FAST AND ACCURATE FAULT DETECTION/LOCATION ALGORITHMS FOR DOUBLE-CIRCUIT/THREE-TERMINAL LINES USING PHASOR MEASUREMENT UNITS

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ABSTRACT

This paper presents new PMU-based fault detection/location algorithms for double-circuit/three-terminal transmission lines. The development of the algorithms is based on distributed transmission line models and synchronized positive sequence voltage and current phasors. The proposed fault detector is very sensitive, such that it can quickly identify faults. In particular, high impedance faults can be easily detected. A fault direction discriminator is also developed to distinguish between internal and external faults with respect to the protected zone. When an internal fault occurs, the discriminator starts the process of fault locating. The methods do not require fault type identification and their computational costs are very low since they do not require iterative operations. Moreover, the algorithms provide excellent performance for transposed and untransposed lines. The EMTP/ATP simulator was used to verify the performance of the methods. The simulation studies show that the algorithms can detect faults quickly, discriminate fault direction correctly, and provide a high degree of accuracy in fault location. The algorithms are independent of various fault and system conditions such as fault types, fault positions, fault path resistance, pre-fault load flows, mutual coupling effect of lines, and line shunt capacitance.

Key Words: fault detection/location, global positioning system (GPS), phasor measurement units (PMUs), transmission lines.

I. INTRODUCTION

Transmission line faults have to be located quickly and accurately in order to repair the faulted section, restore power delivery, and reduce outage time as much as possible. Therefore, the development of a robust and accurate fault detection/location technique under various system and fault conditions is a highly important research area. Many digital algorithms (Aggarwal *et al.*, 1993; Eriksson *et al.*, 1985; Girgis *et al.*, 1992; Ibe and Cory, 1986; Jiang *et al.*, 2000; Kezunovic and Perunicic, 1994; Novosel *et al.*, 1995; Novosel *et al.*, 1996) have been presented to locate faults. A single-end, impedance-based fault location technique (Novosel *et al.*, 1995) is very

attractive because it is simple and does not require communications. The reactance method (Eriksson *et al.*, 1985) works well when the fault does not involve significant fault resistance and load current. The accuracy of single-ended fault locators is affected by various assumptions that are made about the fault resistance, the source impedance, the remote in-feed current, and the line model, etc (Novosel *et al.*, 1995).

In addition, the concept of traveling wave is also proposed for fault locating (Ibe and Cory, 1986). The technique requires good quality transducers and specialized equipment. The differential equation approach for calculating transmission line fault location is proposed by Kezunovic and Perunicic (1994). It requires a high sampling rate to approximate the differential operation and ensure the accuracy of the fault location.

Digital relays and communication systems provide the opportunity to perform fault locating using data from both ends in transmission lines. Therefore,

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the fault location can be estimated with minimal assumptions and sources of error. Since low-speed communication channels are often available, the fault data can be transmitted to a central site or communicated between digital relays or other devices for accurate fault location. Some algorithms (Aggarwal *et al.*, 1993; Girgis *et al.*, 1992; Jiang *et al.*, 2000; Kezunovic and Perunicic, 1994; Novosel *et al.*, 1996) based on two-terminal measurements have been proposed. When the data sampling at two ends is synchronized using GPS, the fault location estimation is very simple and accurate. If the sampling is not synchronized, then nonlinear equations have to be solved and increased computational burden is introduced (Girgis *et al.*, 1992; Novosel *et al.*, 1996).

Real-time wide area measurements from PMUs allow for innovative solutions to traditional utility problems. Positive sequence phasors from all substations equipped with PMUs are then collected at a central location. By collecting these precise synchronized measurements, techniques for monitoring, protection, and control of the power system can be developed and implemented (Hart *et al.*, 2001). For example, ABB is presently developing PMU-based products and advanced solutions. PMU functions are also being integrated into ABB protective relays, providing a hardened platform for substation applications (Hart *et al.*, 2001).

The authors have proposed a PMU-based approach for fault locating in a single-circuit two-terminal transmission line (Jiang *et al.*, 2000). We have also developed a protection scheme for parallel transmission lines using synchronized phasor measurements and the scheme focuses on line relaying design (Chen *et al.*, 2002). The scheme must use three voltages and six currents of the two protected circuits at each line terminal so it only can work when both circuits are in operation. In addition, it needs faulted-circuit identification logic to choose the correct faulted circuit. Since new rights of way for transmission lines are difficult to obtain in Taiwan, many double-circuit and three-terminal transmission lines exist in the Taiwan power system. The Taiwan Power Company has installed many PMUs on its EHV line system. Now, the synchronized measured data has been successfully transmitted to the control center for system monitoring and data recording. Therefore, based on our previous research, new and practical PMU-based fault detection/location algorithms for double-circuit and three-terminal lines are developed. The new approach is very simple since only the positive sequence line parameters and phasors at the ends of transmission lines need to be known for algorithm implementation. The proposed methods are very robust and not affected significantly by various system and fault conditions.

Fig. 1 One-line diagram of a single-circuit transmission line

II. THE PROPOSED FAULT DETECTION/ LOCATION ALGORITHMS AND SYSTEM CONFIGURATION

The principles of the new PMU-based fault detection/location algorithms for transmission lines are described in this section. The paper starts with a single-circuit transmission line to explain the basic principles and then extends the techniques to double-circuit and three-terminal lines.

1. The Fault Detection/location Algorithm for a Single-circuit Transmission Line

Figure 1 shows a single-circuit transposed transmission line. The authors utilize Clarke transformations to decouple the inter-phase quantities and then a fault detection/location technique is developed using two-terminal synchronized phasors and a distributed line model (Jiang *et al.*, 2000). In this paper, we adopt the symmetrical components transformation to resolve the coupling effect among the inter-phases. Since the positive sequence quantity appears in all fault types, this quantity is used in the fault detection/location algorithm. Therefore, the developed algorithm does not require fault type identification, which avoids possible problems due to incorrect fault type discrimination.

As shown in Fig. 1, the fault point voltage V_F is related to the two-terminal synchronized voltage and current phasors. The relationships are shown as (Jiang *et al.*, 2000):

$$V_F = \frac{1}{2}(V_R + Z_C I_R)e^{\Gamma DL} + \frac{1}{2}(V_R - Z_C I_R)e^{-\Gamma DL} \quad (1)$$

$$V_F = \frac{1}{2}e^{-\Gamma L}(V_S + Z_C I_S)e^{\Gamma DL} + \frac{1}{2}e^{\Gamma L}(V_S - Z_C I_S)e^{-\Gamma DL} \quad (2)$$

where L is the total length of the transmission line, Γ and Z_C are the positive sequence propagation constant and surge impedance respectively, and V_R , V_S , I_R , I_S are the synchronized positive sequence phasors of the receiving end/sending end voltages and currents, respectively.

By equating the voltage at the fault point from

(1) and (2), the per-unit fault location D can be solved by the following equation (Jiang *et al.*, 2000):

$$D = \frac{\ln[(A - C)/(E - B)]}{2\Gamma L} \quad (3)$$

where those quantities A , B , C , and E are expressed as

$$A = \frac{1}{\gamma}[V_R - Z_C I_R] \quad (4a)$$

$$B = \frac{1}{2}[V_R + Z_C I_R] \quad (4b)$$

$$C = \frac{1}{2} e^{\Gamma L} [V_s - Z_C I_s] \quad (4c)$$

$$E = \frac{1}{\gamma} e^{-\Gamma L} [V_S + Z_C I_S] \quad (4d)$$

and

$$M=E-B \quad (5a)$$

$$N=A-C \quad (5b)$$

Since the line shunt capacitance is considered in the line model, the fault location algorithm is very suitable for long distance transmission lines. Moreover, the effect of fault path resistance is completely eliminated using the two-terminal measurements. The two indices M and N can serve as fault detectors (Jiang *et al.*, 2000). The index $|M|$ (the absolute value of index M) will be held at zero under healthy conditions. Once the post-fault data are included in the moving data window, the detection index $|M|$ will rise with a very large slope whether internal or external faults occur. The index is very sensitive to faults even when high resistance faults occur. Considering physical measurement inaccuracies and calculation errors, $|M|$ may not equal zero. Therefore, a pre-defined threshold is needed to avoid an error action. The index N has the same behavior as the index M . Extensive simulation studies show the performance of the fault detection/location algorithm for a single-circuit transmission line is excellent under various power system and fault conditions (Jiang *et al.*, 2000). In this paper, only the index M is adopted to detect faults.

From (5), we know that the fault detection index is composed of two complex phasors, i.e. $M=E-B=|E|\angle\theta_E-|B|\angle\theta_B$. For no fault cases, we know that $|E|=|B|$ and $\angle\theta_E=\angle\theta_B$, so that $|M|=0$. Moreover, by the angle difference between the two complex phasors, we can attain faulted-zone discrimination when faults occur. From the $\arg(E/B)=\arg(|E|\angle\theta_E/|B|\angle\theta_B)=\angle\theta_E-\angle\theta_B$, the internal and external faults can be discriminated by the following criteria (Jiang *et al.*, 2002):

Fig. 2 One-line diagram of a double-circuit transmission line

Internal faults: $abs[arg(E/B)] \neq 0$ (6a)

$$\textbf{External faults: } abs[arg(E/B)] = 0 \quad (6b)$$

where $abs(\bullet)$ denotes absolute value and $arg(\bullet)$ denotes phase angle.

The response of the discrimination criteria is fast and sensitive when a fault happens. For internal fault cases, the absolute value of the $arg(E/B)$ rises to a certain value. For external fault cases, the absolute value of the $arg(E/B)$ will fast decay to zero. Hence, internal faults can be asserted when the value of $abs[arg(E/B)]$ is over the pre-determined threshold.

In summary, the proposed fault location system uses the index $|M|$ to detect faults and then (6) is utilized to distinguish between internal and external faults. When an internal fault is confirmed, we use the index D in (3) to accurately locate the fault.

2. The Fault Detection/location Algorithm for Double-circuit Lines

The single-circuit fault detection/location technique mentioned above can be easily applied to double-circuit lines with zero sequence mutual coupling as shown in Fig. 2. Since only the positive sequence quantity is used in the proposed algorithm, the method will be independent of the coupling effect between both circuits, which is only presented in the zero-sequence network. Therefore, we can adopt the single-circuit algorithm to locate faults for each line of the double-circuit lines, respectively.

The advantage of the proposed method is that the algorithm is capable of locating faults when both lines are in operation or only one is in service. It is obvious that the new algorithm is superior to our previous method (Chen *et al.*, 2002).

3. The Fault Detection/location Algorithm for Single-circuit Three-terminal Lines

Consider a three-terminal line as depicted in Fig. 3. The PMUs are installed at buses S , R , and T . Therefore, we can obtain three-terminal synchronized voltage and current phasors. There are three possible faulted line sections, which are L_R , L_S , and L_T as

a fault indeed occurs in L_R , the fault location index D_1 converges to the interval of $[0,1]$.

(b) Subroutine2: V_P is estimated using the data at bus T .

Similarly, combining (7)-(9) and (11), we can derive another fault location index D_2 that is given by

$$D_2 = \frac{\ln[(A_2 - C_2)/(E_2 - B_2)]}{2\Gamma L_R} \quad (15)$$

where those quantities A_2 , B_2 , C_2 , and E_2 are expressed as

$$A_2 = \frac{1}{2}(V_R - Z_C I_R) \quad (16a)$$

$$B_2 = \frac{1}{2}(V_R + Z_C I_R) \quad (16b)$$

$$C_2 = \frac{1}{2}e^{\Gamma(L_T + L_R)}(V_T - Z_C I_T) - \frac{1}{4}e^{-\Gamma(L_S - L_R)}(V_S + Z_C I_S) + \frac{1}{4}e^{\Gamma(L_S + L_R)}(V_S - Z_C I_S) \quad (16c)$$

$$E_2 = \frac{1}{2}e^{-\Gamma(L_T + L_R)}(V_T + Z_C I_T) + \frac{1}{4}e^{-\Gamma(L_S + L_R)}(V_S + Z_C I_S) - \frac{1}{4}e^{\Gamma(L_S - L_R)}(V_S - Z_C I_S) \quad (16d)$$

and

$$M_2 = E_2 - B_2 \quad (17a)$$

$$N_2 = A_2 - C_2 \quad (17b)$$

Similarly, the quantities M_2 , E_2 , and B_2 can be used to detect faults and identify the faulted zone. Moreover, if the fault indeed occurs in L_R , then the two fault location indices D_1 and D_2 will be equal and both will converge to the interval of $[0,1]$.

(ii) A Fault Occurs in L_S

Assume a fault occurs in L_S as shown in Fig. 5. The fault point voltage V_F can be estimated using the measured phasors at bus S and the estimated equation is:

$$\begin{aligned} V_F &= \frac{1}{2}e^{-\Gamma L_S}(V_S + Z_C I_S)e^{\Gamma(D_1 - 1)L_R} \\ &\quad + \frac{1}{2}e^{\Gamma L_S}(V_S - Z_C I_S)e^{-\Gamma(D_1 - 1)L_R} \\ &= \frac{1}{2}e^{-\Gamma(L_S + L_R)}(V_S + Z_C I_S)e^{\Gamma D_1 L_R} \\ &\quad + \frac{1}{2}e^{\Gamma(L_S + L_R)}(V_S - Z_C I_S)e^{-\Gamma D_1 L_R} \end{aligned} \quad (18)$$

Fig. 5 One-line diagram of a three-terminal transmission line when a fault occurs in L_S

The V_F also can be obtained using the estimated phasors at point P . Thus,

$$\begin{aligned} V_F &= \frac{1}{2}(V_P + Z_C I_P)e^{\Gamma(D_1 - 1)L_R} \\ &\quad + \frac{1}{2}(V_P - Z_C I_P)e^{-\Gamma(D_1 - 1)L_R} \end{aligned} \quad (19)$$

where the voltage V_P and current I_P can be expressed as

$$V_P = \frac{1}{2}e^{\Gamma L_R}(V_R + Z_C I_R) + \frac{1}{2}e^{-\Gamma L_R}(V_R - Z_C I_R) \quad (20)$$

$$\begin{aligned} I_P &= I_R'' - I_T'' \\ &= \left[\frac{1}{2Z_C}e^{\Gamma L_R}(V_R + Z_C I_R) - \frac{1}{2Z_C}e^{-\Gamma L_R}(V_R - Z_C I_R) \right] \\ &\quad - \left[\frac{1}{2Z_C}e^{\Gamma L_T}(V_T + Z_C I_T) - \frac{1}{2Z_C}e^{-\Gamma L_T}(V_T - Z_C I_T) \right] \end{aligned} \quad (21)$$

Similarly, combining (18)-(21), we can derive the fault detection and location indices. Moreover, we can easily prove that the fault detection and location equations in this case are the same as (12)-(14). Therefore, the indices M_1 and D_1 still can be applied to detect and locate faults in L_S . However, the index D_1 will be greater than 1.

As shown in Fig. 5, the V_P can be estimated using the data from buses R and T , respectively. Thus,

$$V_P = \frac{1}{2}(V_R + Z_C I_R)e^{\Gamma L_R} + \frac{1}{2}(V_R - Z_C I_R)e^{-\Gamma L_R} \quad (22)$$

and

$$V_P = \frac{1}{2}e^{-\Gamma L_T}(V_T + Z_C I_T) + \frac{1}{2}e^{\Gamma L_T}(V_T - Z_C I_T) \quad (23)$$

From (22) and (23), we obtain

$$\begin{aligned}
& \frac{1}{2}(V_R - Z_C I_R) \\
&= \frac{1}{2}e^{\Gamma(L_T + L_R)}(V_T - Z_C I_T) + \frac{1}{2}e^{-\Gamma L_T}(V_T + Z_C I_T)e^{\Gamma L_R} \\
&\quad - \frac{1}{2}(V_R + Z_C I_R)e^{2\Gamma L_R} \quad (24)
\end{aligned}$$

Substituting (24) into (16a) and then combining (16) and (17), we can obtain

$$\frac{N_2}{M_2} = e^{2\Gamma L_R} \quad (25)$$

From (15) and (25), the fault location index D_2 is

$$D_2 = \frac{\ln(e^{2\Gamma L_R})}{2\Gamma L_R} = 1 \quad (26)$$

Therefore, if the index D_2 is applied to locate faults occurring in L_S , it will converge to 1.

(iii) A Fault Occurs in L_T

When a fault occurs in L_T as shown in Fig. 6, the V_P can be estimated using the data at buses R and S , respectively. At this time, we can obtain the equations, which are similar to (22)-(24), and the following relationship can be derived.

$$\frac{N_1}{M_1} = e^{2\Gamma L_R} \quad (27)$$

From (12) and (27), the location index D_1 is equal to 1.

We also can use the data at buses R and T to derive the fault location. Adopting the technique in (18)-(21), we can prove that the fault location equations in this case are the same as (15)-(17). However, the index D_2 will be greater than 1. Therefore, both of the two fault location indices D_1 and D_2 can be applied to locate faults occurring in L_T .

Therefore, the indices M_1 , D_1 , and D_2 can be applied to detect and locate faults occurring in L_R , L_S , and L_T . Moreover, there are special relationships between the two indices D_1 and D_2 . They can be used to identify the faulted line branch and locate faults. The relationships are as follows:

- (1) $0 < D_1 < 1$ and $0 < D_2 < 1$: the fault occurs in L_R . Then, $D_1 = D_2$, and both of them are accurate fault locations.
- (2) $D_1 > 1$ and $D_2 = 1$: the fault occurs in L_S and D_1 is the actual fault location away from bus R .
- (3) $D_1 = 1$ and $D_2 > 1$: the fault occurs in L_T and D_2 is the actual fault location away from bus R .
- (4) $D_1 = 1$ and $D_2 = 1$: the fault occurs at point P .

Fig. 6 One-line diagram of a three-terminal transmission line when a fault occurs in L_T

In summary, the proposed algorithm first assumes that a fault occurs in line L_R and then the fault detection and location indices, M_1 , D_1 , and D_2 , are obtained. Using the index $|M_1|$, the faults in the three-terminal line system can be completely detected. The quantity $\text{abs}[\arg(E_1/B_1)]$ can identify whether faults occur in the protected zone or not. When the fault occurs in L_R , the values of D_1 and D_2 are the exact fault location. If the fault does not occur in L_R , then we can discriminate the faulted line branch through the logic mentioned above and accurately locate the fault using D_1 and D_2 . Through use of the proposed method, the faulted line branch is correctly determined and the fault point is accurately located in a reliable and simple manner.

4. The Fault Detection/location Algorithm for Double-circuit Three-terminal Transmission Lines

Since only positive sequence data is used in the algorithm, we can regard Fig. 7(a) as one single-circuit line combined with one three-terminal line. Similarly, the transmission line system in Fig. 7(b) is equivalent to two individual three-terminal lines. Therefore, the developed fault detection/location algorithm previously also can be directly applied to transmission line systems as shown in Fig. 7.

5. The Fault Detection/location Algorithm for Untransposed Lines

The algorithms previously developed assume that the transmission line is transposed and use positive sequence parameters to calculate the fault location. If the line is untransposed, the diagonal quantities of the phase impedance and admittance matrices can be averaged to obtain self-impedance and self-admittance. Similarly, the off-diagonal quantities can be averaged to obtain the mutual impedance and admittance. Then, using symmetrical components transformation, we can obtain the approximate positive

Fig. 7 One-line diagrams of double-circuit three-terminal transmission lines

sequence parameters. When the approximate components are applied to calculate the fault location, the simulation results indicate that only slight error is introduced.

For untransposed lines, the approximate line parameters introduce a basis value in the fault detection index under healthy conditions. To remove the basis value, the fault detection index in (5a) is modified as

$$|\overline{M}| = \text{abs}(|M| - |M|_{pre}) \quad (28)$$

where $\text{abs}(\bullet)$ denote the absolute value and $|M|_{pre}$ is the one-cycle ago data with respect to $|M|$.

Therefore, the value of the modified index $|\overline{M}|$ will equal zero for every moving data window under non-fault conditions. The quantity $\text{abs}[\arg(E/B)]$, represented by symbol 'Z' here, also introduces a basis value under no fault conditions. Similarly, it can be modified as (29) to remove the basis value.

$$|\overline{Z}| = \text{abs}(|Z| - |Z|_{pre}) \quad (29)$$

These also can be applied to the fault detection index M_1 for three-terminal lines.

6. The Overall Configuration of the Proposed PMU-based Fault Detection/location System

Figure 8 depicts the overall configuration of the new PMU-based fault location system for three-terminal lines. Three PMUs are installed at buses S, R,

Fig. 8 The overall configuration of the proposed PMU-based fault location system for three-terminal lines

and T. The synchronized positive voltage and current phasors are transmitted to a central location and then we calculate the fault detection and location indices, M_1 , D_1 , and D_2 . When the index $|M_1|$ detects a fault, then the quantity $\text{abs}[\arg(E_1/B_1)]$ is used to identify whether the fault is an internal fault, occurring in L_R , L_S , or L_T , or not. If the fault occurs in the protected zone, through the faulted line branch identification logic, by using the indices D_1 and D_2 , the faulted section and fault location are obtained. For two-terminal double-circuit lines, system configurations of fault location systems are similar to those of three-terminal lines and only the indices M and D are applied to detect and locate faults.

III. PERFORMANCE EVALUATION

To verify the performance of the proposed fault detection/location algorithms, the EMTP/ATP simulator was used to generate fault data (European EMTP

Table 1 The parameters of the simulated system

Equivalent source voltage:
$E_S=1\angle 20^\circ$ (p.u.), $E_R=1\angle 0^\circ$ (p.u.),
$E_T=1\angle 10^\circ$ (p.u.)
Equivalent system impedance:
$Z_{S1}=0.238+5.72j(\Omega)$, $Z_{R1}=0.238+6.19j(\Omega)$,
$Z_{T1}=0.155+5.95j(\Omega)$
$Z_{S0}=2.738+10j(\Omega)$, $Z_{R0}=0.833+5.12j(\Omega)$,
$Z_{T0}=1.786+7.58j(\Omega)$
Transmission line parameters:
$L_S=150$ km, $L_R=100$ km, $L_T=80$ km
$R_1=0.0058(\Omega/\text{km})$, $L_1=0.6341(\text{mH}/\text{km})$,
$C_1=18.4(\text{nF}/\text{km})$
$R_0=0.1067(\Omega/\text{km})$, $L_0=2.2343(\text{mH}/\text{km})$,
$C_0=8.7(\text{nF}/\text{km})$
$R_{0m}=0.10035(\Omega/\text{km})$, $L_{0m}=1.2907(\text{mH}/\text{km})$,
$C_{0m}=-3.4(\text{nF}/\text{km})$

Center, 1987).

1. System Modeling

A 345 kV, 60 Hz transposed double-circuit three-terminal transmission line with zero sequence mutual coupling was modeled as shown in Fig. 7(b). The simulated system can be used to demonstrate the correctness of all the mentioned fault detection/location algorithms for transmission lines including double-circuit lines, three-terminal lines, and lines combining the above two types of lines. The related parameters of the simulated system are shown in Table 1. The transmission line parameters are obtained using the EMTP LINE CONSTANTS program (European EMTP Center, 1987). The sampling frequency is 1920 Hz (32 sampling points per cycle). Full-cycle Discrete Fourier Transform (DFT) is applied to estimate the fundamental phasors. The threshold settings **Th1** and **Th2** for fault detection and faulted zone discrimination are 1000 and 0.2 (rad), respectively.

2. Simulation Results

The simulation studies have been conducted with respect to various system and fault conditions. The error of the fault location algorithm is evaluated as

$$\text{Error}(\%) = \frac{\left| \text{estimated location} - \text{actual location} \right|}{\text{actual location}} \times 100(\%)$$

(30)

Fig. 9 The post-fault response curves of the proposed indices for a phase-'a' to ground fault in L_R

Some selected typical results are presented and discussed below. All of the faults are assumed to occur in circuit 2 in Fig. 7(b).

(i) Cases Studies

Figure 9 shows the post-fault response curves of the proposed indices for a phase-'a' to ground fault (a-g fault) in L_R . The fault position is set at 0.5 (p.u.) away from bus R, the fault resistance is 1 ohm, and fault inception angle is zero degree with respect to phase-'a' voltage waveform at bus S. As shown in Figs. 9(a) and (b), it is seen that the fault is detected quickly and discriminated correctly as an internal fault. From Fig. 9(c), we observe that both of the two indices D_1 and D_2 converge to the interval of [0,1]. Therefore, the fault is located in L_R . The fault location errors of D_1 and D_2 are 0.034% and 0.007%, respectively.

To demonstrate the correctness of the developed faulted line branch identification logic, a phase-'b' to ground fault (b-g fault) in L_S is simulated. The fault is located at 60 km away from point P, i.e. 1.6 (p.u.) away from bus R. The other fault conditions are the same as the above case. From Figs. 10(a) and (b), it is shown that the index M_1 and the quantities E_1 and B_1 indeed give the correct responses when a fault occurs in L_S . Fig. 10(c) depicts the responses of the indices D_1 and D_2 . As shown in the figure, D_1 and D_2 converge to 1.5997 (p.u.) and 1.0 (p.u.), respectively. Therefore, the algorithm correctly identifies the fault in L_S and accurately locates the fault. The fault location error is 0.019% in this case. Fig. 11 shows the responses of the proposed indices for a phase-'a' to ground fault in L_R . The fault position is set at 0.9

Fig. 10 The post-fault response curves of the proposed indices for a phase-'b' to ground fault in L_S

Fig. 11 The post-fault response curves of the proposed indices for a high impedance fault in L_R

(p.u.) and the fault resistance is 300 ohm. From this figure, we observe that the indices still work very well even when a high impedance fault occurs. The fault location errors of D_1 and D_2 are 0.087% and 0.018%, respectively. Therefore, the algorithm is virtually unaffected by the fault path resistance.

To verify the correctness of the proposed faulted zone discriminator under external faults, we add a single-circuit line, whose line length is 50 km, at buses S and R , respectively. Figs. 12(a) and (b) show the response curves of the proposed indices for a phase 'a'-'b' to ground fault (a-b-g fault) occurring 20 km away from the left-hand side of bus S . Figs. 12(c) and (d) show the results for a phase-'c' to ground fault occurring 20 km away from the

Table 2 The performance of the algorithm for untransposed lines

Actual fault location	Estimated fault location error (%)			
	a-g	a-b-g	a-b-s	a-b-c-g
0.1 (p.u.)	0.066	0.671	1.092	0.041
0.3 (p.u.)	0.103	0.457	0.819	0.093
0.5 (p.u.)	0.159	0.793	0.555	0.417
0.7 (p.u.)	0.312	0.370	0.343	0.060
0.9 (p.u.)	0.536	0.246	0.191	1.170

Fig. 12 The post-fault response curves of the proposed indices for external faults

right-hand side of bus R . It is shown that the index $|M_1|$ still can detect an external fault and the proposed fault direction discriminator indeed gives the correct response.

(ii) Testing of the Algorithm for Untransposed Lines

The line parameters for untransposed lines are also obtained using the EMTP LINE CONSTANTS program and the related data is the same as for transposed lines previously considered. A phase 'a'-'b' to ground fault is simulated and the fault position is set at 0.3 (p.u.) in L_R . Fig. 13 shows the performance of the algorithm for untransposed lines. As shown in Figs. 13(a) and (b), it is seen that the modified fault detector $|M_1|$ and fault direction discriminator $|Z_1|$ give the correct responses. In this case, the estimated fault location errors of D_1 and D_2 are 0.457% and 0.011%, respectively. Extensive simulation studies have been performed and the selected location results using the index D_1 are shown in Table 2. The results indicate that the algorithm works well for untransposed lines.

Table 3 The statistical results of the algorithm for transposed lines

Actual fault location	Fault inception angle	Fault resistance	Estimated fault location error (%)			
			a-g	a-b-g	a-b-s	a-b-c-g
0.1 (p.u.)	0°	1	0.040	0.185	0.095	0.081
		100	0.040	0.185	0.095	0.081
		300	0.024	0.171	0.095	0.081
	90°	1	0.073	0.082	0.083	0.069
		100	0.073	0.082	0.083	0.069
		300	0.238	0.076	0.083	0.069
0.5 (p.u.)	0°	1	0.034	0.154	0.123	0.263
		100	0.034	0.154	0.123	0.263
		300	0.031	0.161	0.123	0.263
	90°	1	0.221	0.302	0.343	0.263
		100	0.221	0.302	0.343	0.263
		300	0.277	0.300	0.343	0.263
0.9 (p.u.)	0°	1	0.131	0.440	0.364	0.185
		100	0.131	0.440	0.364	0.185
		300	0.087	0.436	0.364	0.185
	90°	1	0.786	0.010	0.017	0.176
		100	0.786	0.010	0.017	0.176
		300	0.736	0.003	0.017	0.176

Fig. 13 The post-fault response curves of the proposed indices for untransposed lines

(iii) Statistical Results

The performance of the proposed algorithm under various fault conditions for transposed lines is presented in this subsection. Table 3 shows the statistical results of fault location using the index D_1 . From the table, it is obvious that the proposed fault algorithm provides excellent performance under different fault conditions such as different fault types, fault positions, fault resistances, and fault inception angles. The average fault location error under various fault conditions is well below 1%.

IV. CONCLUSIONS

New PMU-based fault detection/location algorithms for double-circuit/three-terminal lines are presented in this paper. Basic principles, detail formulation, and overall system configuration are also given. The proposed algorithms are very simple, robust, and accurate for fault detection/location. By only using the indices M_1 , D_1 and D_2 , the fault can be detected and located correctly. Special faulted line branch identification logic is also developed and proved for three-terminal lines. Extensive simulation studies for transposed and untransposed lines verify that the performance of the methods is excellent and the average error of fault location is well less than 1% under various system and fault conditions.

The results demonstrate the feasibility and effectiveness of the proposed fault detection/location algorithms for double-circuit/three-terminal lines. These techniques can be easily implemented as a PMU-based approach or embedded in digital relays using GPS for data synchronization. The practical synchronized data measured by PMUs in the Taiwan power system is being collected and recorded; we hope to obtain the measured data and report field test results in the near future.

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NOMENCLATURE

<i>ABB</i>	Asea Brown Boveri
<i>ATP</i>	Alternative Transients Program
<i>DFT</i>	Discrete Fourier Transform
<i>EHV</i>	Extra High Voltage
<i>EMTP</i>	ElectroMagnetic Transient Program
<i>GPS</i>	Global Positioning System
<i>PMU</i>	Phasor Measurement Unit

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