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THE COMBINATION OF DISCRETE WAVELET TRANSFORM AND FUZZY LOGIC ALGORITHM FOR FAULT CLASSIFICATION ON TRANSMISSION SYSTEM

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Abstract. *In the literature for fault classification, several decision algorithms have different solutions and techniques. The most research works have only considered the fault diagnosis for single bus systems and two-bus systems. In fact, transmission lines are connected to each other and become a large grid connected system. During faults, it is necessary for the protection system to deal with a complicated transmission network. This paper proposes a new technique using discrete wavelet transform (DWT) and Fuzzy Logic in order to identify the fault types on transmission systems. The DWT is used to detect the high frequency components from these signals. Positive sequence current signals are used in fault detection decision algorithm. The variations of first scale high frequency component that detects fault are used as an input for the fuzzy logic. Various cases studies based on Thailand electricity transmission systems have been investigated so that the algorithm can be implemented. Fuzzy logic is also compared with the comparison of the coefficients DWT technique. The proposed method gives satisfactory accuracy, and will be very useful in the development of a modern protection scheme for electrical power transmission systems.*

Keywords: Wavelet transform, Transmission system, Fault, ATP/EMTP, Fuzzy logic

1. **Introduction.** The algorithm development for detecting the faults on the transmission lines has been progressed, especially in recent years. By the end of the 1990s, the fault classification and identification techniques have been proposed based on either the transient-based protection [1-4] or artificial neural network [5-8]. For transient-based protection, in order that this technique can be accurately applied in operation, the application of wavelet transform is used [1-4,9-15]. The wavelet transform was initially proposed in the literature for fault classification by O. A. S. Youssef [2]. These several papers based on wavelet transform have different solutions [9-17]. In previous research works [3], by considering the pattern of the spectra, the comparison of the coefficients detail (cD) from first scale that can detect fault is considered. The division algorithm between the maximum coefficients of discrete wavelet transform (DWT) at 1/4 cycle of phase A, B, and C is performed. For identifying the phase with fault appearance, the comparisons of the maximum ratio obtained from division algorithm have been performed so that the types of fault can be analysed. As a result, in several research papers, the fault current signals are decomposed into various scales of the wavelet transforms. Although the wavelet transform is very effective in detecting transient signals generated by the faults, it may not be adequate to complete characterization.

In addition, artificial intelligence (AI) has been also reported in the literature for fault classification [5-8,17-21]. In several research papers, the back-propagation neural network

(BPNN) [8] is employed as well as Probabilistic neural network [20] in order to identify types of fault on the transmission line. When carefully investigated, most research works have only considered the fault diagnosis for single bus systems and two-bus systems [4,6-9]. In fact, transmission lines are connected to each other and become a large grid connected system. During faults, it is necessary for the protection system to deal with a complicated transmission network. As a result, these algorithms can give precise results in fault analysis; the effects of loop structure of the transmission network have not been taken into account. Even if artificial neural network algorithm can give precise results in fault types, it is partly limited by the slow training performance. This drawback of artificial neural networks should be improved; otherwise the other types of artificial intelligence should be developed instead. It is interesting to investigate an appropriate fuzzy logic if the fault types on the transmission line can be identified using wavelet transform and fuzzy logic [22-27] for being included in newly-developed protection systems.

Therefore, this paper presents a development of a new decision algorithm used in the protective relays in order to identify types of fault along the transmission systems. The fault conditions are simulated using ATP/EMTP. The current waveforms obtained from the simulation are extracted using the wavelet transform. The validity of the proposed algorithm is tested with various fault inception angles, fault locations and faulty phases. In addition, the construction of the decision algorithm is detailed and implemented with various case studies based on Thailand electricity transmission systems. The considered transmission systems have a radial and loop structure in order to show the advantage of the proposed method.

2. Power System Simulation Using ATP/EMTP.

The ATP/EMTP is employed to simulate fault signals at a sampling rate of 200 kHz (The sampling time used in ATP/EMTP is 5 μsec). The investigated system is a part of Thailand electricity transmission network systems as illustrated in Figure 1 and Figure 2. To avoid complexity, the fault resistance is assumed to be 10 Ω. Fault patterns in the simulations are performed with various changes in system parameters as follows:

- Fault types are classified into 10 types; single phase to ground (SLG), double-line to ground (DLG), line to line (L-L) and three-phase fault (3-P).
- Fault locations are varied from 10% to 90%, with the increasing of 10% of the transmission line length.
- Inception angle on a voltage waveform is varied between 0°-330°, with the increasing step of 30°. Phase A is used as a reference.

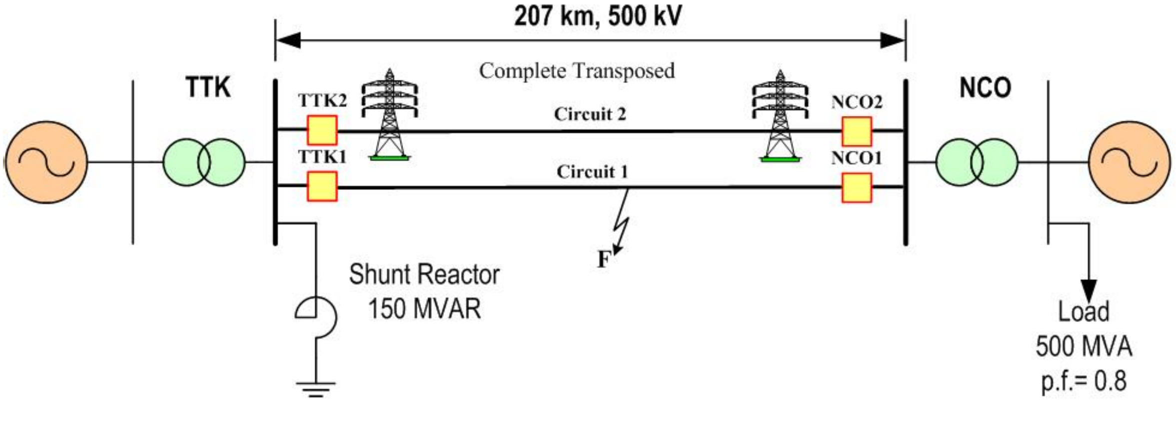


Figure 1. The system used in simulations studies for double circuit structure (System 1) [28]

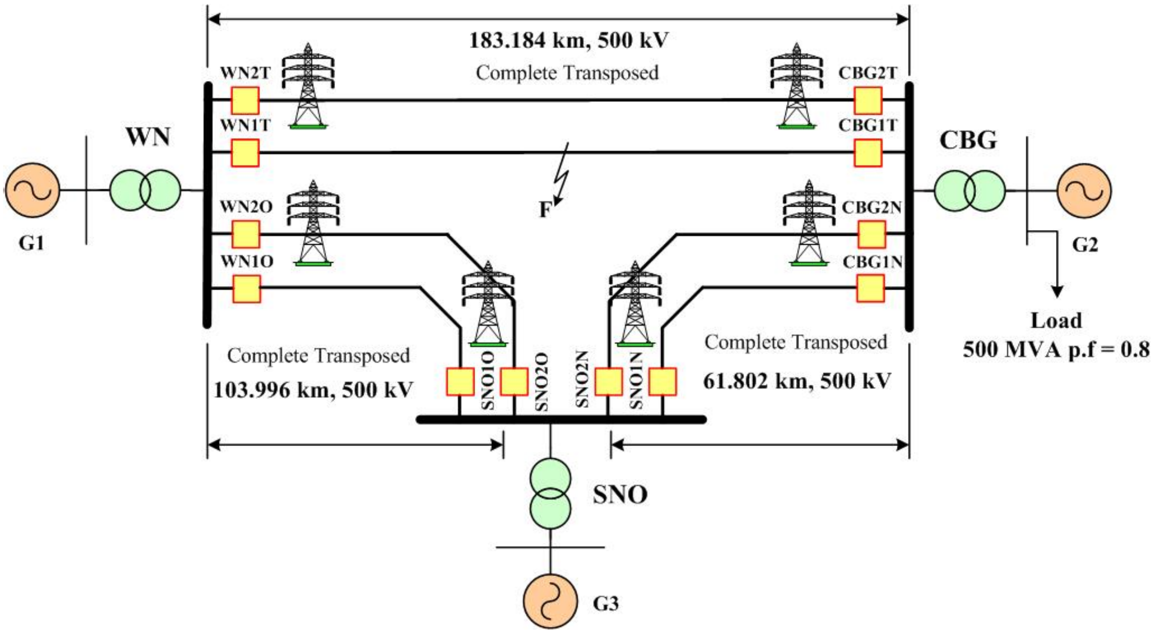


Figure 2. The system used in simulations studies for loop structure (System 2) [28]

3. **Decision Algorithm and Results.** The fault signals generated using ATP/EMTP are interfaced to the MATLAB/Simulink for a construction of fault diagnosis process. Fault detection decision is processed using the positive sequence current signals. The Clark's transformation matrix is employed to calculate the positive sequence and zero sequence of currents. The mother wavelet daubechies4 (db4) is employed to decompose high frequency components from the signals as shown in Figure 3.

With several trial and error processes by performing many simulations, it has been found that, during the faults, all coefficients obtained from the positive sequence currents at every bus have a change of more than 5 times of a normal value; this is the effect of a loop structure of the transmission network. The comparison among the maximum coefficients in first scale of each bus, which can detect fault, is performed in order to detect the faulty bus. In case of double circuit, the maximum coefficients obtained from the same bus are also compared in order to detect the faulty circuit. Finally, the coefficients in scale 1 from DWT are used in decision algorithm for the fuzzy logic in our case study.

The decision algorithm, therefore, are constructed based on the fuzzy logic. A structure of the fuzzy logic consists of 4 inputs and 1 output as illustrated in Figure 4. The output variables of the fuzzy logic are designated as value range of 1 to 10, corresponding to various types of faults as illustrated in Table 1.

The division algorithm between the maximum coefficients of DWT at 1/4 cycle of phase A, B, and C are performed as input variables for fuzzy logic as shown in Equations (1) to (10).

$$I^{L}_{A,B_{\max(post)}} = \frac{I^{L}_{A,\max(post)}}{I^{L}_{B,\max(post)}} \tag{1}$$

$$I^{L}_{B,C_{\max(post)}} = \frac{I^{L}_{B,\max(post)}}{I^{L}_{C,\max(post)}} \tag{2}$$

$$I^{L}_{C,A_{\max(post)}} = \frac{I^{L}_{C,\max(post)}}{I^{L}_{A,\max(post)}} \tag{3}$$

where, L is the scale of wavelet transform that can detect fault; $I^L_{A,\max(post)}$ is maximum coefficient at 1/4 cycles of phase A for post-fault current; $I^L_{B,\max(post)}$ is maximum coefficient at 1/4 cycles of phase B for post-fault current; $I^L_{C,\max(post)}$ is maximum coefficient at 1/4 cycles of phase C for post-fault current; $I^L_{A,B_{\max(post)}}$ is maximum value obtained from division algorithm between $I^L_{A,\max(post)}$ and $I^L_{B,\max(post)}$; $I^L_{B,C_{\max(post)}}$ is maximum value obtained from division algorithm between $I^L_{B,\max(post)}$ and $I^L_{C,\max(post)}$; $I^L_{C,A_{\max(post)}}$ is maximum value obtained from division algorithm between $I^L_{C,\max(post)}$ and $I^L_{A,\max(post)}$.

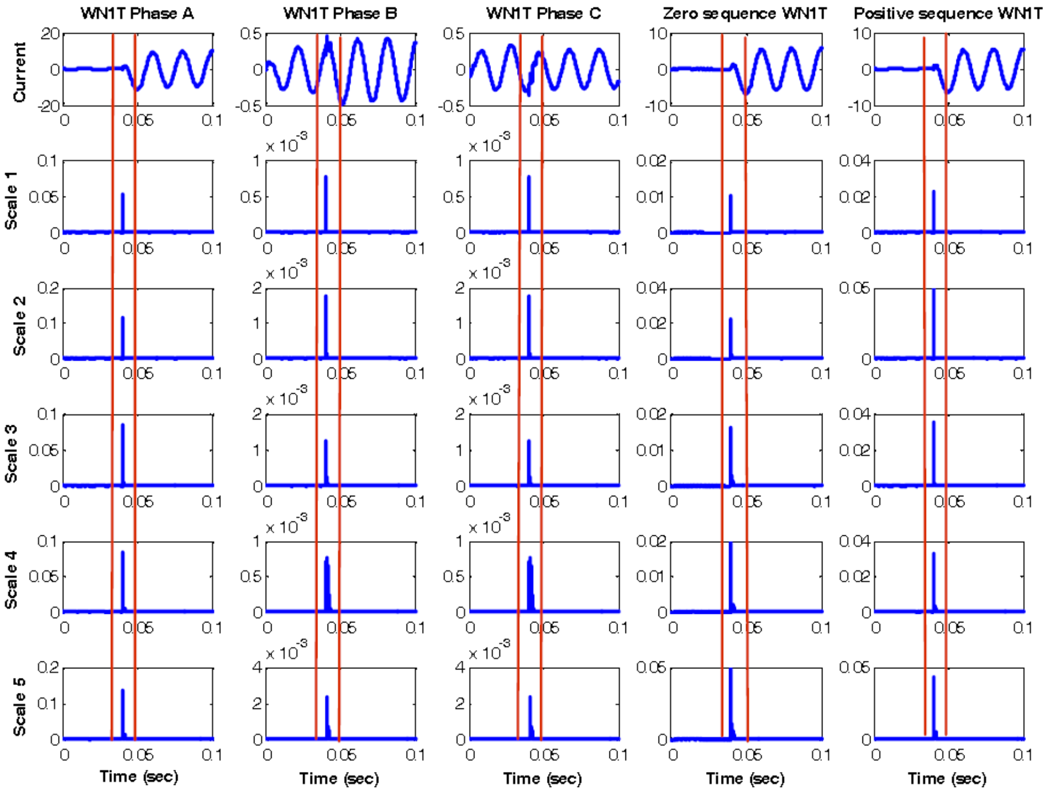


FIGURE 3. DWT from scale 1 to 5 for the positive sequence of current signals

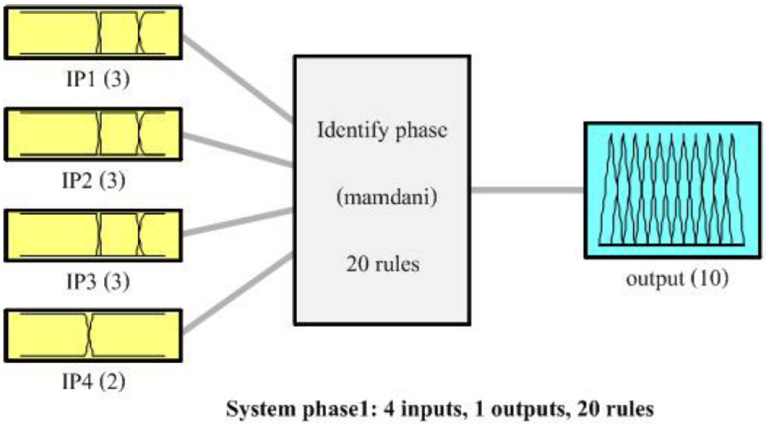
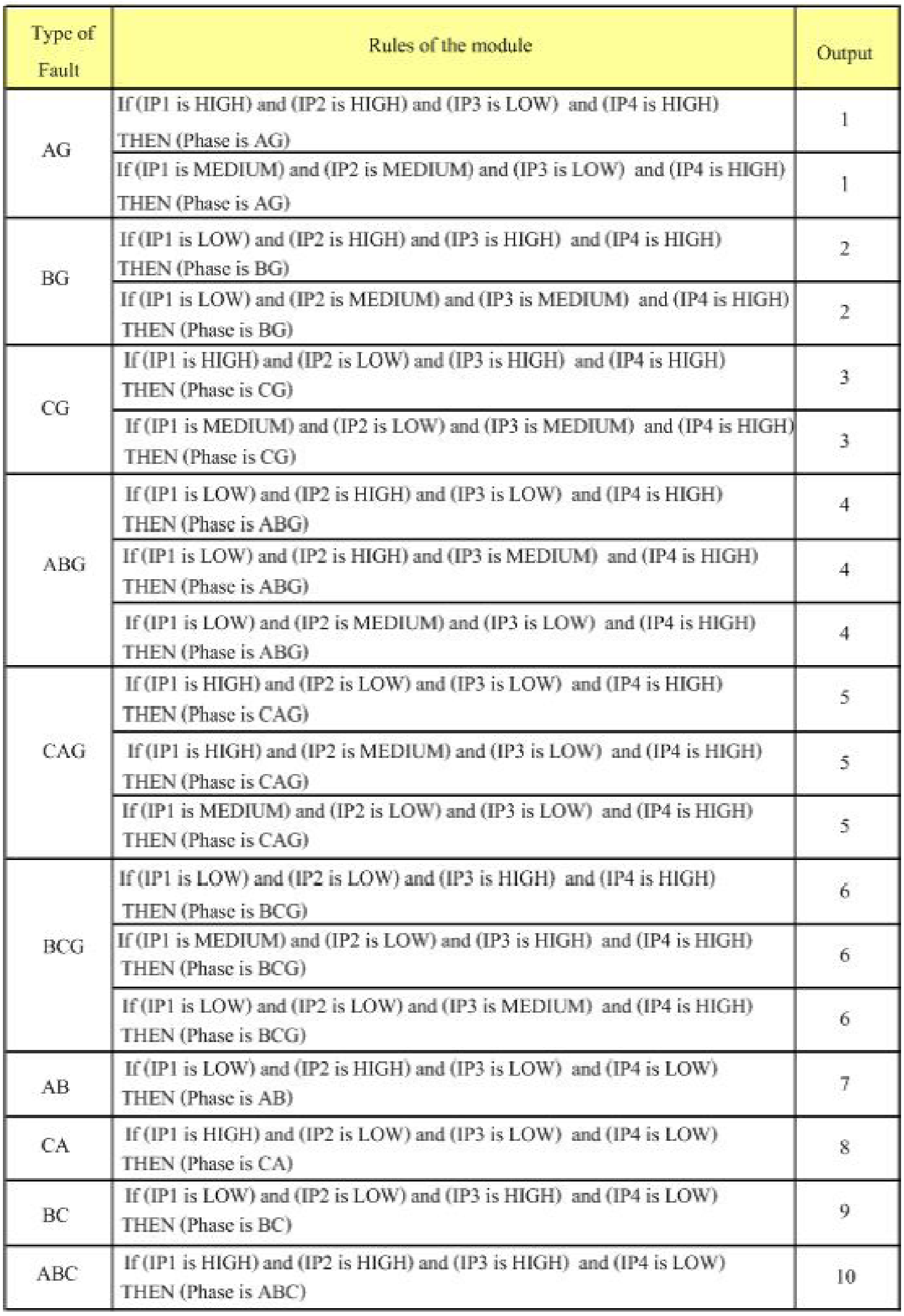


FIGURE 4. Structure of fuzzy logic for classifying the fault that occurs

Table 1. Rules of fuzzy logic for double circuit structure



Type of Fault	Rules of the module	Output
AG	If (IP1 is HIGH) and (IP2 is HIGH) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is AG)	1
	If (IP1 is MEDIUM) and (IP2 is MEDIUM) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is AG)	1
BG	If (IP1 is LOW) and (IP2 is HIGH) and (IP3 is HIGH) and (IP4 is HIGH) THEN (Phase is BG)	2
	If (IP1 is LOW) and (IP2 is MEDIUM) and (IP3 is MEDIUM) and (IP4 is HIGH) THEN (Phase is BG)	2
CG	If (IP1 is HIGH) and (IP2 is LOW) and (IP3 is HIGH) and (IP4 is HIGH) THEN (Phase is CG)	3
	If (IP1 is MEDIUM) and (IP2 is LOW) and (IP3 is MEDIUM) and (IP4 is HIGH) THEN (Phase is CG)	3
ABG	If (IP1 is LOW) and (IP2 is HIGH) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is ABG)	4
	If (IP1 is LOW) and (IP2 is HIGH) and (IP3 is MEDIUM) and (IP4 is HIGH) THEN (Phase is ABG)	4
	If (IP1 is LOW) and (IP2 is MEDIUM) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is ABG)	4
CAG	If (IP1 is HIGH) and (IP2 is LOW) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is CAG)	5
	If (IP1 is HIGH) and (IP2 is MEDIUM) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is CAG)	5
	If (IP1 is MEDIUM) and (IP2 is LOW) and (IP3 is LOW) and (IP4 is HIGH) THEN (Phase is CAG)	5
BCG	If (IP1 is LOW) and (IP2 is LOW) and (IP3 is HIGH) and (IP4 is HIGH) THEN (Phase is BCG)	6
	If (IP1 is MEDIUM) and (IP2 is LOW) and (IP3 is HIGH) and (IP4 is HIGH) THEN (Phase is BCG)	6
	If (IP1 is LOW) and (IP2 is LOW) and (IP3 is MEDIUM) and (IP4 is HIGH) THEN (Phase is BCG)	6
AB	If (IP1 is LOW) and (IP2 is HIGH) and (IP3 is LOW) and (IP4 is LOW) THEN (Phase is AB)	7
CA	If (IP1 is HIGH) and (IP2 is LOW) and (IP3 is LOW) and (IP4 is LOW) THEN (Phase is CA)	8
BC	If (IP1 is LOW) and (IP2 is LOW) and (IP3 is HIGH) and (IP4 is LOW) THEN (Phase is BC)	9
ABC	If (IP1 is HIGH) and (IP2 is HIGH) and (IP3 is HIGH) and (IP4 is LOW) THEN (Phase is ABC)	10

Table 2. Maximum values of coefficient from wavelet transform at 1/4 cycles

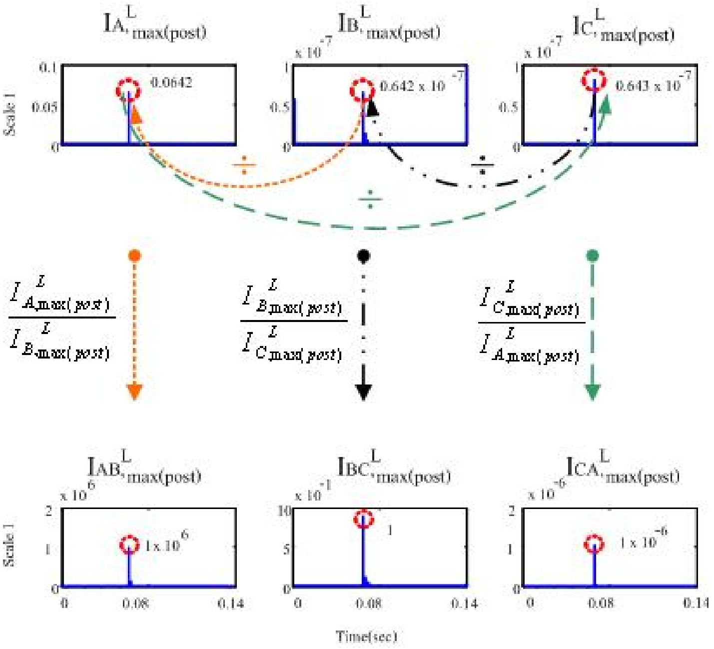
Bus	$I_{A,\max(post)}$	$I_{B,\max(post)}$	$I_{C,\max(post)}$	$Z_{\max(post)}$	$Z_{\max(pre)}$
TTK	64.29E-03	6.43E-08	6.435E-08	21.38E-03	2.559E-22
NCO	11.45E-03	3.10E-05	3.101E-05	3.06E-03	1.353E-22

Maximum coefficient of DWT at each bus is detected as shown in Table 2, then, is divided and employed in the division algorithm. The results obtained from the division algorithm proposed in this paper are shown in Figure 5.

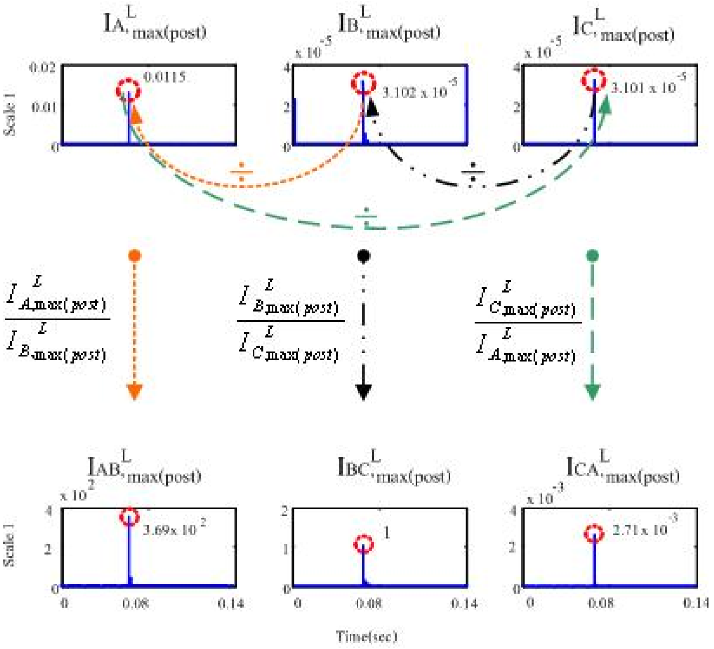
The input variables can be calculated as follows:

$$I^{L}_{P1,\max(post)} = \frac{I^{L}_{A,B_{\max(post)}}}{I^{L}_{B,C_{\max(post)}}} \tag{4}$$

$$I^{L}_{P2,\max(post)} = \frac{I^{L}_{B,C_{\max(post)}}}{I^{L}_{C,A_{\max(post)}}} \tag{5}$$

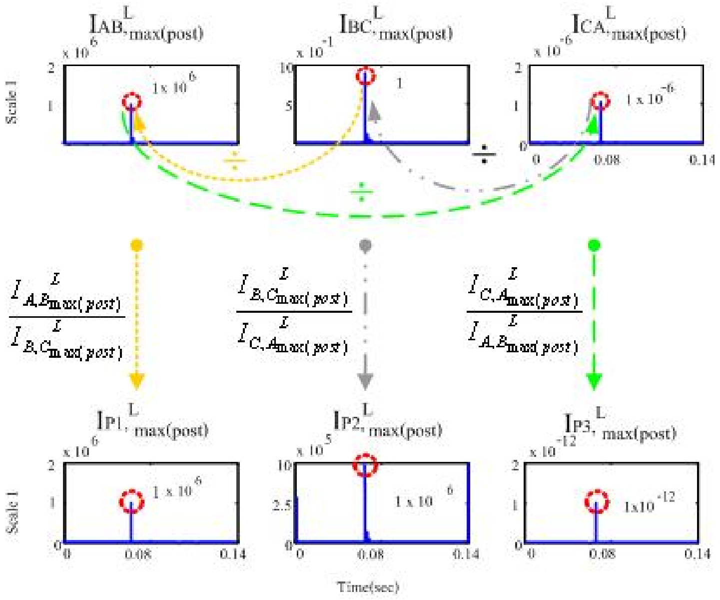


(a) TTK bus

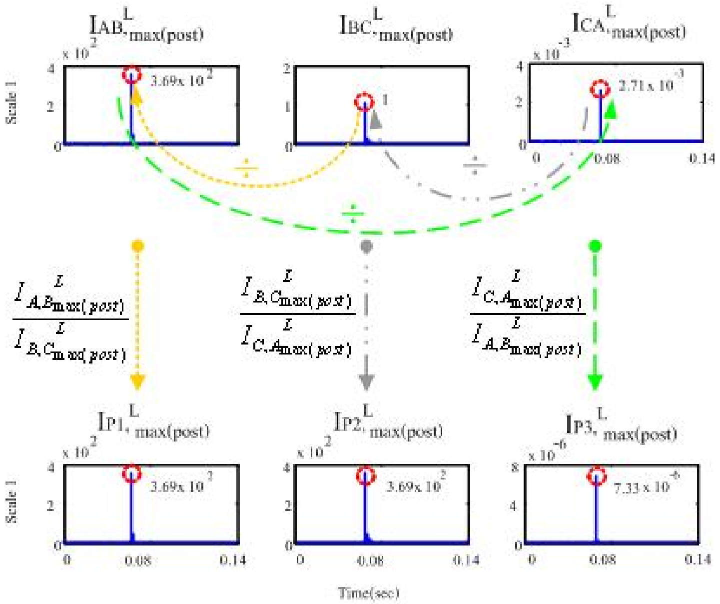


(b) NCO bus

Figure 5. Result of maximum value obtained from division algorithm



(a) TTK bus



(b) NCO bus

Figure 6. Result of maximum ratio used as input variables from the division algorithm

$$I^L_{P3,\max(post)} = \frac{I^L_{C,A_{\max(post)}}}{I^L_{A,B_{\max(post)}}} \tag{6}$$

For detecting the zero sequence current with a fault condition, we process the following algorithm.

If $\left(Z^L_{\max(post)} \geq 5 \times Z^L_{\max(pre)}\right)$ or $\left(Z^L_{chk} \geq 0.00005\right)$
then

$$I^L_{P4,\max(post)} = 1 \tag{7}$$

else

$$I^L_{P4,\max(post)} = 0 \tag{8}$$

end

where, $Z^L_{chk} = \frac{Z^L_{\max(post)}}{Z^L_{\max(pre)}}$ is indicator used in detecting the ground fault; $Z^L_{\max(post)}$ is maximum coefficient from DWT of zero sequence current at the time of 1/4 cycles after detecting faults; $Z^L_{\max(pre)}$ is maximum coefficient from DWT of zero sequence current at the time of 1/4 cycles before the inception of faults; $I^L_{P1,\max}, \ldots, I^L_{P4,\max}$ are input variables of the fuzzy logic.

From Figure 6, it is shown that maximum value obtained from division algorithm is calculated, then, can be divided again. In addition, if the result obtained from division is more than 100 then it is supposed to be 100 as shown in Equations (9)-(10).

If $\left(I^L_{P1,\max(post)}, \ldots, I^L_{P3,\max(post)}\right) \geq 100$

then

$$\left(I^L_{P1,\max}, \ldots, I^L_{P3,\max}\right) = 100 \tag{9}$$

else

$$\left(I^L_{P1,\max}, \ldots, I^L_{P3,\max}\right) = \left(I^L_{P1,\max(post)}, \ldots, I^L_{P3,\max(post)}\right) \tag{10}$$

end

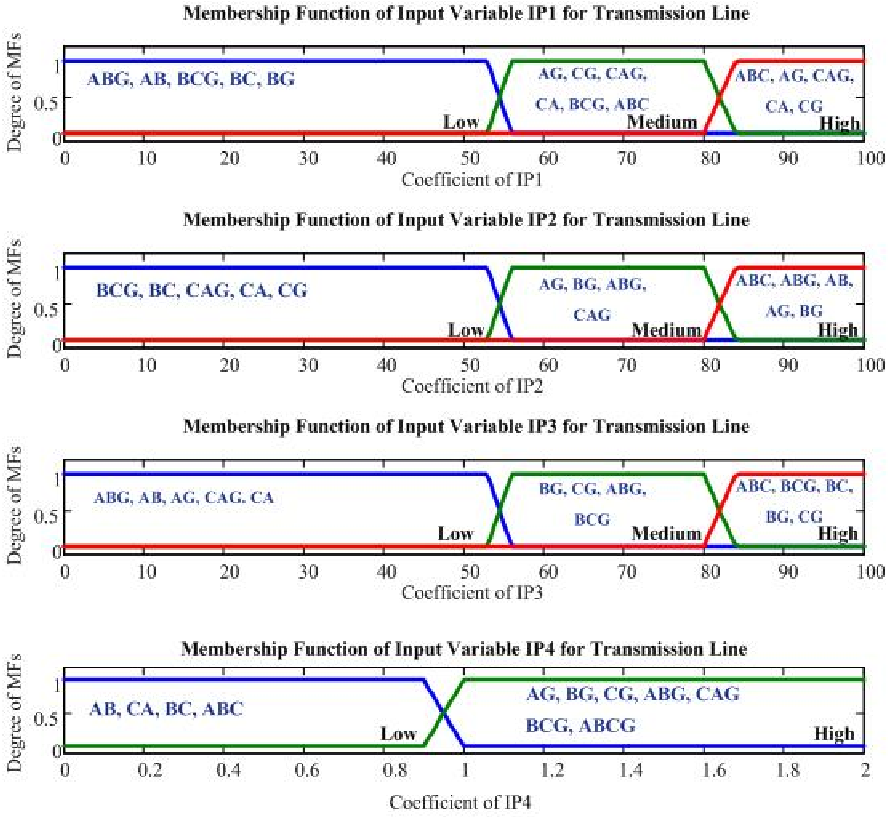
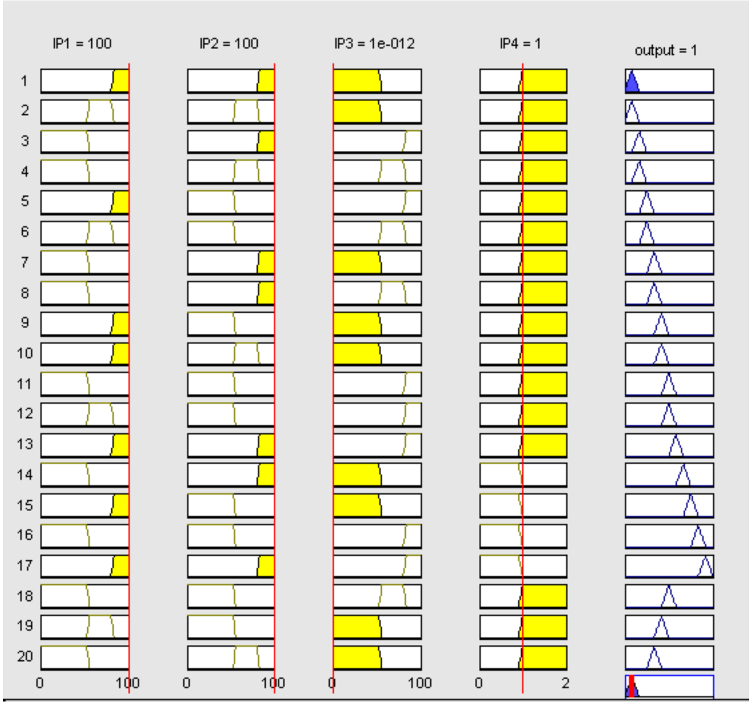


FIGURE 7. Membership function of input variables of the fuzzy logic

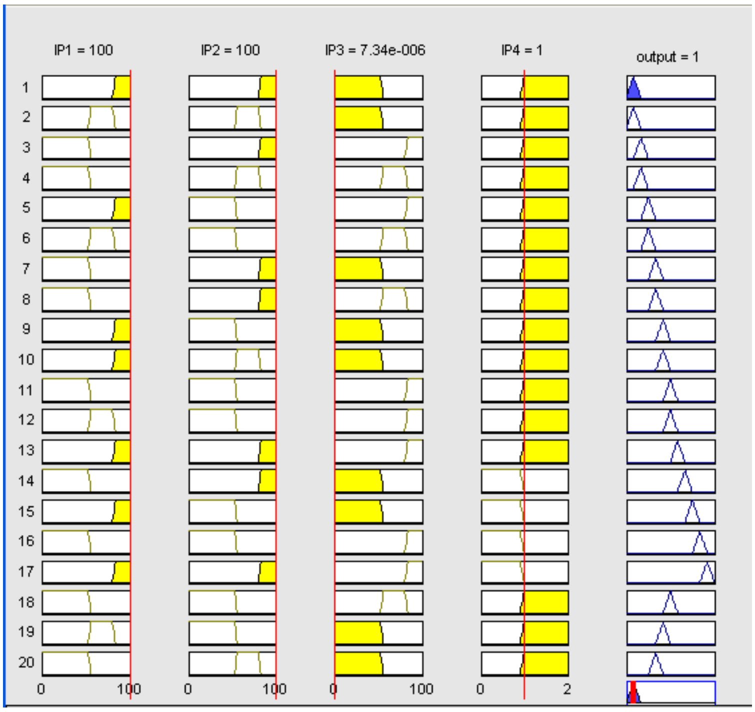
Membership functions for input variable are defined as low, medium, and high as shown in Table 1 and Figure 7. Results illustrated in Tables 2 to 3 are obtained from one case study of AG fault. From Table 3 and Figure 8, it is shown that the results obtained from the decision algorithm proposed in this paper, are obtained by applying the rules listed in Table 1. From Figure 8, it can be seen that the index value at output TTK is 1 and

TABLE 3. Result obtained from AG fault

Bus	$P1_{,\max(post)}$	$P2_{,\max(post)}$	$P3_{,\max(post)}$	$P4_{,\max(post)}$	Output
TTK	100	100	1.001E-12	1	1.00
NCO	100	100	7.336E-06	1	1.00

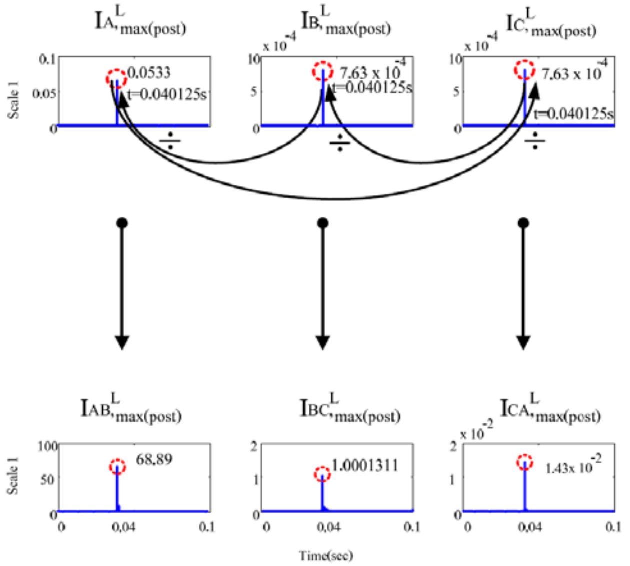


(a) TTK bus

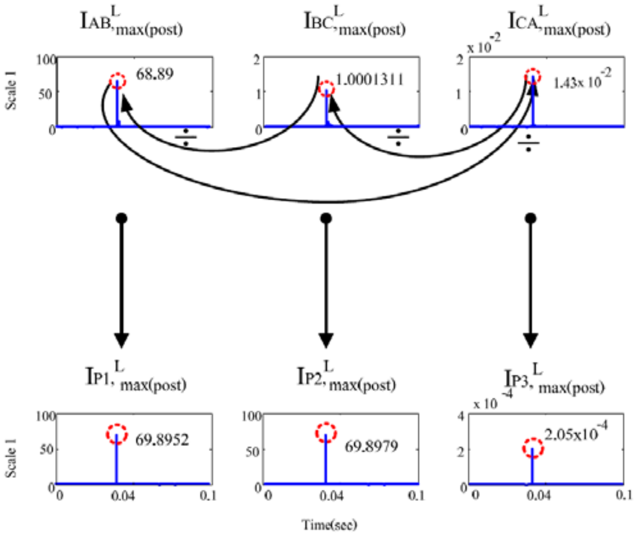


(b) NCO bus

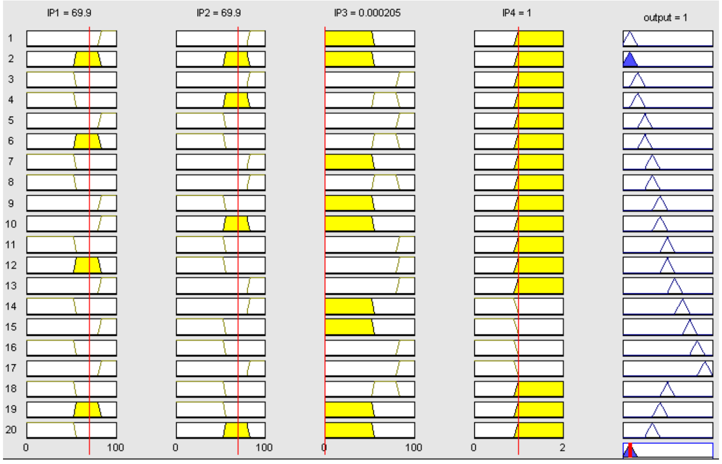
FIGURE 8. Mamdani's rule and defuzzification module with COG method for classifying the fault types



(a) Maximum value obtained from division algorithm



(b) Maximum ratio used as input variables



(c) Mamdani's rule and defuzzification module with COG method for classifying the fault

Figure 9. Example of fuzzy logic for AG fault

Table 4. Results of fault classification (case studies are 7722 cases)

Average accuracy	DWT and Fuzzy Logic		Comparison of the coefficients DWT [3]	
	System 1	System 2	System 1	System 2
Single phase to ground (SLG)	100%	10%	95.36%	10%
Double-line to ground (DLG)	100%	95.01%	100%	71.76%
Line to line (LL)	100%	98.77%	93.20%	98.77%
Three-phase (3 – P)	100%	99.07%	100%	99.07%
Average	100%	98.21%	97.14%	92.40%

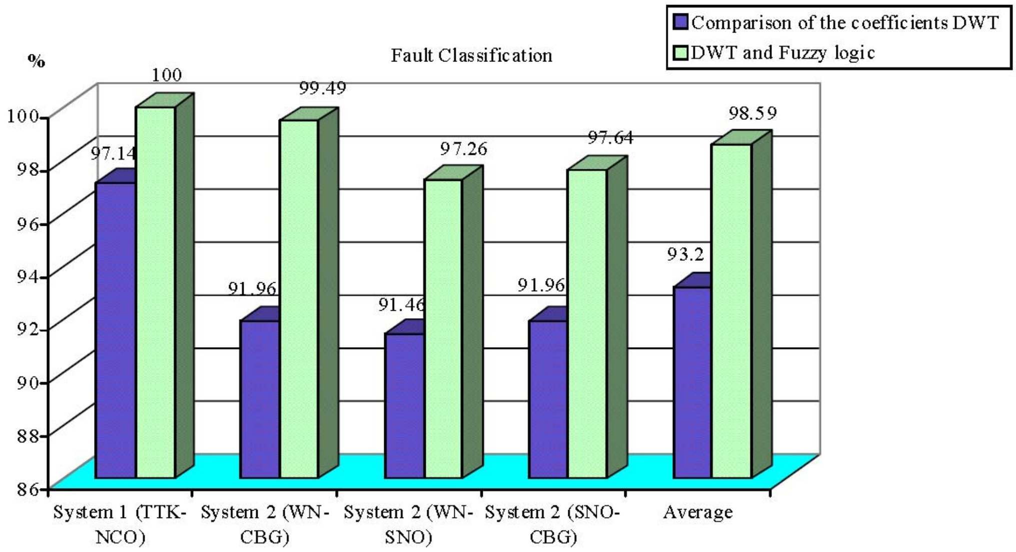


Figure 10. Results of fault classification

that at NCO is also 1. This means that the fault is classified as a phase A to ground fault, which occurs at the TTK and NCO bus. Moreover, the index value at output is 1 as illustrated in Figure 9. This means that there is a phase A to ground fault occurring at the WN bus, which is correlative to the fault signals in Figure 3.

Case studies are varied so that the decision algorithm capability can be verified. The considered system is illustrated in Figure 1 and Figure 2. Various case studies are performed with various types of faults at each location on the transmission line including the variation of fault inception angles and locations at each transmission line as shown in Table 4 and Figure 10. Moreover, the results from the proposed algorithm are compared with those from the fault diagnosis developed by Makming et al. [3] in order to show the advantage of the proposed technique. From Table 4, it is shown that the average accuracy of fault classification from the decision algorithm proposed in this paper is highly satisfactory.

4. **Conclusions.** This paper proposed a technique using combination of discrete wavelet transform and fuzzy logic in order to classify the fault on transmission system. The considered systems have the loop structure and double circuit structure; this allows to show the advantage of the proposed technique. Positive sequence current signal is used in fault detection. The maximum values from the first scale at 1/4 cycle of phase A, B, C and zero sequence of post-fault current signals obtained by the DWT have been used as an

input pattern of fuzzy logic in a decision algorithm. The results are clearly seen that the accuracy from the combination of discrete wavelet transform and fuzzy logic algorithm is highly accepted. The further work will be the improvement of the algorithm so that locations of fault along the transmission line can be identified.

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