6.5078 MV, 7.7113 MV, 8.6198 MV, 10 MV, 8.8588 MV, and 8.3243 MV for tower numbers 1 to 6, respectively. This simulation also examines the effect of arrester performance in various arrester installation locations. Figure 17 shows a simulation of a series of the

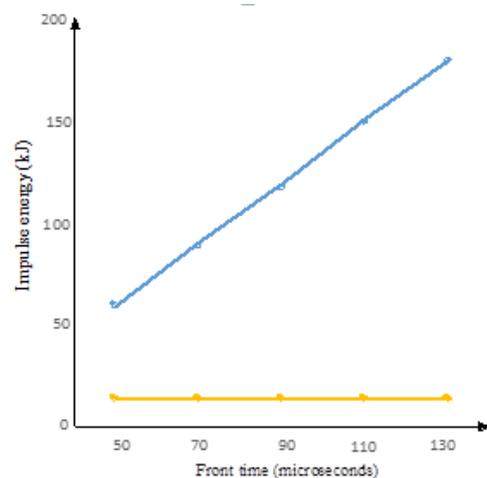
lightning strike with arresters placed on tower 1. The arrester on tower 1 has a voltage drop of 89.05 % with a voltage level of 0.7124 MV. Meanwhile, towers 2 to 6 did not experience significant decreases of peak voltage, with the values of 10.99 %, 0.54 %, 0 %, 0.81 %, and 0.8 %, respectively.

The peak voltage of phase wires for towers 2 to 6 are 6.9173 MV, 8.5731 MV, 10 MV, 8.7873 MV, and 8.2579 MV, respectively. Figure 18 shows the simulation result with the placement of TLA on towers 1 and 5. The peak lightning voltage on the phase wires in each tower is different. The highest to



*The yellow line is charge limit in the arrester

Figure 14. Comparison of current charge values to tau variations



*The yellow line is energy limit in the arrester

Figure 15. Comparison of impulse energy values to tau variations

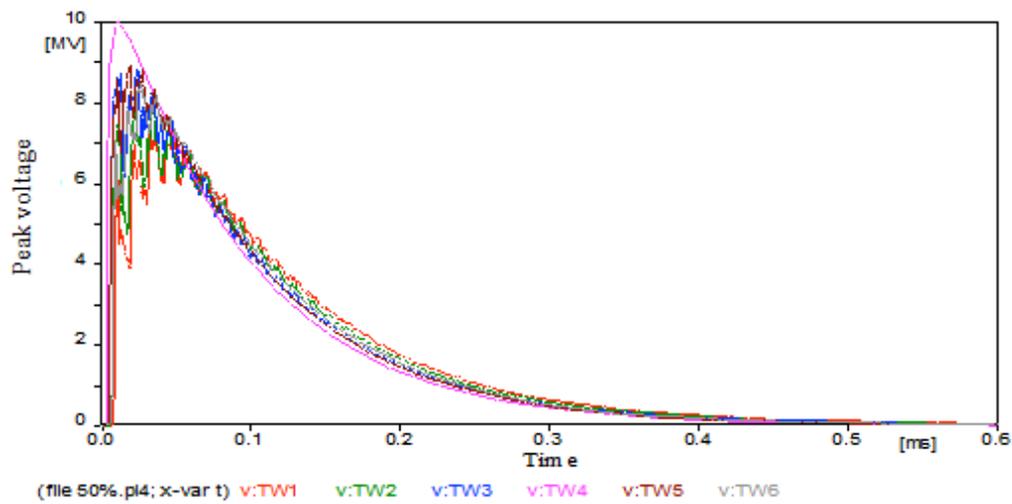


Figure 16. Simulation result of the output of the lightning strike circuit without arrester

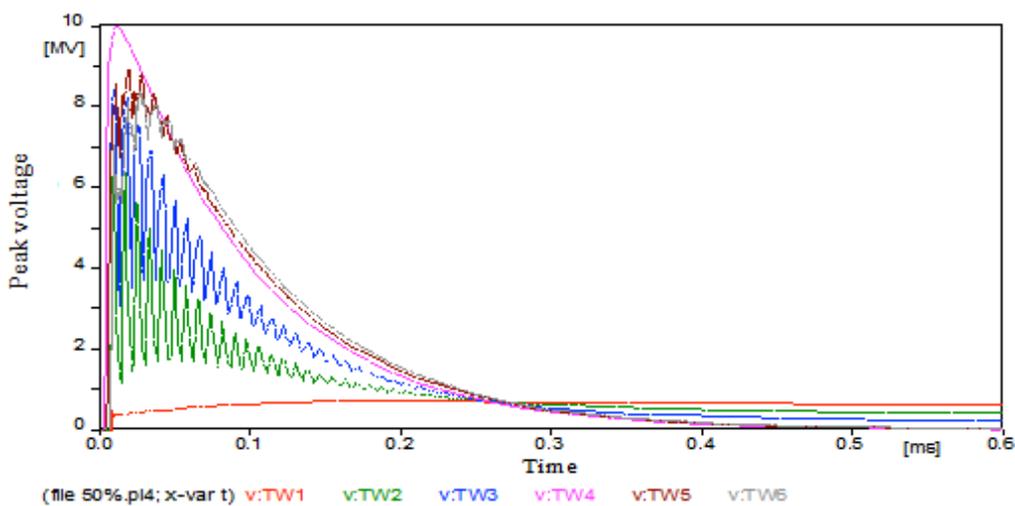


Figure 17. Simulation results show a series of lightning strikes on transmission lines with arresters placed on tower 1

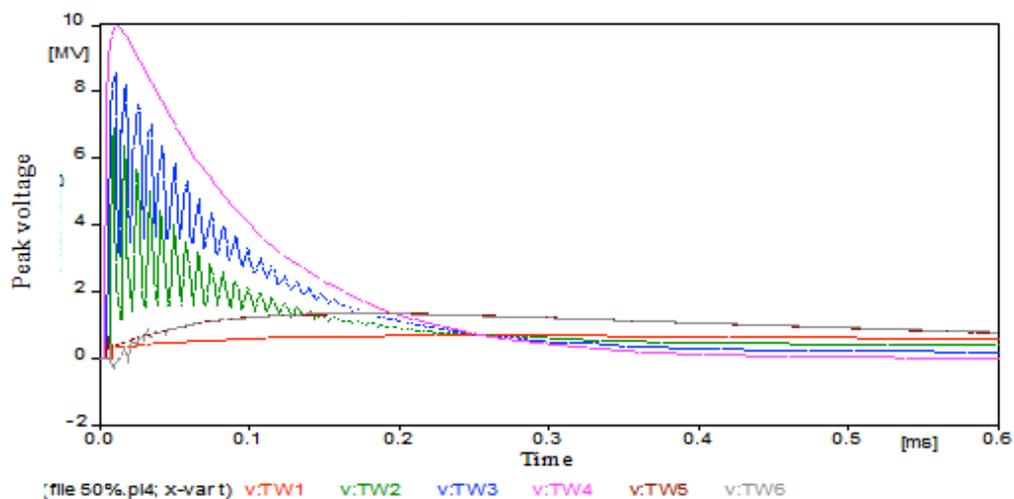


Figure 18. Simulation result of a lightning strike on transmission lines with arresters placed on towers 1 and 5

the lowest peak voltage is found in towers 4, 3, 2, 6, 5, and 1. The most significant decrease in peak voltage on phase wires is found between towers 1 and 5. The peak voltage drop on phase wires from towers 1 to 6 are 89.67 %, 11 %, 0.52 %, 0 %, 84.61 %, 83.49 %,

respectively, while the recorded peak voltage was 0.7113 MV, 6.9167 MV, 8.5746 MV, 10 MV, 1.3636 MV, 1.3746 MV, respectively. Moreover, the simulation results for the installation of arresters in towers 1, 2 and 6 can be seen in Figure 19. From the graph above,

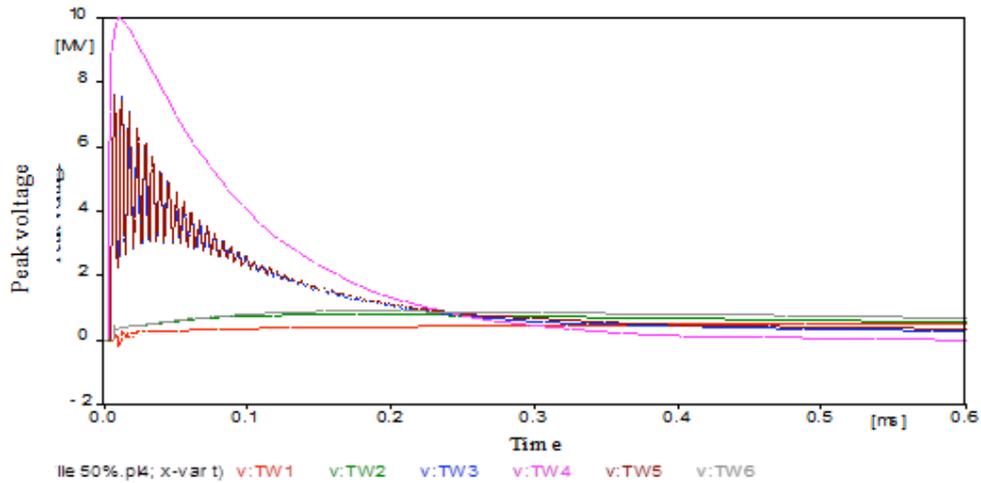


Figure 19. Simulation result of a lightning strike on transmission lines with arresters placed on towers 1, 2 and 6

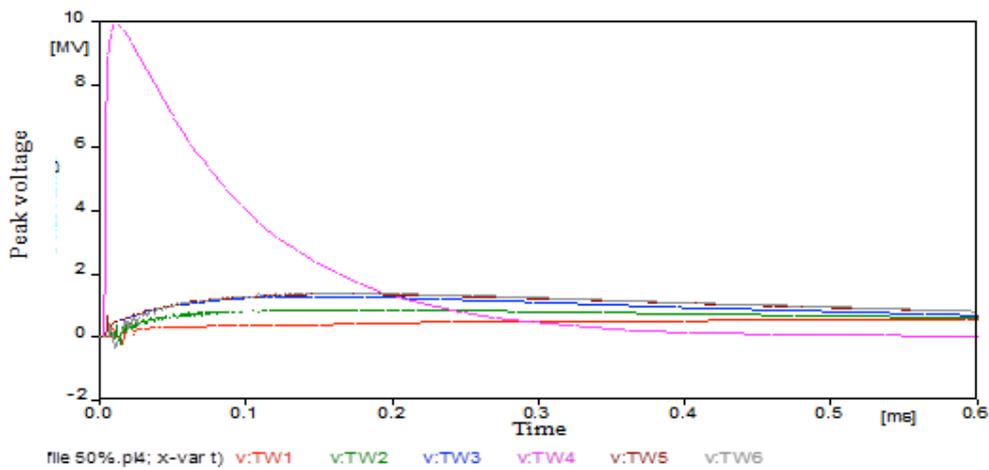


Figure 20. Simulation result of a lightning strike on transmission lines with arresters placed on towers 1, 3, 4 and 5

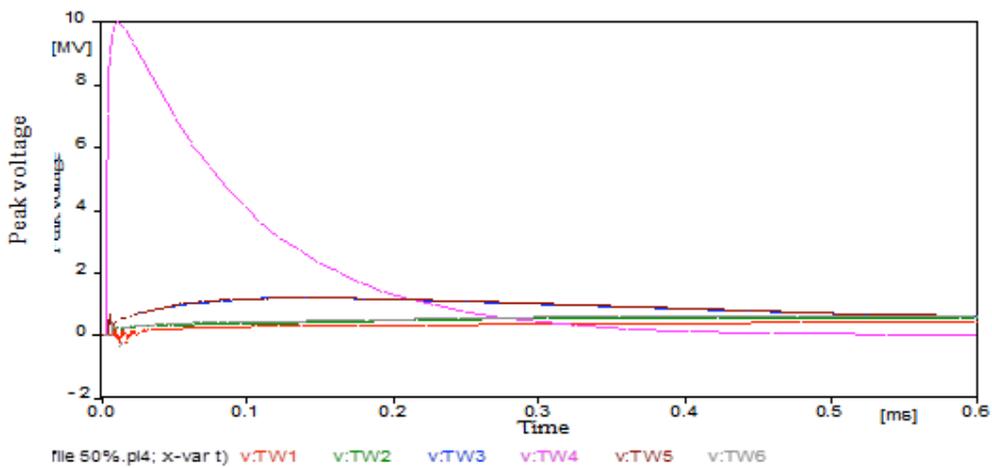


Figure 21. Simulation result of a lightning strike on transmission lines with arresters placed on towers 1, 2, 3, 4, 5 and 6

the data obtained for peak voltage on phase wires in towers 1 to 6 include 0.5153 MV, 0.8021 MV, 7.6114 MV, 10 MV, 7.613 MV, 0.8971 MV, respectively and the percentages of reduction of peak voltage are 92.08 %, 89.68 %, 11.69 %, 0 %, 14.04 %, 89.22 % for towers 1 to 6, respectively.

The simulation results for the installation of arresters in towers 1, 3, 4 and 5 can be seen in Figure

20. From the graph above, the data are as follows: the peak voltages of lightning on phase wire are 0.5471 MV (decreased 91.59 %), 0.8519 MV (decreased 89.04 %), 1.284 MV (decreased 85.1 %), 10 MV (decreased 0 %), 1.3615 MV (decreased 84.63 %), and 1.3811 MV (decreased 83.41 %) for towers 1 to 6, respectively. Figure 21 is a simulation result with the placement of arresters in towers 1, 2, 3, 4, 5, and 6.

The lightning peak voltages on phase wire are 0.4679 MV, 0.5674 MV, 1.2248 MV, 10 MV, 1.2322 MV, and 0.6219 MV for towers 1 to 6, respectively. The voltage drop values are as follows: 92.81 %, 92.64 %, 85.79 %, 0 %, 86.09 %, and 92.53 % for towers 1 to 6, respectively.

In addition, the location of lightning strikes on overhead lines does not have a significant effect on travelling waves with the theory of wave reflection and waves transmitted on the system. However, the location of the lightning strike still influences the overvoltage in the substation by changing the distance of the travelling wave towards the substation [27]. Then, the simulation results also show that the installation of arresters for all phases in several towers can reduce the overvoltage in the tower. This is in a good agreement with [28][29]. However, for economic and maintenance reasons, the installation of arresters should be on a tower that often gets lightning strikes.

IV. Conclusion

Based on the simulation and data analysis that has been done, some conclusions can be drawn: the variations of the wave front time duration (Tf) and strike duration (tau) on lightning impulses affect the current and integral currents that occur in arresters. Tsta variations in lightning impulses do not affect the current charge and impulse energy. Tf is proportional to current charge and impulse energy. The small tau leads to the current toward zero faster. Lightning strikes of 10 MV on the ground wire without mounting arresters resulted in the increases of voltage on the phase wires on tower 1 until 6 were 6.5078 MV, 7.7113 MV, 8.6198 MV, 10 MV (tower had flashover event), 8.8588 MV and 8.3243 MV, respectively. After the installation of arresters in each tower for phase wires, the subsequent decrease of peak voltage on tower 1 until 6 were 0.4679 MV (92.81 %), 0.5674 MV (92.64 %), 1.2248 MV (85.79 %), 10 MV (0 %), 1.2322 MV (86.09 %) and 0.6219 MV (92.53 %), respectively. Protection of the transmission line to reduce overvoltage in phase wires by installing arresters in each tower is better than installing the standing alone arrester or without installing any arresters.

Acknowledgement

We thank all those who have supported this research.

Declarations

Author contribution

F. Murdiya contributed as the main contributor of this paper. All authors read and approved the final paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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