Research Article

Classification of Lightning and Faults in Transmission Line Systems Using Discrete Wavelet Transform

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In Thailand, electrical energy consumption has been rapidly increasing, following economic and population growth. In order to supply constant power to consumers, reliability is an important factor the electric utility needs to consider. Common disturbances that cause severe damage to transmission and distribution systems are lightning and faults. The system operator must deal with these two phenomena with speed and accuracy. Thus, this study aims to investigate the differential behaviour of transmission systems when disturbance such as lightning strikes and faults occurs in a 115-kV transmission line. The methodology consists of using the ATP/EMTP program to model the transmission system by the 115-kV Electricity Generating Authority of Thailand (EGAT) and simulate both lightning and fault signals in the system. The discrete wavelet transforms are then applied to obtain the signals in order to evaluate the characteristics and behaviour of both signals in terms of high-frequency components. The obtained data will then be used to construct the fault and lightning classification algorithm based on DWT and travelling wave theory. The proposed algorithm shows the effectiveness in classifying the fault and lightning based on the transmission system that was modelled after the actual system in Thailand. Thus, it can further improve the protection scheme and devices in terms of accuracy and reduce the response time for an operator to address the disturbance and ensure the reliability of the system in the future.

1. Introduction

Presently, technological development and economic growth make electricity important in both industry and daily life. Therefore, to cater to this demand and improve power systems, the Electricity Generating Authority of Thailand (EGAT) has started the innovation of a degenerative transmission system in the range of 115-230 kV. The project is expected to be completed in 2017 and will increase the capacity of substations, thus increasing the energy flow in the systems. After the completion of these projects, the growing demand of electricity usage will be met, and electricity will be accessible to large areas. However, the expanding power networks frequently cause power-transmission accidents. These accidents are divided into 2 types: accidents caused by natural phenomena (lightning) and those caused by the system structure (fault). The accidents caused by natural phenomena seriously damage life and property. However,

these do not commonly occur in systems, whereas faults on the power line occur more often in complex than in normal networks.

The literature review on various researches and studies in the field of fault and lightning on power system has been done. There are three main objectives of lightning for the researcher to focus on: the electric field, the magnetic field, and the influence of lightning on equipment in power systems. Lin Li and Vladimir A. Rakov [1] recorded information about lightning incidents in USA from 2004 to 2005 to analyse the characteristic of lightning electromagnetic field. Jun Zou et al. [2] invented a model for estimating the electromagnetic field caused by direct lightning and distribution in the Lightning-Protection System (LPS). The model is based on a double-conductor system, which can be reduced to a two-port equivalent circuit. However, due to a lack of grounding system, the estimation capacity is limited. In addition, there are a number of studies on the

characteristics of lightning. Andrei Ceclan et al. [3] presented a procedure for reconstructing the spatial waveforms of the lightning return-stroke current base using a numerical-field synthesis method and Fourier transform. The combination of these methods is proven to increase the efficacy of lightning detection. Ian Cotton et al. [4] compared voltage induced by lightning and switching on a 1-km pipeline of parallel overhead transmission line. Although the switching-induced voltage is lower than the lightning-induced voltage, either can cause damage to devices and systems. Vishwanath Hegde and Vinoda Shivanand [5] observed induced currents caused by lightning strikes to the ground near a steel-reinforced concrete building. The relation among the peak values of the induced currents and three main factors, namely, the height of a building, its roof, and the lightning rods used, is studied. It is found that the building's height and several attributes of the lightning rods are the major contributing factors. Amedeo Andreotti and Luigi Verolino [6] presented a novel lightning current function that is more complex than an ideal lightning current function, but obtains an exact waveform; thus, the novel method can completely replace the ideal model without any impact on the processing time. Sometimes, the analysis by a single method is not comprehensive, so some researches apply various methods to utilize the features of each method in order to obtain the best results; for example, Vesna Javor and Predrag D. Rancic [7] presented a novel lightning current function by coordination between differential integral equation and Fourier transform, in which the first-order positive sequence of lightning return stroke and the subsequent lightning stroke is analysed. The results demonstrated that an offered function can be used to analyse every type of lightning return stroke. Silvestar Sesnic et al. [8] estimated the time of the maximum transient current at the horizontal axis of finite-ground electrode, using the coefficient of reflection to analyse the conditions of soil and air by combining the Laplace transform and Cauchy residue theorem. Afterwards, because of the development of technologies, many researchers began to apply this development in their research to improve the accuracy and efficiency, like Pooyan Manoochehrnia et al. [9] and Marcos Rubinstein [10]. Pooyan Manoochehrnia et al. analysed lightning events in Switzerland from 1999 to 2007 using Benford's law. The results proved that Benford's law is not suitable for determining the analytical characteristics of lightning, because it can only analyse low lightning currents. However, the law is reasonable to locate the position of lightning. J. A. Morales and E. A. Orduna [11] installed magnetic sensors in the power system using the time detected by sensors to estimate the spread of the field and the discharge. E. A. A. M. Luz et al. [12] investigated the induced voltage and current at a transformer in a hydroelectric plant using the finite-difference time-domain method. Their analysis was based on computer simulation and was used to determine the effect of a 1-kA lightning strike at phase A. It was found that the induced voltage follows the lightning point.

When faults occur in the power systems, the characteristic of voltage and current change. Thus, various methodologies that analysed the change in the signal have been used for the protection system. The method for fault location

and classification on transmission line has been reviewed in K. Chen et al. research [13]. Mehrdad Majidi et al. [14] proposed a method to predict the location of single-line, line-to-line, double-line-to-ground, and three-phase faults that occurred in a transmission network. The observation network was based on 39 buses, and the variable parameters are the resistance and line percentage. The operation of this method is unlike that of the conventional method. The proposed method only requires a phasor measurement unit (PMU). The results showed that fault detection by PMU is highly efficient. In addition, the substitution theorem and least-square method were also used to estimate the voltage and current before and after the fault occurred. Moreover, Liang X. D. et al. [15] used the synchrophasor technology for real-time monitoring of a wide-area system. A study proposed a fault-detection method based on the maximum amplitude of the fault, based on the theoretical and PMU data when the fault occurred, and resolving the condition based on a comparison of the EM when the fault occurred. The results of the presented method show high efficiency for detecting faults. F. B. Costa et al. [16] observed a two-terminal transmission system by using the traveling-wave method. The research analysis only used the time of the transient; the polarity and magnitude of the transient were ignored. The real-time analysis has high efficiency for detecting and identifying internal and external faults. Furthermore, the sampling rate and velocity of wave traveling in a line directly affect the detection accuracy. Yao Luis et al. [17] had analysed the fault current by using the discrete wavelet transform (DWT) with consideration of the impact on the mother wavelet, level of wavelet, sampling frequency, and inception angle of faults on the behaviour of wavelet current signals. The result verifies that all these parameters have an impact on the behaviour of signals, especially at the level of the wavelet. Therefore, a suitable issue between a level and signal waveform is necessary for the efficiency of signal analysis. Furthermore, Darwish et al. [18] had presented a method to protect a long transmission line with an installed compensator. This method chose two dissimilar mother wavelets for analysis, which were simulated and processed by PSCAD/EMTDC and MATLAB. The methodology using convolutional sparse autoencoder to detect and classify faults on transmission line has been proposed [19]. The research applied DWT based methodology on high-technology devices for fault protection system. For instance, Korkal et al. [20] inserted global position system (GPS) to detect the time of traveling waves and locate fault positions by DWT. Nagy et al. [21] used the time detected by wireless sensors distributed in the power system to locate the fault areas, based on the coefficient of DWT.

Following the literature reviews above, we concluded that numerous researchers focused on various impacts that occur in the system, such as pre- and postattribution of faults and the influence of faults on devices by using dissimilar methods: FT and DWT. Each method has an exclusive property. FT and DWT have a similarity in displaying the time and frequency domains. FT is unable to display time and frequency together, but DWT is able to do so. From the lightning and fault analyses, both parameters are significantly

essential. Therefore, DWT is more appropriate than FT. Although there are numerous studies on lightning and faults, there are only a few that focused on the apparent coexistence in lightning and faults. Consequently, it is impossible to differentiate both forms. In addition, those case studies are inadequate. Therefore, the objectives of this research are analysing both lightning and the faults that occur in two terminal lines of transmission systems. The system under study is 115-kV transmission line that was modelled after Thailand's transmission system. The ATP/EMTP software has been used to simulate lightning and fault signal on transmission line, and DWT based methodology has been used for the algorithm. The influence of inception angles, phase lines, and the position at which lightning and faults had occurred in the system has been taken into consideration to evaluate the performance of the proposed methodology in various case studies.

2. Theory

2.1. Discrete Wavelet Transform. Wavelet transform is one form of signal processing by using mathematical model to describe the structure of the analysed signal in a practical form. The assumption is that signals are composed of a set of similar small functions called "Mother Wavelet" combined by scaling and shifting. The general equation of wavelet at scale 'a' and position 'b' can be illustrated in (1).

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \quad (1)$$

where $\psi(t)$ = function of mother wavelet; a = coefficient of scaling; b = coefficient of shifting.

The discrete wavelet transforms (DWT) are analysed by shifting and scaling position of mother wavelet in discontinuous interval and can be calculated using (2) with n , m and k parameters being integral numbers.

$$DWT(m, n) = \frac{1}{\sqrt{a_0^m}} \sum_k f(k) \psi\left[\frac{n - kb_0 a_0^m}{a_0^m}\right] \quad (2)$$

where n = Number of data; m = coefficient of scaling; k = coefficient of shifting.

The Daubechies Wavelets (db) have been selected for the proposed algorithm due to the effectiveness in the analysed transient signal in the power system, especially in case fault and lightning occur on the transmission system [22]. The Daubechies wavelet transform can be defined as (3).

$$\psi(x) = \sqrt{2} \sum_{k=0}^{2N-1} (-1)^k h_{2N-1-k} \varphi(2x - k) \quad (3)$$

where

h_{2N-1-k} = filter coefficients.

3. Simulation and Result

The simulating circuit consists of a sending substation (RYG), receiving substation (CTI), and a load of 150 MVA. The

TABLE 1: Parameters of the multi-storey model, $v = 300 \text{ m}/\mu\text{s}$.

Transmission Tower Parameter					
Z_1	180	R_1	12.390927	L_1	0.0024947
Z_2	180	R_2	13.892908	L_2	0.0027971
Z_3	180	R_3	13.892908	L_3	0.0027971
Z_4	140	R_4	31.248555	L_4	0.0062914

distance between RYG and CTI is 88.5 km, and the voltage is 115 kV. The one-line diagram for the simulation circuit is shown in Figure 1(a). A transmission pole used in this research is exhibited in the multistorey transmission tower model shown in Figure 1(b), which is a structure based on EGAT. The multistorey model was divided into 4 parts: the top tower, upper phase, middle phase, and lower phase. Each part included a surge impedance (Z), resistance (R), and inductance (L), and the ground part included footing resistance (R_g). All these parameters are shown in Table 1. The detailed parameter of 115 kV transmission line and tower is described in the Appendix.

The objective of this research was to observe the characteristic of currents when lightning and faults occur. The simulated lightning was based on $1.2/50 \mu\text{s}$, and the amplitude was 20 kA. The velocity of the lightning wave traveling into line was that of the speed of light, $300 \text{ m}/\mu\text{s}$. This procedure determines the static variables, which are the voltage, distance between transmission lines, load capacity, ground resistance, time at which lightning and faults occurred, and amplitude of the lightning currents. The study variables are the inception angles, phase lines, and positions at which lightning and faults occurred.

The simulation in this paper observed three main factors. The first is the position of the lightning and fault, which varied from 10% to 90% of the distance of the transmission line, with a step size of 10% of the line distance. The second factor is the inception angle, which varied from 0 to 150 degrees, where each observed angle increased by 30 degrees. The third is the phase line, which varied between phase A, phase B, and phase C. All factors were observed on 5 incidence cases, consisting of 1 lightning case and 4 fault cases. The fault cases were single-line, line-to-line, double-line-to-ground, and three-phase faults. In this paper, we show the result of the lightning case and the single-line-fault, which were the most frequent occurrences in the power system.

(a) Behaviour of Lightning Strikes in a Transmission Line.

In this case, there is a lightning strike at phase A, and the effects of the two parameters, inception angle and lightning position, on the characteristic of current at the sending and receiving substations were observed. Figures 2(a) and 2(b) are the sending and receiving characteristic current graphs. Figures 2(c) and 2(d) are the wavelet-transformed graphs from Figures 2(a) and 2(b).

From the sending substation, the three-phase currents suddenly increase at the time of the lightning strike. The amplitude of the lightning phase, phase A, is higher than that of the others, and the amplitude that increases is equal to the amplitude of the lightning current. The other phases, phase

FIGURE 1: System for simulation. (a) One-line diagram of simulated circuit. (b) Multistorey transmission tower model.

B and phase C, increase as well, because lightning induces a change in the magnetic field, while, in turn, it induces an increase in the current of the other phases. From the receiving substation, the behaviour of the three currents is similar to that at the sending substation.

In terms of direction, the current of phase A increases in the negative direction because of the lightning return stroke. It suddenly occurs in the range of 0.1-10 ms then slowly decreases and disappears at 100 ms. Phase B and phase C have the opposite changing direction to phase A, because these two phases are not affected by the return stroke. However, this simulation only focuses on the time of lightning occurrence in the range of 2-4 ms, so the lightning vanishes after 4 ms. At that time, the three-phase currents return to the normal condition.

The inception angle varied from 0° to 90° . The waveform of the three-phase currents is sinusoidal, which has amplitude in the positive and negative directions according to the angle; thus, as the inception angle changes, the amplitude of the current changes as well. Moreover, when the lightning location changes from 30% to 70% of the transmission line, it is found that the current characteristic also depends on

the position of the lightning. The position is referenced from the sending substation. Changing the position from 30% to 70% of the transmission line means that the distance between the lightning point and the sending substation increases, while the distance between the lightning point and the receiving substation decreases. This distance directly impacts impedance inverse current. Thus, the location increase makes the amplitude of the current at the sending substation decrease and the amplitude of the current at receiving substation increase.

By considering the sending substation, the waveform of the wavelet suddenly increases in the negative direction at the time of the lightning strike. After that time, the waveform gradually returns to the initial conditions. From the receiving substation, the behaviour of the wavelet is similar to the waveform at the sending substation, which suddenly increases at the time of the lightning strikes, but the coefficient is lower than that at the sending substation because of the effect of impedance from the lightning position.

Likewise, as shown in Figure 3, the amplitude of the current was dependent on the lightning position. The current at the sending end tended to decrease and, on the other

FIGURE 2: Case of lightning strike at phase A at 30% of transmission line (inception angle 0°). (a) All phases at sending substation (RYG). (b) All phases at receiving substation (CTI). (c) Positive sequence at sending substation (RYG). (d) Positive sequence at receiving substation (CTI).

FIGURE 3: Summary of DWT results when the location of lightning was varied (inception angle 0°).

hand, that at the receiving end tended to increase. The results of Figures 4(a) and 4(b) indicate two conclusions. First, the inception angle slightly affects the coefficient, but the lightning position strongly affects the coefficient. Second, the inception angle is not affected by the arrival time, but the

lightning position is highly affected by the time of arrival time from the distance between the lightning point and the end substation. Thus, the arrival time detected by the nearer station will be faster than that of the other station.

(b) Behaviour of Single-Line Fault on Transmission Line. In this case, a single-line fault occurred at phase A, and the effect of the parameters, the inception angle and fault position, was observed on the characteristic of the current at the sending and receiving substations. Figures 5(a) and 5(b) are the characteristic current graphs at the sending and receiving substations. Figures 5(c) and 5(d) are graphs of Figures 5(a) and 5(b) after the wavelet transform.

From the sending substation, the current at the fault phase, phase A, increased in the positive direction. The direction of the change is according to the current waveform. At 2 ms, the time at which the fault occurred, the direction of the fault phase is positive, so the amplitude also increases in the positive direction. The amplitudes of the other two phases, in which the fault does not occur, slightly increase because the effect of the change in the magnetic field is less.

From the receiving substation, the characteristic of the three-phase currents is similar to that at the sending substation, where the amplitude of the current at phase A is higher than that at phase B and phase C. The direction of phase A

FIGURE 4: Summary of DWT of positive-sequence current results when inception angles of lightning condition were varied (lightning location 30%). (a) Sending substation (RYG). (b) Receiving substation (CTI).

FIGURE 5: Case of phase-A-to-ground fault at 30% of transmission line (inception angle 0°). (a) All phases at sending substation (RYG). (b) All phases at receiving substation (CTI). (c) Positive sequence at sending substation (RYG). (d) Positive sequence at receiving substation (CTI).

also changes in the same direction as the sending substation due to the direction of the current waveform when the fault occurred. Phase B and phase C slightly change for the same reason mentioned at the sending substation.

In the wavelet graph in Figures 5(c) and 5(d), a peak only happened when the fault occurred. The effect of the inception angle and position on the wavelet are considered next.

The results in Figure 6 indicate that the coefficient of the wavelet was dependent on the location of the fault. The distance directly impacted the impedance, which in turn affected the inverse current. Thus, the position increase led to a decrease in the amplitude of the current at the sending substation and an increase in the amplitude of the current at the receiving substation. The results in Figures 7(a) and

FIGURE 6: Summary of DWT results when the location of single line fault condition was varied (inception angle 0°).

7(b) show that the coefficient also depended on the inception angle. The waveform of the current is sinusoidal with the amplitude being dependent on the angle, so the inception angle changes the amplitude of the current changes as well.

At the sending substation, the characteristic of the positive current is slightly changed; thus, DWT is better than the positive current because this method can identify the high-frequency component. From the perspective of the wavelet signal, the coefficient of the wavelet is more apparent than that of the positive current method. The coefficient suddenly occurred at the time of a fault. From the receiving substation, the characteristic of both currents is similar to that at the sending substation, in that the changing amplitude of the positive current is less and the coefficient of wavelet is obvious.

Further observation was made for other faults, namely, line-to-line, double-line-to-ground, and three-phase faults, in which the angle and position condition were varied as in the previous section. Figures 8(a), 8(b), and 8(c) illustrate three example cases, in which the inception angle was constant, and the fault position was varied. The figure displays that all types of faults had same characteristic, in which the relation between the position and the coefficient at the sending and receiving stations was opposite.

Next, the inception angle was varied, and the fault position was constant. The observed conditions were the same as the previous. Figures 9(a), 9(b), and 9(c) show the behaviour of the coefficient when the fault position is 30% of the transmission line, and the inception angle was changed from 0° to 360° in the case of line-to-line, double-line-to-ground, and three-phase faults. The figure shows that all faults have the same characteristic. The trend of the coefficient at the sending substation is the same as that at the receiving substation, which is a sinusoidal signal.

In short, the current attributes from the ATP simulation program are not comprehensive for the analysis of lightning and faults because the differentiation between these is not obvious. Next, a transformation will be used to make the current waveform more evident.

4. Algorithm for Discrimination between Fault and Lightning

The previous section described the behaviour of wavelets when lightning and faults occur in the transmission system. This section will describe the discrimination algorithm between lightning and faults in transmission line. The important parameters used for classification consist of 3 parameters: the initial variables, comparison variables, and check variables. The initial variable is maximum DWT coefficient of three-phase current zero sequence. The comparison variables are maximum DWT coefficient of Phases A, B, and C. The check variables are the normalization of maximum DWT coefficient of each phase by dividing the comparison variables by the initial variable. The example of the algorithm process is illustrated as shown in Figure 10, and the equation to calculate the check variables of phases A, B, and C can be done using (4)–(6), respectively.

$$S_{A_{com}} = \frac{I_a S_{max}}{Zero S_{max}} \quad (4)$$

$$S_{B_{com}} = \frac{I_b S_{max}}{Zero S_{max}} \quad (5)$$

$$S_{C_{com}} = \frac{I_c S_{max}}{Zero S_{max}} \quad (6)$$

where $Zero S_{max}$ = Initial variable, which is the wavelet coefficient of zero sequence. $I_a S_{max}$ = Comparison variable, which is the wavelet coefficient of phase A. $I_b S_{max}$ = Comparison variable, which is the wavelet coefficient of phase B. $I_c S_{max}$ = Comparison variable, which is the wavelet coefficient of phase C. $S_{A_{com}}$ = Check variable of phase A. $S_{B_{com}}$ = Check variable of phase B. $S_{C_{com}}$ = Check variable of phase C.

Figure 11 shows a flow chart that is used to discriminate between lightning and faults. The chart is based on the three previously described concepts. Because lightning is far more devastating than faults, the coefficient of lightning is higher than that of a fault. The minimum of the wavelet coefficient at a positive sequence has initial variables higher than those of a fault. For this reason, the chart can separate lightning and faults based on the minimum positive sequence (Pos_min); Pos_min higher than 53 indicates lightning. Tables 3 and 4 show the result of discrimination based on this flow chart. The data in this table are based on varying the parameters of inception angle, phase, and location along the transmission line. Only a maximum positive sequence (Pos_Smax) in the lightning case is higher than 53. The other cases, in which Pos_Smax is less than 53, are fault cases.

Table 2 shows the parameters in a normal state. All terms in this case are low, which indicates that the wavelet coefficient of the normal state is low at each phase. Its influence on all the variables in the normal case is low.

Table 3 shows the parameters when lightning strikes at an inception angle of 0° and at a location of 30% of the transmission line. The minimum wavelet coefficient of the positive sequence is higher than 53, and the initial variables show that the value of each phase is clearly different, of which

FIGURE 7: Summary of DWT of positive sequence current results when inception angles of single line fault condition were varied (Fault location 30%). (a) Sending substation (RYG). (b) Receiving substation (CTI).

FIGURE 8: Summary of DWT results when location of the fault was varied (inception angle 0°). (a) Line-to-line fault. (b) Double-line-to-ground fault case. (c) Three-phase fault.

FIGURE 9: Summary of DWT results when the inception angle of the fault condition was varied (fault location 30%). (a) Line-to-line fault. (b) Double-line-to-ground fault. (c) Three-phase fault.

FIGURE 10: Operation for discrimination between lightning and fault.

FIGURE 11: Flow chart for classification between lightning and fault.

phase A is the highest. Thus, lightning strikes at the phase case.

Table 4 shows the 3 parameters when single-line faults occur in a transmission line. A comparison between Tables 3 and 4 shows that the coefficient of the positive sequence in the lightning case is higher than that of the fault cause, which is consistent with the previous one; the coefficient of lightning is higher than any fault case. The initial variables, I_{a_Smax} , I_{b_Smax} , I_{c_Smax} , and coefficient of phase A, are

higher than those of phase B and phase C. Furthermore, the grounding fault is considered using zero sequence. The values indicate that the coefficient of the zero sequence is higher than 0.00153. According to the flow chart, it is concluded that the fault occurring in the transmission line is single-line-to-ground at phase A.

Figure 12 shows the results of lightning and fault classification. The results indicate that the proposed method classifies faults and lightning with 100% accuracy with varied

TABLE 2: Variables at normal condition of transmission system.

Normal Condition					
Initial variable					
Pos_S _{max}	Pos_R _{max}	Ia_S _{max}	Ib_S _{max}	Ic_S _{max}	Zero_S _{max}
3.1 x 10 ⁻⁵	9.8 x 10 ⁻⁵	2.6 x 10 ⁻⁵	9.5 x 10 ⁻⁵	2.6 x 10 ⁻⁵	2.4 x 10 ⁻⁵
Compared Variable					
S_A _{com}	S_B _{com}	S_C _{com}			
1.0552	0.0385	1.0552			
Check Variable					
S_Ph _{max}	S_Ph _{min}				
1.0552	0.0385				

TABLE 3: Lightning condition.

Initial variable								
Lightning location on transmission line	Voltage angle	Pos_S _{max}	Pos_R _{max}	Pos_min	Ia_S _{max}	Ib_S _{max}	Ic_S _{max}	Zero_S _{max}
30%	0°	336.9104	222.5332	222.5332	224.5902	56.1444	56.184	7.554
Compared variable								
Fault location on transmission line	Voltage angle	S_A _{com}	S_B _{com}	S_C _{com}				
30%	0°	29.7314	7.4324	7.4377				
Check variable								
Fault location on transmission line	Voltage angle	S_Ph _{max}	S_Ph _{min}					
30%	0°	29.7314	7.4324					
Result								
Type	Pos_min higher than 53						Lightning	
Phase	S_A _{com} higher than other phases,4 times						Phase A	

TABLE 4: Single-line-to-ground fault condition.

Initial variable								
Lightning location on transmission line	Voltage angle	Pos_ $S_{\max}$	Pos_ $R_{\max}$	Pos_min	Ia_ $S_{\max}$	Ib_ $S_{\max}$	Ic_ $S_{\max}$	Zero_ $S_{\max}$
30%	0°	13.3318	8.8739	8.8739	8.8806	2.2321	2.2195	0.0893
Compared variable								
Fault location on transmission line	Voltage angle	S_ A_{com}	S_ B_{com}	S_ C_{com}				
30%	0°	99.4347	24.9921	24.8515				
Check variable								
Fault location on transmission line	Voltage angle	S_ $Ph_{\max}$	S_ $Ph_{\min}$					
30%	0°	99.4347	24.8515					
Result								
Type	Pos_min lower than 53						Fault	
Phase	S_ A_{com} higher than other phases,4 times						Phase A	

inception angle and position. The classification among faults had lower accuracy than lightning cases. The single-line fault had a slight error at positions 50% and 80% of transmission line. The error of the line-to-line fault was slight at positions

20%, 40%, and 50% of line. A slight error was found in the double-line-to-ground fault at positions near the terminal line. The last fault case was the three-phase fault. Three-phase faults, as shown in Figure 12(d), have an accuracy trend

FIGURE 12: Accuracy of each type of fault when inception angle and phase were varied. (a) Lightning type. (b) Single-line fault. (c) Line-to-line fault. (d) Double-line-to-ground fault. (e) Three-phase fault.

similar to that of the double-line-to-ground fault, which has a slight error at the terminal end, at positions 70% to 90% of the line.

5. Conclusion

This research aimed to analyse the behaviour and characteristics of transmission system when lightning and faults

occur. Analyses were performed by obtaining the signal and high-frequency component from a wavelet transform. From the characteristic, the three-phase currents were found to increase to higher values than the normal state currents. The increasing currents of the lightning phase are higher than those without lightning, because this phase is directly affected by the lightning current, whereas the others are indirectly affected by the change in the magnetic fields. The fields induce

TABLE 5: Parameter of 115 kV transmission line and tower.

Tower characteristic	
Tower Name	DA1
Conductor size	795 MCM ACSR/GA
Ruling span	330 m. (Distance from tower to tower)
Conductor characteristic	
Size	795 MCM ACSR/GA
Diameter	26.80 mm.
Number of conductors	1 conductor per bundle
Current capacity	845 A per conductor
Max. sag of conductor	10.55 m.
Overhead ground wire characteristic	
Size	3/8" (HS) Galvanized steel
Diameter	9.144 mm.
Number of conductors	1 conductor

an increase in current. The behaviour of faults is similar to that of lightning, in which the amplitude of the fault phase increases and the others slightly increase. The change in the faults is lower than that in lightning because the short-circuit current caused by lightning is higher due to the amplitude of lightning currents. However, the short-circuit current caused by faults is low because of the fault phase. The short-circuit currents depend on the fault phase, so a three-phase fault, which has the maximum fault phase, has the highest short-circuit currents. Simultaneously, a single-phase fault, which has the minimum fault phase, has the least short-circuit currents. The positive currents originate from three-phase currents separated into three elements: positive, negative, and zero sequences. The positive sequence was observed, and the direction of positive currents was found to depend on the direction of the lightning and fault phase. Based on the wavelet transform, it was shown that the coefficient of the wavelet depends on the inception angle and the position of the lightning and faults. Because the original current is sinusoidal, which has positive- and negative-amplitude currents varying in angles, the coefficient changes according to the angle. In addition, the positions also affect the coefficient because the distance between the reference and accident positions caused an impedance. This research referenced accident points from the sending substation; thus, as the distance increases, the coefficient of the wavelet detected at the sending substation decreases. Meanwhile, the trends at the receiving substation are the opposite.

The result from the proposed classification algorithm, the proposed method, classifies faults and lightning with 100% accuracy in all case study, while in case of fault it can achieve lower accuracy due to the slight error in detecting the high frequency component of DWT in different types of fault. One of the reasons is the current signal in some types of fault when applied DWT generated the similar coefficient value. This result, in the algorithm, identifies wrong types of faults. In case of lightning, the algorithm can correctly identify because the lightning signal has significant differentiate characteristic.

Appendix

The details of 115 kV transmission line and tower from EGAT transmission system using in ATP/EMTP software simulation are shown in Table 5. The calculation of surge impedance for high voltage transmission tower using in simulation based on IEEE and CIGRE can be calculated by using (A.1)–(A.4).

$$Z_i = 60 \log_e \cot \left\{ 0.5 \tan^{-1} \left(\frac{d_i}{2h_i} \right) \right\} \quad (\text{A.1})$$

$$\Delta R_i = \begin{cases} \frac{2Z_1}{(l_1 + l_2 + l_3)} \ln \left(\frac{1}{0.8144} \right); & (i = 123) \\ \frac{2Z_4}{(l_4)} \ln \left(\frac{1}{0.8144} \right); & (i = 4) \end{cases} \quad (\text{A.2})$$

$$R_i = \Delta R_i l_i \quad (\text{A.3})$$

$$L_i = \frac{4H}{v} \cdot R_i \quad (\text{A.4})$$

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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