Three-Terminal Transmission Line Protection Using Synchronized Voltage and Current Phasor Measurements

Ching-Shan Chen, *Student Member, IEEE,* Chih-Wen Liu, *Member, IEEE,* and Joe-Air Jiang, *Member, IEEE*

***Abstract*-- This paper presents a new relaying algorithm for EHV three-terminal transmission line protection using synchronized voltage and current phasors. The development of the scheme is based on distributed transmission line model and the mutual coupling effect of lines is decoupled using Clarke transformation. Then, a robust fault detection index composed of voltages, currents, and modal line parameters is derived. The proposed detection index can quickly identify faults and correctly distinguish between internal faults and external faults with respect to the protected-zone. In particular, the index can easily detect a high impedance fault. A faulted-phase selector is also designed to provide single-pole tripping for single-phase to ground fault and to issue three-phase tripping for other fault types. The relaying algorithm offers complete protection function including fault detection, faulted-zone discrimination, and fault type classification for three-terminal lines. The simulation studies verify that the scheme provides excellent performance.**

***Index Terms*-- Computer relaying, digital protection, Global Positioning System (GPS), Phasor Measurement Unit (PMU), three-terminal transmission lines.**

I. INTRODUCTION

Three-terminal transmission lines often offer considerable economic, technical, and environmental advantages over two-terminal lines for EHV power transmission purposes. Such transmission lines are difficult to protect using conventional unit or non-unit protection techniques [1]. Therefore, the protection of three-terminal transmission lines is a very challenging problem.

The non-unit distance protection scheme is very common for three-terminal line protection, but the problems of underreach and overreach arise due to fault location, high impedance fault, source impedance variation, remote in-feed/out-feed currents, etc. Therefore, Y. Q. Xia et al. [2] proposed an adaptive distance protection scheme to improve its performance.

Although current differential schemes (unit protection schemes) are relatively fast in terms of fault clearance times, they become insensitive to low levels of fault current when high impedance faults occur. For the sake of high reliability, a differential relaying scheme for Teed circuits based on voltage and current signal comparison is proposed [3].

Other schemes use fault transient signals to develop new protection schemes for Teed feeder transmission system. The methods can be designed as non-unit [4] or unit [5] protection scheme and can achieve high-speed response of protective relaying.

The synchronized sampling and phasor measurements for relaying and control are described in [6]. Better relaying and fault location performance can be achieved using multi-terminal synchronized measurements. The authors have developed some schemes for two-terminal transmission line protection [7]-[9]. Since the new rights of way for transmission lines are difficult to obtain in Taiwan, a lot of three-terminal transmission lines have existed at Taipower system in recent years. Therefore, based on our previous researches, we develop a new high-speed protective relaying scheme for three-terminal lines using synchronized voltage and current phasors. The function of the complete protection scheme includes fault detection, fault direction discrimination, and fault classification. The proposed scheme is not affect significantly by various system and fault conditions.

A new application of PMUs for three-terminal transmission line protection is presented in this paper. The basic operating principles and overall configuration of the protection scheme are described in section II. Simulation studies used to demonstrate the performance of the scheme are presented in section III. Finally, conclusions are given.

II. THE BASIC OPERATING PRINCIPLES AND OVERALL CONFIGURATION

The operating principles of the advanced protection scheme using GPS for data synchronization are described below. The paper starts with a two-terminal line to explain the basic principles and then presents the techniques for a three-terminal transmission line.

A. Review of protection schemes for two-terminal lines

A single-circuit transposed transmission system is shown in Fig. 1. The authors utilize Clarke transformation to decouple the inter-phase quantities. A PMU-based fault protection scheme is developed using two-terminal synchronized phasors and distributed line model [7]-[9]. In

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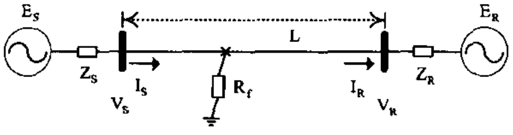

Fig. 1. One-line diagram of a signal-circuit transmission system.

particular, only one composite index can achieve the relaying tasks such as fault detection, fault direction discrimination, and fault classification [9]. The fault detection index can be expressed as

$$\begin{aligned} M_m &= \frac{1}{2}\exp[-\Gamma_m L][V_{Sm} + Z_{Cm} I_{Sm}] \\ &\quad -\frac{1}{2}[V_{Rm} + Z_{Cm} I_{Rm}] \\ &= E_m - B_m \qquad m = 0, \alpha, \beta \end{aligned} \tag{1}$$

where

L: Total length of the protected line.

Γ_m: Modal propagation constant.

Z_{Cm}: Modal surge impedance

V_{Rm}, V_{Sm}, I_{Rm}, I_{Sm}: The synchronized m-mode phasors of receiving end/sending end voltages and currents, respectively.

The effect of fault path resistance is eliminated entirely using two-terminal measurements. The proposed method takes into account shunt capacitance charging current compensation automatically compared to conventional current differential protection scheme for long distance transmission lines.

The relaying function is discussed below.

1) Fault Detection

The fault detection index $|M_m|$ (the absolute value of index M_m) will be held at zero under healthy conditions [7], [9]. However, the detection index will rise with a very large slope whether internal or external faults. For an internal fault, the index will quickly rise to a steady value. In external fault cases, the index $|M_m|$ will decay with time. Consider the physical measurements inaccuracies and calculation errors, $|M_m|$ may not equal to zero. Therefore, a predefined threshold is needed to avoid an error action.

2) Fault Direction Discrimination

The fault detection index is composed of two complex phasors, i.e. $M_m = E_m - B_m = |E_m|\angle\theta_{Em} - |B_m|\angle\theta_{Bm}$. By the angle difference between the two phasors, we can attain fault direction discrimination [9]. From the $\arg(E_m/B_m) = \arg(|E_m|\angle\theta_{Em} / |B_m|\angle\theta_{Bm}) = \angle\theta_{Em} - \angle\theta_{Bm}$, the internal and external faults can be discriminated by the following criteria:

***Internal fault*:** $\mathbf{abs[arg(E_m/B_m)] \neq 0}$ (2-1)

***External fault*:** $\mathbf{abs[arg(E_m/B_m)] = 0}$ (2-2)

where abs(•) denotes absolute value and arg(•) denotes the phase angle.

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if $|M_0^a|$, $|M_0^b|$ and $|M_0^c|$ > Threshold
   if $|M_\beta^a|$ < Threshold then a-phase to ground fault;
   else if $|M_\beta^b|$ < Threshold then b-phase to ground fault ;
   else if $|M_\beta^c|$ < Threshold then c-phase to ground fault ;
   else double phase to ground fault;
   end
else if $|M_\alpha^a|$ < Threshold then b-c phase short fault;
else if $|M_\alpha^b|$ < Threshold then c-a phase short fault;
else if $|M_\alpha^c|$ < Threshold then a-b phase short fault;
else
  three-phase ground or short fault;
end
```

Fig. 2. The algorithm of fault classification and phase selection.

For an internal fault case, the absolute value of the $\arg(E_m/B_m)$ quickly rises to a certain value. For an external fault case, the abs[arg(E_m/B_m)] will fast decay to zero. For the sake of high reliability, we set a threshold incorporated with a counter limit to discriminate the faulted zone.

3) Fault Classification and Phase Selection

Stability studies show that there are improvements in system stability and power transfer capability when single-phase tripping is applied. The proposed scheme uses Clarke transformation to decouple mutual coupling effect of lines. With respect to different fault types, some modal components in (1) will disappear and cannot be used. In [9], the authors assume that the basis of the transformation is phase-'a', 'b', and 'c' respectively and collocates with the proposed fault detection index to obtain fault classification and phase selection algorithm shown in Fig. 2. The algorithm can be used to quickly classify the fault types and to perform faulted phase selection. Thus, the scheme can achieve single-pole tripping for single-phase to ground faults.

B. Algorithms of protection schemes for three-terminal lines

This section describes the operating principles of the proposed protection scheme for three-terminal lines. The basic principles are extended from two-terminal protection scheme discussed above. Now, consider a three-terminal line as shown in Fig. 3. The PMUs are installed in bus S, R, and T. Therefore, we can obtain three-terminal synchronized voltage and current phasors.

Assume that an internal fault occurred in L_R as shown in Fig. 3. The voltage V_P at point P and the current I_2 can be calculated from the measured voltage and current phasors at buses S and T. For simplification, we assume that the line parameters of transmission lines are equal. The formulas are expressed as follows

$$\begin{aligned} V_{Pm} &= \frac{1}{2}e^{-\Gamma_m L_S}\left(V_{Sm} + Z_{Cm} I_{Sm}\right) \\ &\quad + \frac{1}{2}e^{\Gamma_m L_S}\left(V_{Sm} - Z_{Cm} I_{Sm}\right) \qquad m = 0, \alpha, \beta \end{aligned} \tag{3}$$

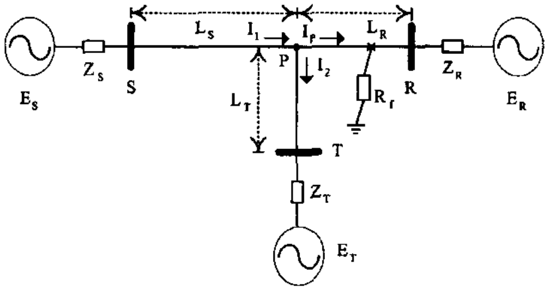

Fig. 3. One-line diagram of a three-terminal transmission system.

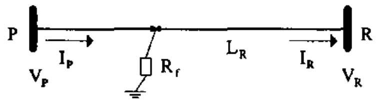

Fig. 4. The reduced system from a three-terminal line system.

$$
\begin{aligned}
I_{Pm} &= I_{1m} - I_{2m} \\
&= \left[\frac{1}{2Z_{Cm}} e^{-\Gamma_m L_S}\left(V_{Sm} + Z_{Cm} I_{Sm}\right) - \frac{1}{2Z_{Cm}} e^{\Gamma_m L_S}\left(V_{Sm} - Z_{Cm} I_{Sm}\right)\right] \\
&\quad - \left[\frac{1}{2Z_{Cm}} e^{-\Gamma_m L_T}\left(V_{Tm} + Z_{Cm} I_{Tm}\right) - \frac{1}{2Z_{Cm}} e^{\Gamma_m L_T}\left(V_{Tm} - Z_{Cm} I_{Tm}\right)\right]
\end{aligned} \tag{4}
$$

Thus, the analysis of the internal fault case mentioned above can be reduced to be a two-terminal system shown in Fig. 4. At this time, the two-terminal protection scheme described in section A can be used to derive the fault detection index for three-terminal lines as follows

$$
\begin{aligned}
M_m &= \frac{1}{2}\exp\left[-\Gamma_m L_R\right]\left[V_{Pm} + Z_{Cm} I_{Pm}\right] \\
&\quad - \frac{1}{2}\left[V_{Rm} + Z_{Cm} I_{Rm}\right]
\end{aligned} \qquad m = 0, \alpha, \beta \tag{5}
$$

Therefore, if a fault occurs in L_R, the fault can be easily identified by the index in (5). Assume that an external fault occurs in the right-hand side of bus R. Using the method described above, the equivalent circuit of three-terminal system can be reduced as Fig. 5. From section A, we know that the detection index in (5) also can detect the external fault.

The index $|M_m|$ also can be applied to detect internal and external faults occurred in any line segment. In short, if a fault occurs in the three-terminal transmission line system, the scheme only uses the index in (5) to detect the faults.

After fault detection, the proposed scheme simultaneously performs the fault direction discrimination and the fault classification subroutines. The algorithms are the same as ones mentioned in section A.

In summary, the scheme first assumes that a fault occurs in line L_R, and then the fault detection index $|M_m|$ in (5) is obtained. Using the index $|M_m|$, the three-terminal line system is completely monitored. The index achieves relaying tasks including fault detection, fault direction discrimination, and fault classification. Similarly, we also can assume that a fault occurs in L_S or L_T and then other two fault detection indices can be obtained. These two fault detection indices also can perform the same tasks as the index in (5).

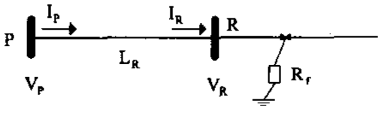

Fig. 5. The diagram of an external fault occurred in the right-hand side of bus R.

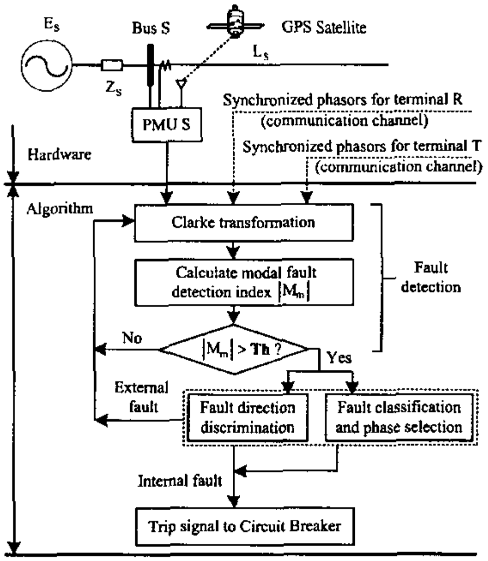

Fig. 6. The overall configuration of the proposed protection scheme.

From the above analysis, we can find that the three-terminal protection scheme reserves the advantages of two-terminal scheme. The proposed scheme is not affected significantly by fault resistance. Moreover, the scheme considers the effect of shunt charging capacitance. It is very suitable for long distance transmission line protection.

C. The Overall Configuration

A new scheme, offering a high-speed response and high sensitivity has been developed utilizing the advanced PMU technology combined with wide band communication networks. The overall configuration of the proposed protection scheme is shown in Fig. 6.

As three-terminal signals are used for protection algorithm, an accurate synchronous signal is needed, or time tags for

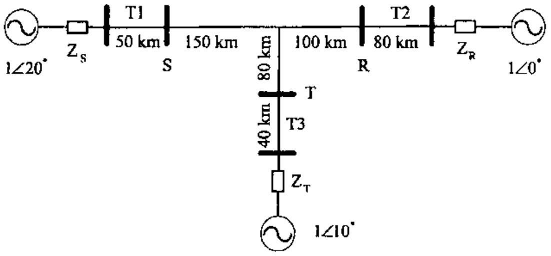

Fig. 7. The one-line diagram of the simulated three-terminal line system.

data collected at each terminal are needed for fault detection calculation. The GPS acts as an ideal synchronous signal; the signals collected at different location can be used correctly. Utilizing recent advances in communications technology for wide band communication networks, it makes high-speed and large bandwidth data communication feasible. Therefore, the data transmission delay can be minimized.

In this paper, the threshold (**Th = 2000**) is used to serve as fault detection level. With regard to fault direction discrimination, the threshold levels are **TL_zero** = 0.7 (rad), and **TL_alpha** = **TL_beta** = 0.2 (rad) for zero-mode, and alpha/beta-mode respectively. When four consecutive samples of the absolute value of $\arg(E_m/B_m)$ are over the predefined threshold, an internal fault is identified. Otherwise, the faults are discriminated as external faults.

III. RESPONSE EVALUATION

To verify the performance of the proposed scheme, a 345kV transposed three-terminal line system is modeled using EMTP/ATP simulator [10]. The simulated EHV transmission system is shown in Fig. 7. The lines T1, T2, and T3 are used to evaluate the performance of external faults. All parameters of lines are equal, which are the same as ones [8]. The practical considerations such as current transformer, capacitive voltage transformer and anti-aliasing filter whose cutoff frequency is 360 Hz are also included in the simulation. The sampling frequency used is 1920 Hz (32 sampling points per cycle). The full-cycle Discrete Fourier Transform (DFT) is adopted to calculate the fundamental voltage and current phasors.

The simulation studies have conducted with respect to various fault conditions such as fault position, fault types, and fault path resistance, etc. The selected results are discussed below.

A. Relay Response for Internal faults

An internal 'a'-phase to ground fault is selected as a sample to present the performance of the protection scheme. The fault position is set at 50 km away form bus R, and fault resistance is 1 ohm. Fig. 8 graphically illustrates the typical response of the proposed scheme for the single-phase to ground fault. As shown in fig. 8-(a) and (b), the scheme can detect the fault and identify the internal fault at the time 1.562 ms and 3.646 ms after fault inception, respectively. Using fig. 8-(a), (c), and (d) incorporated with fault classification algorithm shown in fig. 2, the fault is also correctly identified as 'a'-phase to ground fault. Thus, the scheme will issue a single-pole tripping to circuit breaker.

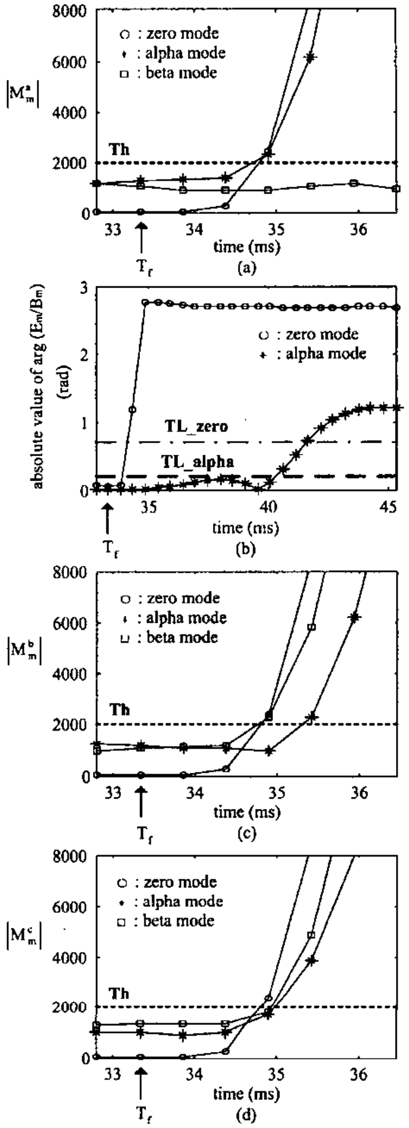

Fig. 8 Relay response for an internal fault occurred in L_R.
(a) The behaviors of modal fault detection index $|M_m|$ under phase-'a' basis.
(b) The response curves of abs[$\arg(E_m/B_m)$].
(c) and (d) are the behaviors of modal fault detection index under phase-'b' and -'c' basis, respectively.
T_f = fault inception time.

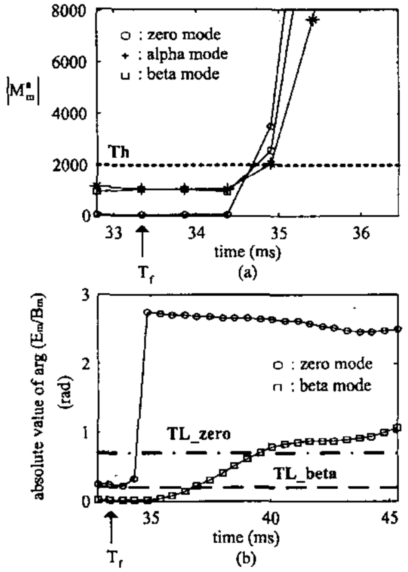

Fig. 9. Relay response for an internal fault occurred in L_S.
(a) The behaviors of modal fault detection index $|M_m|$ under phase-'a' basis.
(b) The response curves of abs[arg(E_m/B_m)].
T_f = fault inception time.

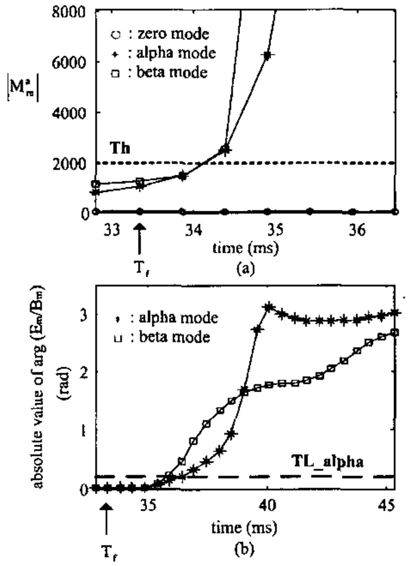

Fig. 10 Relay response for a high impedance fault.
(a) The behaviors of modal fault detection index $|M_m|$ under phase-'a' basis.
(b) The response curves of abs[arg(E_m/B_m)].
T_f = fault inception time.

Fig. 9 illustrates the response of the scheme for an internal fault ('b'-phase to ground fault) occurred in 30 km away from bus S. Fig. 9-(a) verifies that the detection index in (5) gives the correct response when a fault does not occur in L_R. As shown in fig. 9-(b), the scheme correctly identifies the internal fault. The tripping decision time of the internal fault is 3.646 ms. Extensive simulation studies demonstrate that the tripping decision time including fault detection, fault direction discrimination, and fault classification of the protection scheme is almost well within half a cycle under various system and fault conditions.

B. High Impedance Faults

Fig. 10 shows the response of the scheme for a three-phase to ground fault occurred in 20 km away from bus R. The fault resistance is 300 ohm. As seen from fig. 10-(a), the alpha-mode and beta-mode fault detection indices correctly detect the fault. Fig. 10-(b) illustrates that the fault occurs in the protected zone. Therefore, the protection scheme provides high resistance coverage.

C. Relay Response for External faults

Assume that a 'c'-'a' phase short fault occurs in T2 and the fault position is set at 30 km away from bus R. As shown in fig. 11-(a), the fault is detected at the time 2.604 ms after fault occurrence. Fig. 11-(b) illustrates that the protection scheme correctly identifies the external fault. Extensive external fault studies with respect to different fault conditions verify that the scheme can work well and never gives misoperation.

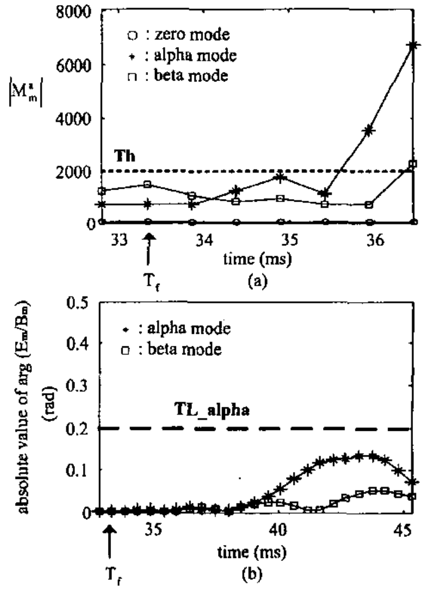

Fig. 11 Relay response for an external fault.
(a) The behaviors of modal fault detection index $|M_m|$ under phase-'a' basis.
(b) The response curves of abs[arg(E_m/B_m)].
T_f = fault inception time.

IV. CONCLUSIONS

A new PMU-based protection scheme for EHV three-terminal transmission lines is presented in this paper. Simulation results show that the scheme gives correctly response under various system and fault conditions. The tripping decision time including fault detection, faulted-zone discrimination, and fault classification is mostly within half a cycle. The algorithm considers the effect of shunt charging capacitance such that the scheme is very suitable for long distance transmission line protection. Moreover, the protection scheme also provides high resistance coverage. Extensive studies demonstrate the feasibility and effectiveness of the proposed relaying algorithm for three-terminal line protection.

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VI. BIOGRAPHIES

Ching-Shan Chen was born in Taichung, Taiwan, in 1976. He received his M.S. degree in electrical engineering from National Taiwan University, Taipei, Taiwan in 2000. He is currently working toward his Ph.D. degree in electrical engineering department of NTU. His interested research includes computer relaying and the application of PMUs to power system protection.

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