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RESEARCH ARTICLE

Comparative Fault Detection Between DWT and STFT in Overcurrent Relays

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ABSTRACT This study proposes a protection relay using a microcontroller to detect and classify faults in transmission lines based on the Wavelet transform. An experimental model was constructed from an actual 115 kV transmission system prototype. The current signal was observed based on the fault type, phase, and position. Clark's transform and the discrete Wavelet transform (DWT) were applied to transform signals for analysis. The positive and zero sequences obtained from Clark's transform were used for fault detection and fault classification, respectively. Moreover, the performances between the DWT and the short-time Fourier Transform (STFT) were compared in terms of accuracy and processing time. In addition, the double-detection technique was used to confirm the accuracy of fault detection. Results show that the proposed method is efficient for fault detection and classification. This finding allows the researcher to choose the appropriate analytical method. Moreover, it can also be used as the basis for overcurrent relay algorithm design in the effort to develop more advanced technologies.

INDEX TERMS Discrete wavelet transform (DWT), fault classification, fault detection, overcurrent relay, short-term Fourier transform (STFT), transmission system.

I. INTRODUCTION

Protection systems are incredibly important in power electrical systems. The best protection system needs to detect faults quickly and with high accuracy to reduce damage that may spread. Protective system performance is essential because it affects the reliability of the power system. Moreover, the best protection system must have high accuracy to identify faults. Typically, there is a support maintenance team to ensure affected systems are restored promptly. A relay is a protection device that responds based on determined conditions. There are various relay-protection types.

The fault signals are typically input to the relay. The popular relay protection types are overcurrent [1], [2] and distance relays [3], [4]. The overcurrent relay analyzes the current signal by comparing the current's magnitude against a predetermined setting. The advantage of using the overcurrent relay pertains to the small amount of data needed for analysis. However, the weak point of overcurrent relay was the decision method of the relay only able to detect fault, but it does not identify the fault location. While distance relay can be used to identify the fault location [3], [4] but the processing time was not satisfied. Typically, distance relay is applied permissive transfer trip scheme (PTT) to solve the drawback of time processing. This relay type uses current and voltage data to calculate the impedance. Impedance ratios can be converted to transmission line distances. Conversely, calculating impedance by using current and voltage data is also disadvantageous because the calculated distance has an approximate value and may lead to errors.

The Phasor measurement units (PMUs) method was proposed in the past to use for fault analysis. The method is based on high-speed sensors that measure voltage and current of the power system with accuracy in the order of one

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microsecond [5], [6]. However, due to the noise effect on voltage and current signal. It directly affects the accuracy of fault detection. Therefore, it was rarely used later.

Next, Fourier transformation (FT) [7] and Short-time Fourier Transform (STFT) [8] were popularly used later in the past. However, due to the disadvantage of slower processing, Fast-Fourier-Transform (FFT) [9] was developed. Although FFT method was faster processes and detection than traditional FT, and STFT, but there still has the weak point in decomposition signal domain. Original signal can decompose signal to Amplitude-Time domain and Amplitude-frequency domain. A decomposition to Amplitude-Time at any frequency range cannot be done in FFT. Meanwhile, Wavelet (WT) can do, hence, WT replaces FFT. The WT method [10], [11], [12], [13], [14], [15] was one of methods commonly used in electrical field. The reason was signals generated from electrical system normally include noise like transient effect, high-frequency effect etc. Therefore, WT method was mathematical technique that can decompose signal to the desirable signal, without loss of information. Moreover, traveling wave (TW) was combined with the WT for better performance [16], [17]. The processing method can detect peak current that suddenly increases due to the influence of fault occurrence. At the same time, it can detect the time of the peak current traveling to the terminal of line or substation. So, it can estimate the distance of fault. Moreover, Lai Jiang, et al. 's research [18] proposed the second-generation wavelet (SGW) which provided similar result with TW&WT method. However, it is not widely used due to decomposed signals relying only on previous step signal. Thus, it has a chance of processing errors.

Seriously, the performance of WT method depends on the topology of power system [19], [20], initial system variable [21], type of wavelet [22], [23], etc.

The result of research that focused on parallel transmission line and T type of transmission line, showed that topology of power systems directly affected characteristics of traveling wave. As a result, the wavelets are also different. Therefore, choosing the proper parameters is essential. The current signal was more sensitive than the voltage signal. Thereby, fault analysis based on WT method by using current signal has more pronounced change than voltage signal. Moreover, the type of wavelet was also significant [24], even though the original signal was the same, but the mother wavelet was different. The result of wavelet coefficient also unalike. Mother wavelets normally used in electronic field research were Harr and Daubechies wavelets. The reason was the waveform was similar to the initial system variable.

Concluding of the result of research [25], [26], [27], it found that even parameters of (1) power system topology, (2) voltage level and (3) type of wavelet variable but it also provided satisfactory fault detection results. However, when considering on the Ahmed R. adly and et al research [28] and Peyman Jafarian and Majid Sanaye-Pasand research [29], it can be found that WT method provided satisfied result only applied in simple power system topology like single end terminal transmission line.

To make it more clear, positive, and negative points of each method were displayed in Table.1.

TABLE 1. Performance of existing method.

Method	Fault		Performance
	Detecting	locating	
Based on typical relays [1-4]	Yes	No	Moderate efficacy
Phasor measurement unit (PMU) method [5-6]	Yes	No	This method relied on sensor to detect voltage and current signal. It cannot avoid the effect of noise on the signal, so the performance was not satisfied.
Traveling-wave [16-17]	Yes	Yes	Good only in simple network
Fourier Transform (FT) [7]	Yes	Yes	Detecting time was long due to signal analysis process
Short-time Fourier Transform (STFT) [8]	Yes	Yes	Detecting time was faster than FT method due to processing steps that have been revised to be more concise.
Fast-Fourier-Transform (FFT) [9]	Yes	Yes	Performance was better than FT and STFT, but the method cannot extract signal to amplitude-time at any frequency range.
Discrete WT Transform (DWT) [22-24]	Yes	Yes	Provide the best result which can detect and locate faults within a satisfactory period. However, it is suitable for simple system networks.

Concluding of all literature reviews [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], this study focuses on the characteristics of fault signals generated from the transmission system. All types of faults (single-line (SL), line-to-line (LL), double-line-to-ground (DLG), and three-phase (3P) faults) are observed when the phase and location of the fault vary. Current and voltage are considered. However, the focus of this study is on the overcurrent relay operated based on current data. Moreover, the efficiency of fault analyses conducted in this study can also be improved by using methods such as Clark's transformation, FT, and WT. The fault signal that was considered in this study was generated in the experimental model which was set up in our King Mongkut's Institute of Technology Ladkrabang (KMITL) laboratory. The prototype of the experimental model was based on an actual 115 kV transmission system. The performance of the proposed method was verified in terms of accuracy and detection time. The results show that optimal setting conditions (suitable analysis method, sampling rate, etc.) result in high accuracy and short processing times. Moreover, short-time Fourier transform (STFT) and Discrete Wavelet Transform (DWT) [30] presented in the past of literatures were used to compare the performance with our proposed method. These findings are beneficial and can be used as a basis for the design of fault-detection transmission-system algorithms. At the same time, they can lead to performance improvements in relay devices. The major contributions of this study are the followings:

- The proposed algorithm has been implemented in relay-replicate hardware and transmission system on laboratory level, which was modelled after actual 115 kV transmission line.
- The performances of the Discrete Wavelet Transform (DWT) were presented in this paper. In addition, a performance between short-time Fourier transform (STFT) and the Discrete Wavelet Transform (DWT) were compared. The results can be used by researchers as guidelines for the choice of the appropriate method.
- The performance of the proposed algorithm was evaluated in detecting, locating faults, and response time.

This study comprises five sections. Section II describes the background and related theories. Section III presents the experiments. The process of fault detection and classification is presented in section IV. Section V concludes this study.

II. SIGNAL TRANSFORMATION METHOD

Several mathematical methods were proposed to use for the signal analysis. n. Fourier Transform (FT) and Wavelet Transform (WT) were famous and well-known in electrical systems signal analysis can transform the original signal from the based-on time domain to the frequency domain and the transformation was expressed by shown as equation 1. Fourier Transform (FT) and Wavelet Transform (WT) are famous and well-known in electrical systems signal analysis

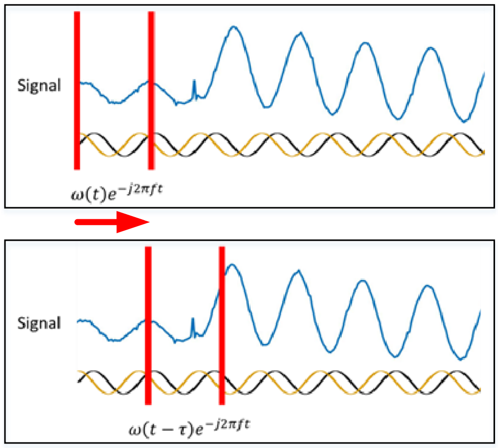

FIGURE 1. Analyzing signal by using Short Time Fourier Transform (STFT).

can transform the original signal from the based-on time domain to the frequency domain and the transformation was expressed by shown as equation 1. Thus, the Fourier Transform is appropriate to use to analyze analyses of high-frequency fault signals generated from electrical systems due to the fault causing high frequency occurrence.

$$FT\ (\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}\,dt \tag{1}$$

Moreover, due to processing time when using Fourier Transform to analyze signal was too long so Short Time Fourier Transform (STFT) were invented. The STFT analyzed the original signal by using a moving window displayed in equation 2 and Fig. 1.

$$STFT\ (\omega) = \int_{-\infty}^{\infty} x(t)\omega(t-\tau)e^{-j2\pi ft}\,dt \tag{2}$$

where

ωt = was windows function

However, the Fourier Transform also has the limitation which was the magnitude of signal in time domain and frequency domain cannot be extracted at the same time. This affected the time that high frequency occurrence cannot detected so the Wavelet Transform has been presented to solve this disadvantage.

Wavelet Transform is signal processing developed from Fourier Transform and Short Fourier Transform. There can been adjust time period and frequency. Wavelet Transform consists of Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). Due to the processing time of DWT being less than CWT so this paper will focus only on DWT. A signal was analyzed by adjusting scale of frequency and moving position point on discrete period, as expressed in equation 3.

$$DWT\ (m,n) = \frac{1}{\sqrt{2^m}} \sum\nolimits_k f\ (k)\ \varphi[\frac{n-k2^m}{2^m}] \tag{3}$$

where

m, n, k = Integers
ψ = Mother wavelet

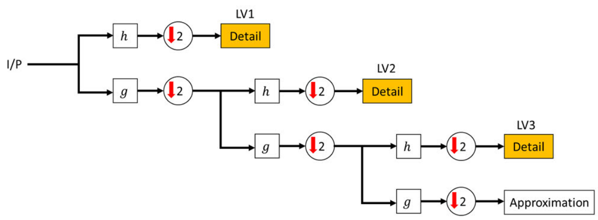

FIGURE 2. The filter operation of Discrete Wavelet Transform (DWT).

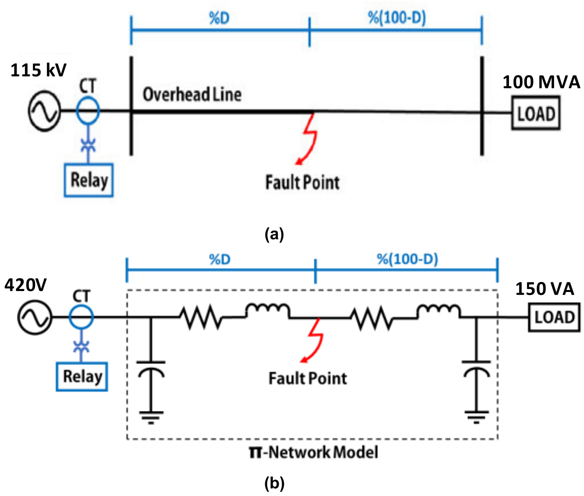

FIGURE 3. The study system in this paper. (a) The study system in this paper and (b) An equivalent model.

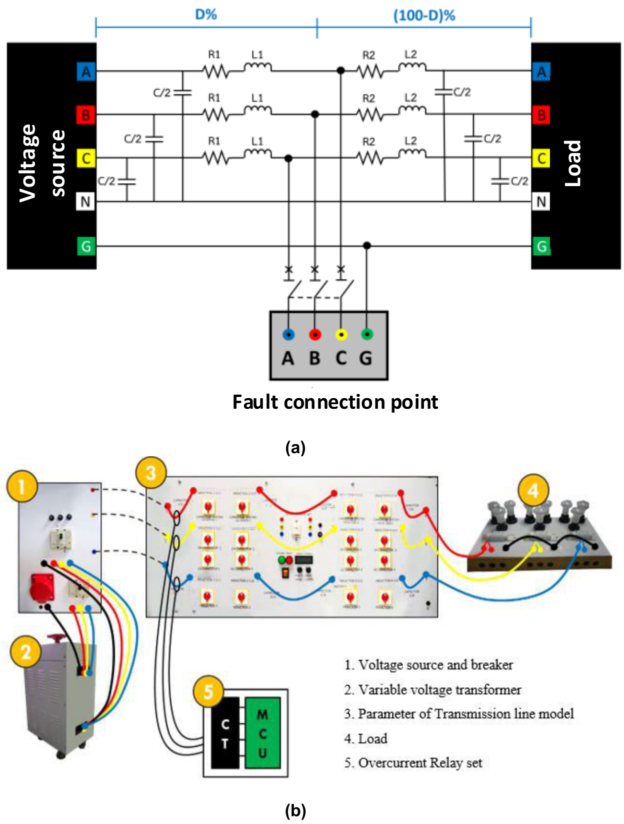

FIGURE 4. The experimental system. (a) A detail of the equivalent model and (b) A connection of equipment.

n = Number of data points
m = Scaling
k = Shifting

DWT has a similar pattern to a filter bank displayed in Fig.2. The frequency of the original signal has been sorted out to two bands, high (h) and low frequency band (g). The frequency that has been sorted out reduces in half from the original signal. The filter of DWT can decompose the original signal to any frequency range. The frequency of each filter step will half reduce from the previous frequency.

III. EXPERIMENTAL SETUP

The experiments conducted in this study are discussed in this section. An experimental model was set up in our KMITL laboratory. The experimental model was created as an equivalent system of the 115 kV actual transmission system. The prototype system is displayed in Fig. 3(a) showing a 115 kV substation connected to a load of 100 MVA) and a 40 km transmission line between the substation and load. A current transformer (CT) and a relay were connected at the substation to detect current signals. Fig. 3(b) is the equivalent model of the system evaluated herein and shown in Fig. 3(a). The equivalent model comprises a 420 V source which is connected 150 VA load based on the Π-network's transmission line.

Moreover, the interconnecting components of the equivalent model are shown in Fig. 4. The model in Fig. 4(a) consists of two sets of pi connections. The fault connection point is a fault occurrence point at various transmission line distances in the range of 0–70%. It is also able to adjust the fault type. The equipment connections are shown in Fig. 4(b). Five sections of equipment are connected: specifically, (1) voltage source and breaker, (2) a three-phase variable voltage transformer (0–420 V), (3) parameter of transmission-line model, (4) load-containing lamps and ballasts, and (5) an overcurrent relay set. Furthermore, the overcurrent relay set consists of a relay processor based on Arduino Due and a class 0.2 current transformer (50 A/333 mV)

IV. WAVELET FOR FAULT DETECTION AND CLASSIFICATION

When abbreviations used in this section was determine as:

α = alpha phase current which is the extract of Clark's Transformation
β = beta phase current which is the extract of Clark's Transformation
0 = zero phase current which is the extract of Clark's Transformation
Positive = Integrated between alpha and beta phase current

The signal analysis process (see Fig. 5) uses are as follows:

1.The Arduino processor in the experimental model receives a three-phase current signal from a current

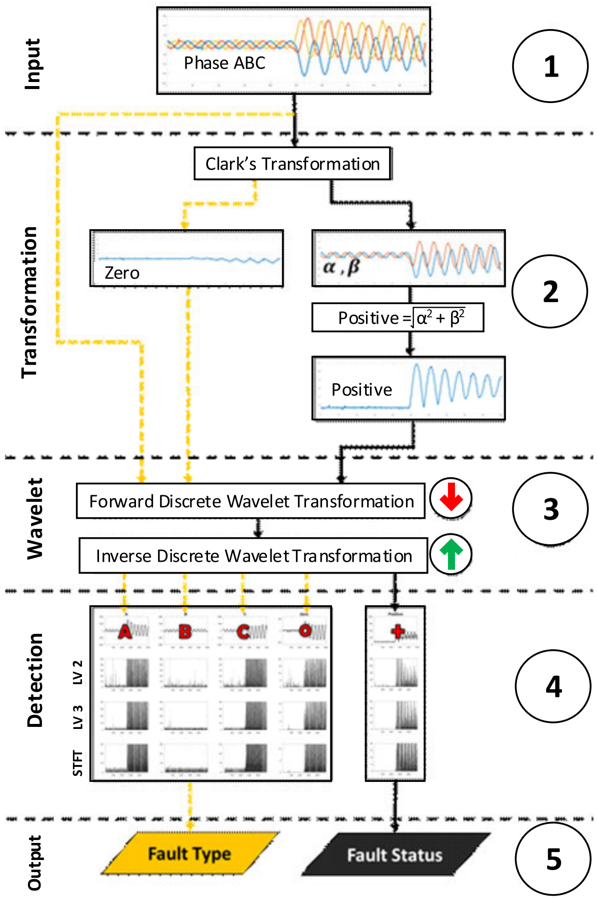

FIGURE 5. Flow chart process of overcurrent relay.

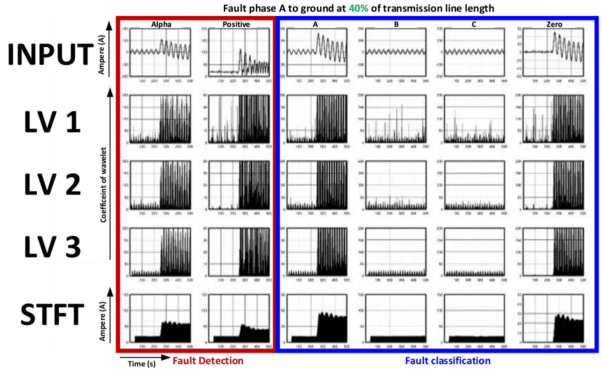

FIGURE 6. Current signal recorded in case of SLG fault phase A at 40% of transmission line length.

transformer in the form of a voltage value in the range of 0–333 mV. Analog signals are then transformed to 12-bit digital values (0–4096)

2.Since the overcurrent relay has two operating functions (detection and classification faults), Clark's transformation is applied to transform the current signal to phases A, B, and C. Input signals are simplified by using Clarke's transform. The output signal is presented in an order with alpha (α), beta (β), and zero sequences. A positive sequence was integrated between the alpha (α) and beta (β) sequences.

3.Third, noise is present in current signals. To solve this problem, DWT is applied at this step.

4.After the current signal is handled by Clark's and DWT transforms, the detection process is completed. The fault signal observation process in this study has two objectives, namely the (1) classification of the fault and (2) identification of fault status. Therefore, the fault was detected by considering five parameters (data of phases A, B, and C, and positive and zero sequences). The positive sequence signal was used to detect faults. Meanwhile, the zero-sequence signal was used to classify ground faults.

5.The output of the proposed algorithm provides a notification on the status of the system. If a fault status is detected, the fault phase is announced by using the data of phases A, B, and C. On the contrary, when the system operates at normal status, the algorithm only displays the status.

The stipulation of the signal investigation was set. The Daubechies scale 2 (db2) family wavelet was used to determine the mother wavelet since the waveform was asymmetric on the left and right sides (similar to a fault signal). At the same time, the sampling rate in this study was set as the maximum value that the hardware can record. This maximum value was based on the single-cycle analysis duration in relation to the analog-to-digital converter. Thus, the maximum sampling rate must be larger than the total analysis duration. Owing to this reason, this study was set at levels 2–3 and the sampling time was set at 0.5 s.

Furthermore, the double detection technique was also applied in this analysis to obtain more accurate information. The relay announces a fault when it receives values (two consecutive times) that exceed the set value.

The experimental model shown in Fig. 4 was used and current signals were recorded subject to the condition that the observed parameters varied.

1.Fault type: Four types of expected transmission system faults were observed; these included the SLG, LL, DLG, and 3P faults

2.Fault phase: The fault phase varied (A, B, and C)

3.Fault distance: The distance of the transmission line, which was referred from the fault position to the source, also varied (40%, 50%, 60%, and 70%)

The current signal was recorded from the experimental model when faults occurred. The signal is displayed in Fig. 6 and is characteristic when an SLG fault (phase A to ground) occurs, and the location is 40% of the transmission line length. The characteristics of alpha and positive sequence currents were determined from the experimental model when Clark's transform was used. The x-axis denotes time (s) and the y-axis current (ampere (A)). Positive sequence currents were analyzed for fault detection. At the same time, the current phases A, B, C, and the zero sequence were analyzed for fault classification. These characteristics were transformed by DWT to extract a coefficient wavelet. Three DWT levels are displayed.

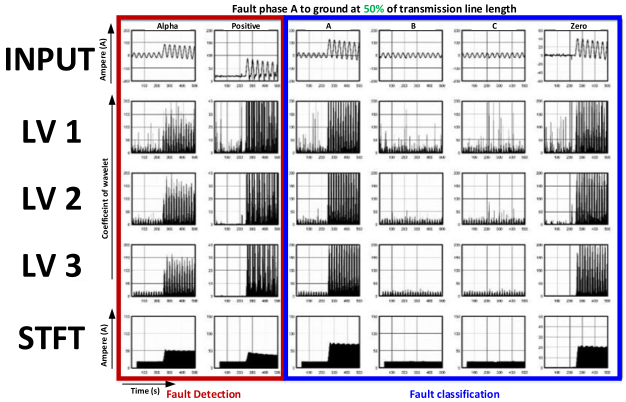

FIGURE 7. Current signal recorded in case of SLG fault phase A at 50% of transmission line length.

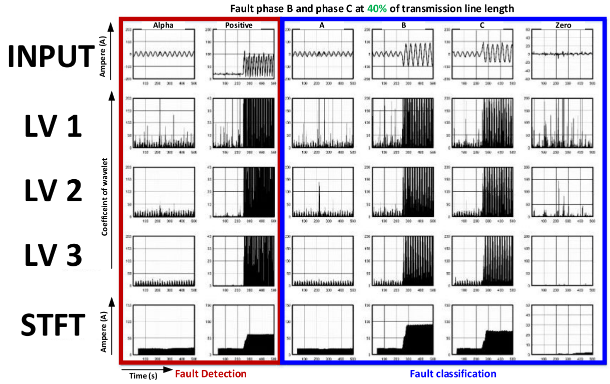

FIGURE 8. Current signal recorded in case of LL fault phase B and C at 40% of transmission line length.

When considering the DWT signal levels 1–3 displayed in Fig. 6 (wherein the x-axis denotes time and the y-axis the wavelet coefficient), it is found that the wavelet signal at level 1 has more noise than that at level 3. This is because the fault occurs in the high-frequency range. Thus, a high DWT level filters high-frequency pass. Thus, the low-frequency noise in the original signal was eliminated. For this same reason, the wavelet coefficients of the three-phase currents at level 3 are also more obvious than those of levels 1 and 2.

In addition, this performance of STFT method was also focused and shown in row 5 of figure.6. In this case, the x-axis denotes time, and the y-axis current. The STFT outcomes show that alpha phase current and positive currents increase when faults occur. Simultaneously, current of phase A and zero sequences current increase. Additionally, the values of phases B and C (during which faults did not occur) are maintained the same.

Moreover, results relevant to fault position changes from 40% to 50% of the transmission line length are displayed in Fig. 6. The magnitudes of the alpha and positive sequence currents are like the response obtained when the fault occurred at 40% of the transmission line length. The magnitudes of both signals suddenly increased when faults occurred. However, when the magnitude values were compared, it was found that the magnitude current at the 50% transmission line length case was lower than the magnitude in the case in which the fault occurred at 40% of the transmission line length.

The characteristic of current displayed in Fig.8 shows three issues. First, only the magnitude of positive sequence current increases. The magnitude of alpha sequence was unchanged even fault occurrence. This demonstrated that alpha phase was not suitable to use for fault analyzation. Therefore, the fault analysis in this study was focused on positive sequence.

When considered coefficient wavelet displayed in row 2 to row 4 of Fig.8, the result found the similar characteristic to previous case which the coefficient extracted by DWT level 3 was more evident than other two level. While the characteristics of STFT signal were considered and it was found that phase and type of fault directly affected the magnitude phase. In this case, due to LL fault occurred in phase B and phase C, the magnitude of fault phase which was phase B and phase C immediately increase. On the contrary, due to fault not occurred at phase A and fault not to ground so the STFT magnitude of phase A and zero sequence was not changed.

According to the characteristic displayed in Fig.6-8, the result can be concluded that positive sequence was suitable for fault analyzation because it includes three phase current data and the ratio of A:B:C phase was 1:1:1. The alpha was not appropriate to use for fault analyzation because this sequence was referenced at phase A. The ratio of A:B:C phase was 2:1:1. It results in the alpha phase unchanged even fault occurred at phase B and C. This unchanging because of an unbalance ratio (ratio of phase B and C was lower than phase A). In addition, DWT level 3 extracted the most evident coefficient wavelet. STFT can detect the changing of a magnitude phase parameter (positive and zero sequence, coefficient wavelet of DWT level 3, STFT of phase A, B and C) were focused on this paper and it will be used to detect and classify faults which will explain further.

The flow chart of fault experimental that was done in this study was shown in Fig. 9. Frist, the experimental model was based on 420V source connected 150 VA load. The fault occurred at the transmission line which linked between the voltage source and load. The fault location variable from 40% to 70% of this transmission line length, location reference at voltage source. Four types of faults, 44 cases, were study cases which current signals under 0.5 and 1 sampling rate were recorded. Clark's Transform will apply to the signal analyzation process. However, due to the alpha phase being deficient to use for fault detection. So, positive sequence was used in the analysis instead. Five data which were (1) current phase A, (2) current phase B, (3) current phase C, (4) positive sequence current, (5) zero sequence current were used to indicate fault status and classify fault by using DWT.

Table 1-5 shows the data of five parameters used for a fault analyzation in this study. Parameter which was positive sequence current in Table.2 was considering at first. This experiment observed the fault situations that type and phase of fault variable and a fault detecting time (ms) was recorded.

TABLE 2. A fault detection based on positive sequence current and sampling rate variable.

0.5 ms Sampling rate															
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		AVG (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	Each	Total	
DWT Level 3	40	3.5	2	3.5	2.5	1	2.5	2	3	1.5	2	2.5	2.18	3.19	0
	50	4	4.5	5.5	2	3	2	3	5	2.5	2	2	3.23		
	60	6	3	5	3.5	2.5	2	2.5	5.5	2	2	2.5	3.32		
	70	5	5.5	6.5	4	3	2	3.5	5.5	2.5	3	4	4.05		
STFT	40	4.5	3	4	3	5	3.5	3	3	2	2.5	3.5	3.36	4.63	0
	50	4.5	4	9	3.5	3.5	3	3.5	5	4	3.5	3	4.23		
	60	6	4.5	10.5	4.5	4	4	3.5	6.5	3.5	3.5	3.5	4.91		
	70	6.5	6	13.5	5	4	4	5	7.5	3.5	5.5	5.5	6.00		
1 ms Sampling rate															
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		AVG (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	Each	Total	
DWT Level 3	40	5	3.5	4	4	7.5	4	3.5	2.5	3	3.5	4	4.05	5.01	0
	50	5.5	5	8.5	4.5	5	3	4.5	8	4	3.5	3.5	5.00		
	60	6	4.5	8.5	5	5	4	4.5	9	3.5	3	3.5	5.14		
	70	6.5	5.5	13	5	4	4	5.5	9.5	2	5	4.5	5.86		
STFT	40	4	2.5	5	3	5.5	4	2.5	2.5	2	2.5	3	3.32	4.63	0
	50	4.5	4	9.5	3.5	3	3	3.5	5	4	3.5	3.5	4.27		
	60	6	4.5	10.5	5	4	4	3.5	7	3.5	4	3.5	5.05		
	70	6.5	5.5	13	5	4	4	4.5	7.5	4	5	5.5	5.86		

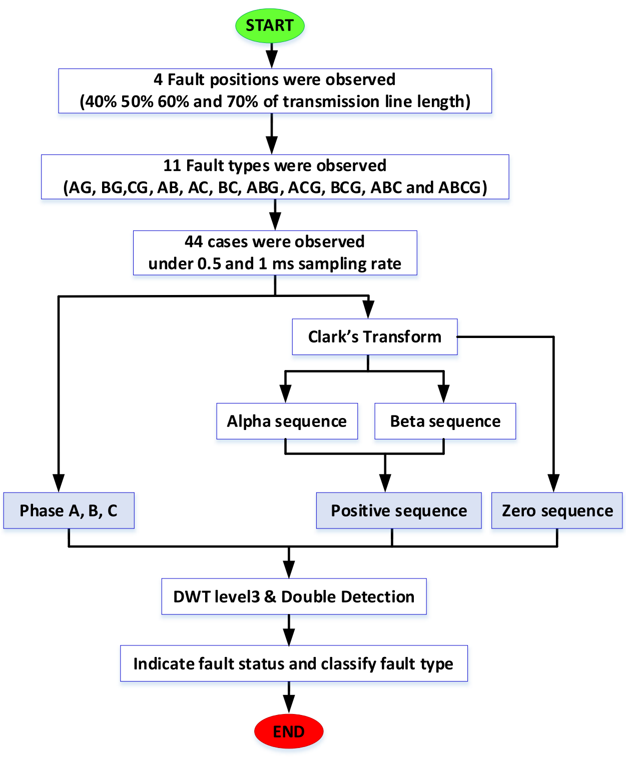

FIGURE 9. Flow chart of fault analyzation.

The performance of detecting fault between DWT method and STFT method was considered.

When considering data of DWT level 3 in Table.2, fault can be detected by using a coefficient wavelet of positive sequence current. The variable of fault position influences a fault detecting time. The fault in the case of % fault position lowest was detected fastest. This reason was the % of fault position related the distance between CT (installed in front of voltage source) and load. Thus, the lowest % of fault position near the CT which was a detection point. So, fault was fastest detecting. This method was accurate in detecting faults, 0 cases of error detection, and the detecting time of all fault cases was within 1-6.5 ms.

In addition, when considering data of STFT, it can be seen that STFT is also accurate in detecting faults. However, the fault detecting time was processed longer than the DWT method which can detect faults within 2-13.5 ms. An average time of DWT and STFT verified that the DWT can detect the fault faster than STFT, without error detection.

On the other hand, the influence of sampling rate on a fault detecting time was also observed. The data in Table.2 displayed that when the sampling rate changed from 0.5 ms to 1 ms, STFT method can detect the fault faster than DWT level 3 method.

Second, a parameter of zero sequence will be considered. The data in Table.3 showed the result of ground fault detection which number 1 status was ground fault occurrence and number 0 statue were no ground fault occurrence. The data in Table 2 shown that sampling rate did not affect the ground detection. The ground fault depended on a zero sequence.

When considering the zero-sequence current applied with DWT Level 3 method, the status in case of SLG and DLG was shown in number 1. While the case of LL and three phase faults show a number 0 status. In addition, when focusing on cases of three phase fault (ABCG), no zero-sequence occurrence even if it was three phase to ground fault. This reason was fault occurred at all phases. It results in three phase fault balance so the value of zero sequence current was less same as the case of ABC three phase fault. Moreover, the data in this table also showed that DWT and STFT methods were accurate methods that could detect ground faults.

TABLE 3. A fault detection based on zero sequence current and sampling rate variable.

0.5 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	1	1	1	0	0	0	1	1	1	0	0	0
	50	1	1	1	0	0	0	1	1	1	0	0	
	60	1	1	1	0	0	0	1	1	1	0	0	
	70	1	1	1	0	0	0	1	1	1	0	0	
STFT	40	1	1	1	0	0	0	1	1	1	0	0	0
	50	1	1	1	0	0	0	1	1	1	0	0	
	60	1	1	1	0	0	0	1	1	1	0	0	
	70	1	1	1	0	0	0	1	1	1	0	0	
1 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	1	1	1	0	0	0	1	1	1	0	0	0
	50	1	1	1	0	0	0	1	1	1	0	0	
	60	1	1	1	0	0	0	1	1	1	0	0	
	70	1	1	1	0	0	0	1	1	1	0	0	
STFT	40	1	1	1	0	0	0	1	1	1	0	0	0
	50	1	1	1	0	0	0	1	1	1	0	0	
	60	1	1	1	0	0	0	1	1	1	0	0	
	70	1	1	1	0	0	0	1	1	1	0	0	

The parameter of positive and zero sequence current was used for indicated fault status and ground fault. After the fault status was confirmed, the fault phase will classify next. The fault phase was classified by using the data of three current phases displayed in Table 3-5. Determine the number 1 was the fault occurrence status and number 0 were no fault occurrence status.

The data is displayed in the Table. 3-5 was current phase A, phase b and phase C, respectively. The data was applied with DWT level 3 and STFT method. The sampling rate varied from 0.5 ms to 1 ms. When the data of phase A was considered, it found that the status in case of AG, AB, AC, ABG, ACG, ABC and ABCG was shown in number 1. While other case shown in number 0. When considering this same principle as the data in Table 4-5. The data in both tables displayed in the same principle as Table.4 which the case of BG, AB, BC, ABG, BCG, ABC and ABCG in Table.4 displayed in number 1 status. Similarly, the case of CG, AC, BC, ACG, BCG, ABC and ABCG in Table. 5 also shown in number 1 status. Therefore, it can be concluded that the number 1 status appeared when fault occurred at that phase. While the fault that fault not occurrence was shown the number 0 status.

After the procurement of fault detection and classification was discussed. The performance of this proposed method will be mentioned next. The performance of DWT and STFT method was displayed in Table.7. Moreover, variable of DWT level (level 2, level 3) was also considered. The performance was considering in terms of (1) accuracy of detecting (2) accuracy of locating and (3) fault detecting time.

When considering the performance under 0.5 sampling rated displayed in Table.7, it was found that DWT level 2-3 can detect the fault faster than STFT method. The level of DWT also influences detection time. However, even the DWT level 2 was fastest detecting fault (only 2.45 ms), but it causes drawback to an accuracy of 97.73%.

When considering the same principle to the data that recorded under 1 ms sampling rate, it can be seen that the increasing of sampling rate causes a fault detecting time increasing. However, when comparing to the data of DWT level 2 under 0.5 ms sampling rated, it found that even the increasing of sampling rated causes the detecting time increasing which increases from 2.45 ms to 3.94 ms but it is more accurate to detect fault which increases from 97.73% to 100%.

At the same time, when considering STFT method, even the data in table. 7 show that performance of DWT is better than STFT when sampling suitable. (In this case, 0.5 ms sampling rate provided better performance than 1 ms sampling rate). However, the variable of sampling rate did not influence the processing time when using STFT method.

From the performance evaluation result, DWT and STFT algorithm can classify fault with no error. However, the DWT level 2 has sole case of malfunction that causes an error result of around 2.27% compared to DWT level 3 and STFT during sampling of 0.5 ms.

Moreover, the other previously presented method [30] was also applied in this paper to verify the performance of the proposed method. The method [30] was classified as fault in transmission line by using DWT method, the type of mother wavelet and scale wavelet were variable. However, even though the result was satisfied but the performance was only verified with the simulation. Its practicality is questionable. Therefore, the method presented in literature no.30 was applied with our experimental setup signal and the result shown in Table.7.

As can see from the data in Table.7, when the sampling rate was 0.5 ms, performance of fault detection and classification of other DWT method was not satisfied. The accuracy was only 77.27% and the reponed time was 5.76 ms.

On the other hand, when the sampling rate was changed to 1 ms, the accuracy of fault detection increased from 77.27%

TABLE 4. A fault detection based on phase A current and sampling rate variable.

0.5 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	1	0	0	1	1	0	1	1	0	1	1	0
	50	1	0	0	1	1	0	1	1	0	1	1	
	60	1	0	0	1	1	0	1	1	0	1	1	
	70	1	0	0	1	1	0	1	1	0	1	1	
STFT	40	1	0	0	1	1	0	1	1	0	1	1	0
	50	1	0	0	1	1	0	1	1	0	1	1	
	60	1	0	0	1	1	0	1	1	0	1	1	
	70	1	0	0	1	1	0	1	1	0	1	1	
1 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	
STFT	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	

TABLE 5. A fault detection based on phase B current and sampling rate variable.

0.5 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	
STFT	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	
1 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	
STFT	40	0	1	0	1	0	1	1	0	1	1	1	0
	50	0	1	0	1	0	1	1	0	1	1	1	
	60	0	1	0	1	0	1	1	0	1	1	1	
	70	0	1	0	1	0	1	1	0	1	1	1	

to 91.34% but the response time was longer. So, it concluded that the performance of real world experimental was essential. Only simulation results may not be enough. This is because the signal used is an ideal signal. Actual experiments should be considered. There effected of noise, environmental conditions, error of equipment etc. directly influence the accuracy of detection.

Therefore, it can conclude three issues as follows.

1.Sampling rate was a significant factor that affected the fault detecting time and accuracy of fault detection. Thereby, the optimal sampling rate was helpful for the fault analysis which it can detect fast and accurately.

2.Both the Discrete Wavelet Transform (DWT) and Short Fourier Transform (STFT) method can be used for fault detection and classification. However, the DWT can achieve better performance in case of selecting the suitable wavelet scale level with sampling rate.

3.Scale level of DWT influence the accuracy of fault analyzation. Noise is commonly found in the signal of electrical systems. The suitability of DWT level can filter the noise

TABLE 6. A fault detection based on phase C current and sampling rate variable.

0.5 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	0	0	1	0	1	1	0	1	1	1	1	0
	50	0	0	1	0	1	1	0	1	1	1	1	
	60	0	0	1	0	1	1	0	1	1	1	1	
	70	0	0	1	0	1	1	0	1	1	1	1	
STFT	40	0	0	1	0	1	1	0	1	1	1	1	0
	50	0	0	1	0	1	1	0	1	1	1	1	
	60	0	0	1	0	1	1	0	1	1	1	1	
	70	0	0	1	0	1	1	0	1	1	1	1	
1 ms Sampling rate													
Method	% Position	SLG Fault (ms)			LL Fault (ms)			DLG Fault (ms)			Three-phase fault (ms)		Case error
		AG	BG	CG	AB	AC	BC	ABG	ACG	BCG	ABC	ABCG	
DWT Level 3	40	0	0	1	0	1	1	0	1	1	1	1	0
	50	0	0	1	0	1	1	0	1	1	1	1	
	60	0	0	1	0	1	1	0	1	1	1	1	
	70	0	0	1	0	1	1	0	1	1	1	1	
STFT	40	0	0	1	0	1	1	0	1	1	1	1	0
	50	0	0	1	0	1	1	0	1	1	1	1	
	60	0	0	1	0	1	1	0	1	1	1	1	
	70	0	0	1	0	1	1	0	1	1	1	1	

TABLE 7. Performance of proposes method.

Method	Performance of proposes method under 0.5 ms sampling rate		
	Time (ms)	% Fault detection	% Fault classification
DWT level 2	2.45	97.73	100
DWT level 3	3.19	100	100
STFT	4.63	100	100
Other DWT method [30]	5.76	77.27	77.27
Method	Performance of proposes method under 1 ms sampling rate		
	Time (ms)	% Fault detection	% Fault classification
DWT level 2	3.94	100	100
DWT level 3	5.01	100	100
STFT	4.63	100	100
Other DWT method [30]	7.32	91.34	91.34

which results in accuracy of signal analysis to be more improved.

V. CONCLUSION

This paper is designed for a protection relay. The study system's prototype is based on 115 kV actual transmission system, which consists of 115 kV substation transfers power to 100 MVA load. The experimental model was set up at our KMITL laboratory to verify the study issue. The experimental model was equivalent circuit from prototype system which was 420 V of voltage source transfers power to 150 VA load with transmission line. The fault characteristic was observed under the condition of fault phase, type, and position variable. Two mathematic methods applied for the signal analysis were Clark's Transform and Discrete Wavelet Transforms (DWT). Moreover, a double detection technique applied in the analyzation procedure to emphasize accuracy. The result concluded that the proposed method was efficient to use for fault detection and classification with satisfying fault-detecting time. The positive sequence current signal was used for fault detection. While the three phases current and zero sequence current signals were used for fault classification. In addition, the performance between DWT and Short Fourier transform (STFT) method was compared. The verification of their performance found that a fault detecting time when using DWT method was faster than STFT. However, the factor of DWT scale and a sampling rate affected the accuracy of detection. Therefore, the optimal setting was essential for signal analysis.

Moreover, the proposed algorithm may apply to commercial devices which can improve performance of both accuracy and response time of protection system in future.

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