A Novel Adaptive PMU-Based Transmission-Line Relay—Design and EMTP Simulation Results

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Abstract—**This paper proposes a novel adaptive relaying scheme based on phasor-measurement units (PMUs) for transmission lines. The proposed adaptive relaying scheme can provide an extremely accurate discrimination between in-zone and out-of-zone faults. Two novel and composite fault discrimination indices in terms of Clarke components of synchronized voltage and current phasors at two ends of a line are derived. A line parameter estimation algorithm is developed and built in the newly designed relay to solve the uncertainty problem of line parameters. The proposed relaying scheme is independent of fault types, fault locations, fault path resistance, fault inception angles, and the variations of source impedance. The tripping decision time of the designed relay is very fast and almost held well within 6 ms for most fault events. All of the EMTP simulation results show that the proposed adaptive relaying scheme provides a high level of dependability and security.**

Index Terms—**Adaptive relaying, global positioning system (GPS), line relaying, phasor-measurement unit (PMU).**

I. INTRODUCTION

THE development of a computer relaying scheme for power systems is technically interesting and promising during the last few decades [1]–[5]. The difficulties of studying the protection of transmission lines have been increasing due to the growth in size and complexity of power systems. Protective relays thus become critical power system equipment, and their behaviors determine the response of power–system-to-fault events.

In general, a relay can be designed to respond to any obtainable measurements or combinations. Based on these measurements, there are many computer-relaying schemes used for protection of transmission lines that have been developed recently [6]–[16]. While the mentioned relaying schemes have been developed searchingly, the proposed schemes still possess some limitations inherently. For example, distance protection is one of the commonly used techniques in the protection of transmission lines, but the distance relay frequently encounters under-reach/over-reach problems [8]. For the protection of an entire line, current differential relay can be used to cope with the mentioned problem. However, it is difficult to determine an acceptable bias characteristic that provides adequate sensitivity to internal faults and complete stability in all external faults and other nonfault conditions [10].

Several investigations have examined various types of pilot relay used in transmission lines [11], [12]. The performance of pilot relay still suffers from some limitations. The sensitivity of pilot relay based on phase-comparison principle, for example, becomes less when there is load flow or fault resistance. Besides, this kind of pilot relay cannot be applied to high-voltage long transmission lines, since it will be affected by shunt capacitance current [12]. To improve the dependability and security of protective relaying schemes, Aggarwal *et al.* [13] suggested using the composite measurements from both line ends. Present communications technology enables the use of data from both ends of transmission lines [5]. Based on these concepts, the proposed relaying scheme is developed.

Since there is the need to clear faults on major transmission lines very rapidly, several protective schemes, using information from travelling waves launched by disturbances, have been suggested recently [14], [15]. The relaying schemes based on the differential equation algorithm (DEA) also possess the performance for a fast response to fault occurrence [16]. The travelling-wave schemes depend on identifying the particular voltage and current increments from all of those that arrive at the relaying point. The identification of the desired signal becomes the essential problem of the usual type of travelling-wave protective discrimination scheme [14]. The proposed indices can easily discriminate the faults so that the requirement for fast relaying can be achieved.

In order to develop protective relaying techniques that cope with various variation factors associated with accuracy for discriminating fault events, an adaptive protective relaying scheme is presented in this paper. The paper is organized into six sections, the first of which is the introduction. In Section II, an adaptive protective relaying scheme based on the PMU technique is presented. In this section, we first briefly describe the configuration of PMU. The strategy for discriminating fault occurrence between in zone and out of zone is described as well. In the third section, we present the fault discrimination index and location index for a three-phase transmission line. The parameter estimation algorithm is also described in this section. The EMTP simulation results are presented in the fourth section. The fifth section is devoted to the discussions of practical considerations associated with the proposed adaptive relaying scheme. Finally, the sixth section is the conclusion.

II. ADAPTIVE PMU-BASED FAULT PROTECTIVE RELAYING SCHEME

The overall diagram of the adaptive PMU-based fault protective relaying configuration is shown in Fig. 1. The designed relay consists of two main units—the PMU and the central discrimination unit.

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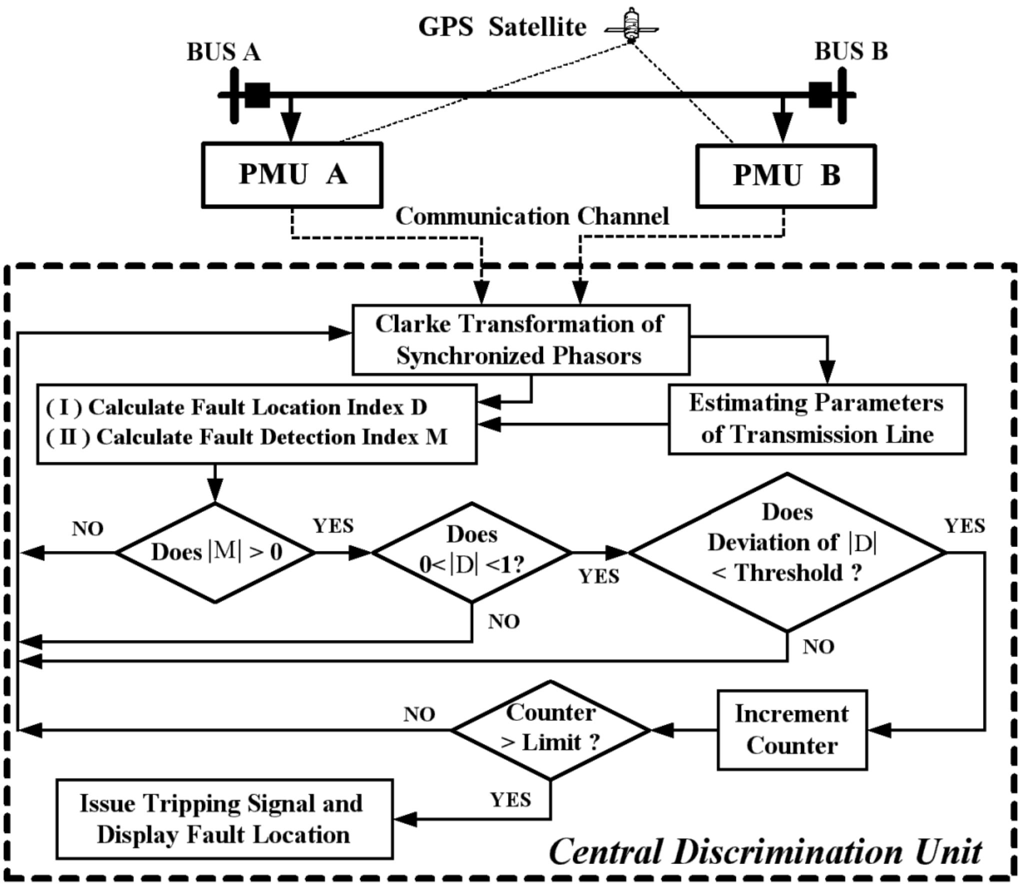

Fig. 1. Configuration of the adaptive PMU-based fault protective relaying system for EHV/UHV transmission lines.

A. PMU Configuration

The three-phase voltages and three-phase currents are measured by PMUs (the detail description including design, implementation, and field test results can be referred to [18]) located at both ends of the line simultaneously. Using the accurate timing signal provided by GPS as the common time base of PMUs, we can highly promote the accuracy of synchronized measurements. These synchronous and accurate measurements are then used to perform the relaying tasks.

B. Central Discrimination Unit

The central discrimination unit is illustrated with the part enclosed by the dashed line shown in Fig. 1. When a fault occurs, the fault components can be acquired in synchronized fashion from both ends of a transmission line. Once the synchronized phasors coming from two communication channels are entered into the central discrimination unit, these phasor quantities are first transformed to modal components by Clarke transformation. Afterward, the unit will generate one set of modal components for every forward step of moving data window.

The estimation of line parameters is processed in the next step. At this stage, the fault detection index M and location index D are calculated. In the newly designed adaptive relay, we combine these two indices to perform relaying tasks. First, the proposed scheme uses the discrimination index $|M|$ to determine whether a fault exists in the considered protection zone or not. Theoretically, the $|M|$ value is zero under normal system operation. As long as the computed $|M|$ value is greater than zero, the relay will perceive that there is a fault existing in the protection zone. Unfortunately, this phenomenon will also occur under external fault cases due to transient disturbance emerged from faults themselves. This fact means that the relaying scheme needs another index to distinguish external fault and internal fault. We use the location index D to do this job. Therefore, index D can be regarded as a restraint for the proposed relay. Besides, in order to prevent the designed relay from mistaking the relaying action, it is necessary to choose a threshold value for the computed $|M|$ value. In the proposed relaying scheme, we adopt the combination of the online-computed mean value and standard deviation value of $|M|$ per two prefault sampling cycle, which is explained in Section V, to serve as a discriminating threshold value.

Next, the designed relay performs the procedure for distinguishing between external fault and internal fault. The location index D has to theoretically be a real-valued number and must be converged to the interval of (0,1) under any internal fault. From the view of numerical computation, it is hard to successively generate a pure real value of location index D under fault conditions. Hence, we must choose a counter limit to precisely determine whether an external fault or an internal fault occurred in the protection zone. In this study, we follow the method that was proposed by Akke and Thorp [16] to choose the counter limit. This tripping decision strategy can guarantee that the proposed relaying scheme will not issue an incorrect tripping signal between external and internal faults.

III. PROPOSED FAULT DISCRIMINATION INDEX

A. Fault Discrimination Index

Consider an arbitrary three-phase transmission line illustrated in Fig. 2, which consists of phase a, b, c, and a ground system consisting of earth and ground wires. We could take the voltages at fault point F (located at $x = DL$ km away from the receiving end) and $x = 0$ as boundary conditions. The fault location index is therefore solved as [17]

$$D_i = \frac{\ln\left[\frac{N(i)}{M(i)}\right]}{2\Gamma(i,i)L} \qquad i = 1,2,3 \tag{1}$$

where $i = 1$, 2, and 3 are used to represent 0, α, and β-modal components of signals. $\Gamma(i,i)$ represents the diagonal entries of the 3×3 model propagation matrix.

$$\begin{cases} N(i) = A(i) - C(i) \\ M(i) = E(i) - B(i) \end{cases} \tag{2}$$

and

$$A(i) = \frac{1}{2}\left[V_{\mathrm{Rm}}(i) - Z_C(i,i) I_{\mathrm{Rm}}(i)\right] \tag{3-1}$$

$$B(i) = \frac{1}{2}\left[V_{\mathrm{Rm}}(i) + Z_C(i,i) I_{\mathrm{Rm}}(i)\right] \tag{3-2}$$

$$C(i) = \frac{1}{2}\exp\left[\Gamma(i,i)L\right]\left[V_{\mathrm{Sm}}(i) - Z_C(i,i) I_{\mathrm{Sm}}(i)\right] \tag{3-3}$$

$$E(i) = \frac{1}{2}\exp\left[-\Gamma(i,i)L\right]\left[V_{\mathrm{Sm}}(i) + Z_C(i,i) I_{\mathrm{Sm}}(i)\right] \tag{3-4}$$

where $A(i), B(i), C(i)$, and $E(i)$ are the entries of 3×1 vectors A, B, C, and E, respectively. $Z_C(i,i)$ represents the diagonal entries of the 3×3 model surge impedance matrix, and V_{Sm}, V_{Rm}, I_{Sm}, and I_{Rm} represent sending end/receiving end voltage and current synchronized modal measurements, respectively.

The index D combined with the computed values $|M|$ or $|N|$ (we call them **fault discrimination index**) can be used as fault detectors. The computed values of $|M|$ and $|N|$ will all be held at zero before the occurrence of a fault [17]. This can be proved by substituting the measured data (V_{Sm}, I_{Sm}) and (V_{Rm}, I_{Rm}) into the formulae of M and N. Since these measured components all satisfy the transmission-line equation, after algebraic manipulations, we can prove that M and N are indeed identical to zero. However, as soon as the measured fault data have been inputted into the algorithm through the moving data window, the computed values of $|M|$ and $|N|$ abruptly deviate from zero, and hence, the fault location index D also quickly converges to the interval of (0, 1). These facts imply that $|M|$ or $|N|$ incorporated with location index D could be employed as indicators of various fault events.

B. Online Parameter Estimation Algorithm

In reality, the line parameters will vary not with the environmental conditions but also with the system operation situations. The parameter uncertainties will affect the accuracy of fault location seriously. The authors' previous study [18] and work of other groups [19], [20] have demonstrated this fact. From this point of view, it is necessary to use the online parameter estimation algorithm to promote the accuracy of fault location index D, and this can further enhance the relaying performance of the proposed relaying scheme.

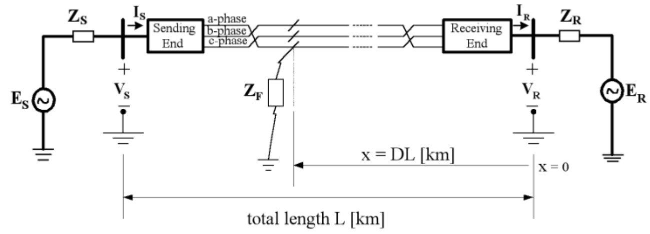

Fig. 2. Three-phase transposed transmission line.

We can monitor online the status of transmission line, and extract the true phasor-measurement data (V_S, I_S) and (V_R, I_R) from both line ends by the new DFT filtering approach [17], [21]. These data can be used to derive the characteristic impedance and propagation constant of transmission line inversely. These line parameters can thus be respectively expressed as the following [17]:

$$Z_{\mathrm{Cm}}(i,i) = \left[\frac{V_{\mathrm{Sm}}^2(i) - V_{\mathrm{Rm}}^2(i)}{I_{\mathrm{Sm}}^2(i) + I_{\mathrm{Rm}}^2(i)}\right]^{1/2} \qquad i \equiv 1,2,3 \tag{4}$$

and

$$\Gamma_m(i,i) = \frac{\cos h^{-1}\left[K_m(i)\right]}{L} \qquad i \equiv 1,2,3 \tag{5}$$

where

$$K_m(i) = \frac{V_{\mathrm{Sm}}(i) I_{\mathrm{Sm}}(i) + V_{\mathrm{Rm}}(i) I_{\mathrm{Rm}}(i)}{V_{\mathrm{Sm}}(i) I_{\mathrm{Rm}}(i) + V_{\mathrm{Rm}}(i) I_{\mathrm{Sm}}(i)} \qquad i \equiv 1,2,3 \tag{6}$$

The letter $i = 1$, 2, and 3 denotes the entry position of the considered vector or matrix, which is also used to represent 0, α, and β-mode components of the computed quantities, respectively. The performance has been demonstrated by EMTP in detail [18].

IV. PERFORMANCE EVALUATIONS

The simulations and evaluations of the designed relay have been performed with the ATP version of the EMTP simulator [22].

A. Simulations Considered

By virtue of EMTP, we intentionally construct a 345-kV transposed transmission-line system, which is similar to the inservice ones of Taipower 345-kV systems. The sample system consists of five transmission lines and busbars that connect to three of those equivalent sources as shown in Fig. 3. Each line is modeled by distributed parameters that are same with [18]. Three ends of the considered system are replaced by Thevenin's equivalent impedance with a different angle than that of the line impedance, and are shown in Table I.

The total time of simulation is $T_{tot} = 200$(ms), and the data are sampled at a sampling rate of 3.84 kHz (64 × 60 Hz). We first conduct dependability and security evaluations for the proposed relaying scheme, and then response performance. We

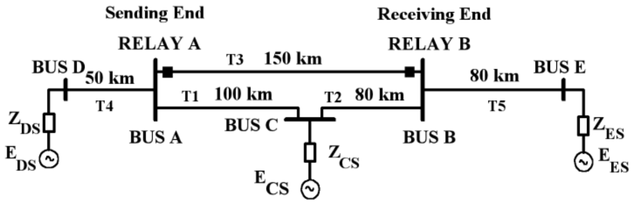

Fig. 3. Sample transmission-line system used in the performance evaluation of the proposed relaying scheme.

follow the method that was proposed by [23] to define the following evaluation measures:

$$\text{Dependability} = \left[1 - \frac{\text{Number of failures to trip}}{\text{Total test events}}\right] \times 100\% \quad (7)$$

$$\text{Security} = \left[1 - \frac{\text{Number of incorrec to perations}}{\text{Total test events}}\right] \times 100\% \quad (8)$$

B. Tripping Decision Time

In order to assess the response performance of the proposed relaying scheme, we define the tripping decision time as follows:

$$\begin{aligned}&\textbf{Tripping Decision Time}\\&=\textbf{The Time Satisfied Tripping Criteria}\\&\quad-\textbf{The Time of Fault Inception}\end{aligned} \quad (9)$$

Note that this tripping decision time does not include the time delay of communication channel and the time for actuating the circuit breaker.

C. Evaluations for Dependability and Security

An extensive series of simulation studies has been carried out to examine the performance of the proposed relaying scheme. Some of the simulation results will be presented.

1) Dependability for Internal Faults: With respect to five different thresholds of index D, we perform 756 tests of internal fault events to evaluate the dependability of the relaying scheme. The results are summarized in Table II. The relaying scheme is regarded as a failure to trip when it takes over the specified decision-limited periods. There are two specified decision-limited periods (i.e., one-cycle and one-and-a-half cycle) that are chosen as restraint periods. It is clearly seen that the larger the threshold of index D is chosen, the better dependability that the relaying scheme possesses. When the threshold of D is set at 0.0285, for example, the dependability of the proposed scheme can be achieved even up to 100 and 98.41% with respect to one-and-a-half cycle and one-cycle decision-limited periods, respectively. From Table II, it can be observed that the relaying scheme can indeed achieve a high level of dependability.

2) Security for External Fault: Fig. 4 typifies the plots of tripping indices $|M|$ and $|D|$ when an external three-phase ground fault has occurred in line segment T4. An examination of this figure indicates that the index $|M|$ varies violently and index $|D|$ may fall into the tripping setting interval (0, 1) (indicated by the circle). This problem can be resolved by the well designed counter limit. A summary of the results obtained in the relaying performance studies described previously is provided in Table III. The inspection of this table indicates that the relaying scheme issues blocking signals for the total amount

TABLE I
PARAMETERS OF EQUIVALENT SOURCE AT BUSES C, D, AND E

Bus C	Bus D	Bus E
$Z_0 = 1.7855 + j7.557$ [Ω]	$Z_0 = 2.738 + j10.000$ [Ω]	$Z_0 = 0.833 + j5.118$ [Ω]
$Z_1 = 0.238 + j5.951$ [Ω]	$Z_1 = 0.238 + j5.7132$ [Ω]	$Z_1 = 0.238 + j6.190$ [Ω]
$E_{CS} = 345$ [kV] line - to - line	$E_{DS} = 345$ [kV] line - to - line	$E_{ES} = 345$ [kV] line - to - line
Phase Angles= (–10°, –130°, 110°)	Phase Angles = (0°, –120°, 120°)	Phase Angles = (–20°, –140°, 100°)

TABLE II
STATISTICAL RESULTS OF THE DEPENDABILITY EVALUATION UNDER VARIOUS PERMANENT INTERNAL FAULTS

Statistical results		Threshold of D	Total tests	Success	Failure	Dependability (%)
Specified decision-limited	1.5 cycle	0.0357	756	756	0	100
		0.0285	756	756	0	100
		0.0114	756	756	0	100
		0.0075	756	753	3	99.60
		0.0039	756	744	12	98.41
	1 cycle	0.0357	756	744	12	98.41
		0.0285	756	744	12	98.41
		0.0114	756	742	14	98.15
		0.0075	756	733	23	96.96
		0.0039	756	689	67	91.14

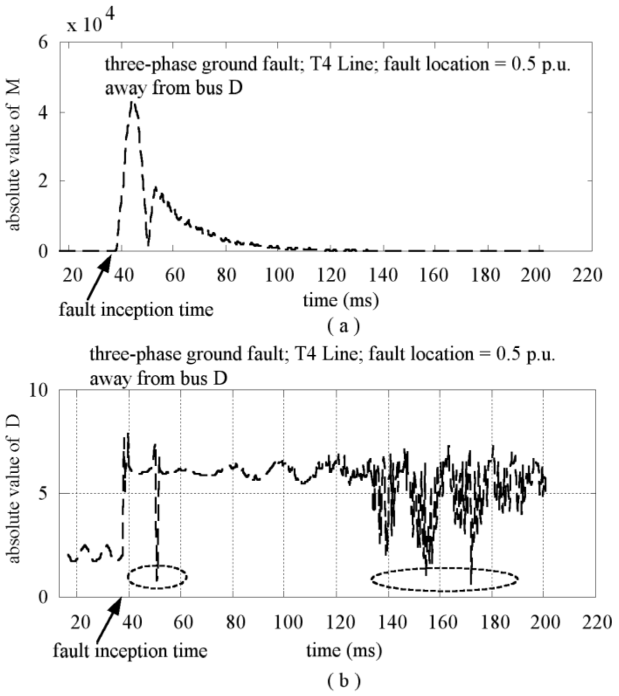

Fig. 4. Typical variations of fault discrimination index $|M|$ and fault location index $|D|$ under external fault.

TABLE III
SIMULATION RESULTS OF THE SECURITY EVALUATION UNDER VARIOUS PERMANENT EXTERNAL FAULTS.

Fault types	Fault resistance	**Fault location	Tested line			
			T1	T2	T4	T5
			*Tripping signal			
c-a phase ground fault	1 Ω	0.1 (p.u.)	0	0	0	0
		0.5 (p.u.)	0	0	0	0
		0.9 (p.u.)	0	0	0	0
	100 Ω	0.1 (p.u.)	0	0	0	0
		0.5 (p.u.)	0	0	0	0
		0.9 (p.u.)	0	0	0	0
b-c phase short fault	1 Ω	0.1 (p.u.)	0	0	0	0
		0.5 (p.u.)	0	0	0	0
		0.9 (p.u.)	0	0	0	0
	100 Ω	0.1 (p.u.)	0	0	0	0
		0.5 (p.u.)	0	0	0	0
		0.9 (p.u.)	0	0	0	0
Security = (1 – (0/48))*100% = 100%						

* Tripping signal: 1 represents tripping; 0: represents blocking
** Reference positions for different line segments are respectively set at T1: bus B; T2: bus C; T4: bus D; T5: bus E.

of tested cases. According to the proposed tripping strategy, for external faults, the scheme never misjudges the events.

3) Security for Intermittent Disturbance: The proposed relaying scheme can provide detailed information immediately after a system disturbance. We have conducted lots of simulations to examine the effect of intermittent disturbance on the security of the proposed relaying scheme.

Fig. 5 shows the plots of indices $|M|$ and $|D|$. In this case, the power compensation is supplied at bus E. The capacity of the capacitor tank is set to be 28.8 MVAR and is switched at a given time. Inspection of the shown figure shows that the switching operation introduces severe transients and, hence, leads violent variation of indices $|M|$ and $|D|$. While the value of index $|D|$ may fall into the setting range of tripping (indicated by the circle) [i.e., the interval of (0, 1)], the relaying scheme still will not issue a tripping signal according to the limitation of decision counter. Other studies associated with the impacts of switching operations on the security are summarized in Table IV. It is clearly seen from Table IV that whenever switching operations are actuated, turning on or turning off, the relaying scheme is independent of the supplied locations and switching status for power compensations. This means that the scheme indeed provides a high degree of security.

D. Evaluations for Response Performance

1) Effects of Fault Types and Fault Positions: Single-phase-to-earth, two-phase-to-earth, three-phase-to-earth, and two-phase short faults away from bus B (receiving end) are simulated. The results are shown in Fig. 6. From the shown figure, it is clearly seen that the tripping decision time of the relaying scheme is relatively insensitive to the fault types and fault locations. The trip decision time is very fast and almost remains well within 6 ms for all of the simulated cases. The maximum tripping decision time of the relaying scheme, for example, takes only 7.03 ms for the fault located at $D = 0.05$ p.u under a three-phase ground fault case. Besides, the proposed relaying scheme exhibits an appealing property (i.e., the relative stable curve of response time).

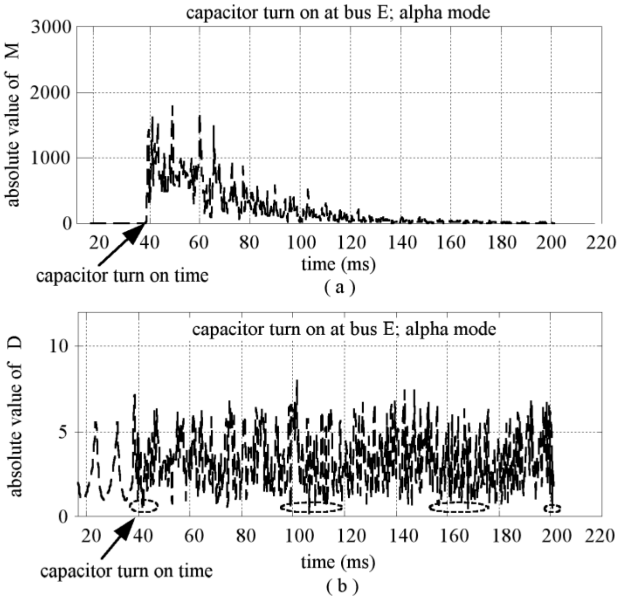

Fig. 5. Typical variations of fault discrimination index $|M|$ and fault location index $|D|$ under switching operations of power-compensated capacitor tank.

TABLE IV
SIMULATION RESULTS OF THE SECURITY EVALUATION OF THE PROPOSED RELAYING SCHEME UNDER SWITCHING OPERATIONS OF POWER-COMPENSATED CAPACITOR TANK

Capacitor tank position		BUS A	BUS B	BUS C	BUS D	BUSE
Switching of capacitor tank	State	on→ off	on→ off	on→ off	on→ off	on→ off
	Trip signal	0	0	0	0	0
	State	off→ on	off→ on	off→ on	off→ on	off→ on
	Trip signal	0	0	0	0	0
Security = (1 – (0/10))*100% = 100%						

Trip Signal: 1 represents tripping; 0: represents blocking

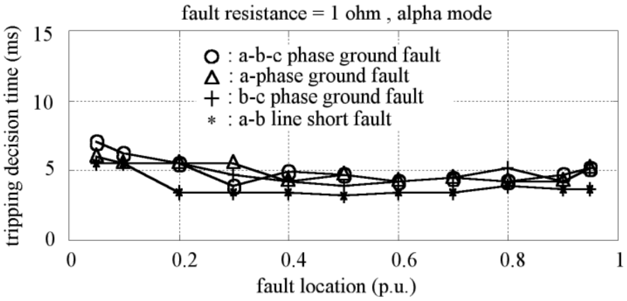

Fig. 6. Effects of fault types and fault locations on the tripping decision time of the proposed relaying scheme.

2) Effects of Fault Resistance: Fig. 7 illustrates the impacts of single-phase ground fault events with respect to the fault resistance variation ranging from 1 Ω to 10 kΩ under three fault distances. The fault locations are purposely set at remote, middle, and proximal ends of the protected line (i.e., located at 0.8, 0.5, and 0.2 p.u., respectively). It is evident from Fig. 7

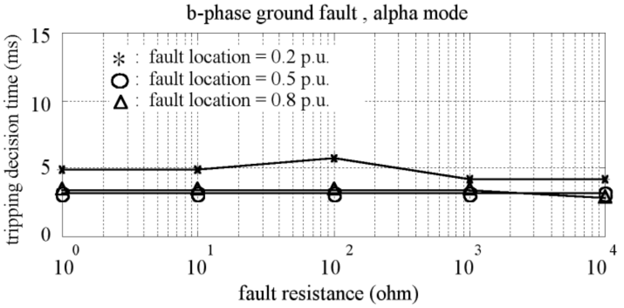

Fig. 7. Effects of fault resistance on the tripping decision time of the proposed relaying scheme.

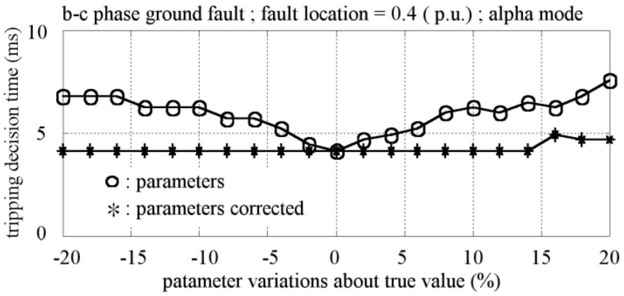

Fig. 8. Effects of line parameter uncertainties on the tripping decision time of the proposed relaying scheme.

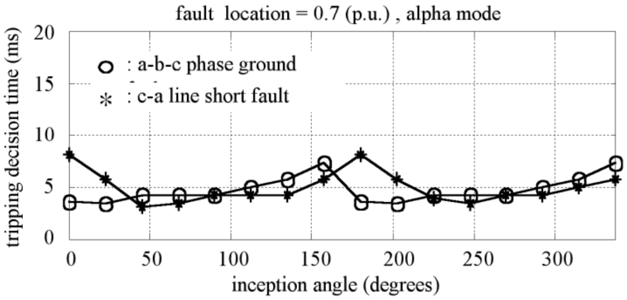

Fig. 9. Effects of fault inception angle on the tripping decision time of the proposed relaying scheme.

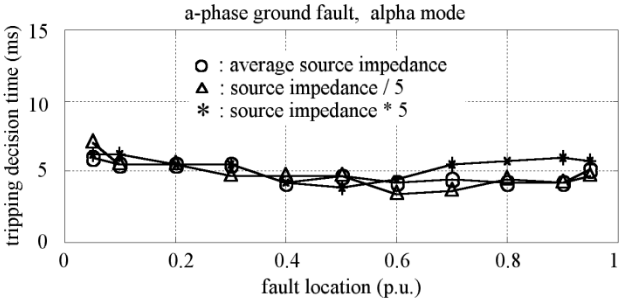

Fig. 10. Influence of source impedance on the tripping decision time of the proposed relaying scheme.

that the scheme is hardly affected by the magnitudes of fault resistance. Even in the extreme case of 10 kΩ, the response of the scheme is still very fast and stable. This means that the proposed scheme inherently possesses an excellent relaying performance that is practically independent of fault resistance.

3) Effects of Line Parameter Uncertainty: In this test case, the variations of various line model parameters in EMTP all range from -20 to $+20\%$. Fig. 8 shows the effects of line parameter uncertainties on the relay performance for a b-c phase ground fault, where the fault location is 0.4 p.u. and fault resistance is 1 Ω. It is discovered that the impact of line parameter uncertainty on the response time of the relaying scheme is approximately proportional to the parameter variations. By using the proposed parameter estimation technique, the relaying scheme can online correct the errors due to this uncertainty regarding parameters and, thereby, provide a nearly perfect relaying performance.

4) Effects of Fault Inception Angle: In this case, the c-a line short fault and three-phase ground fault are chosen as illustrative cases. Fig. 9 shows the simulation results. These two fault events are assumed to occur at point on waves for every 22.5° spacing from 0 to 360°, respectively. The fault inception angle of fault event refers to the phase angle of a-phase. The fault resistance is set to be 1 Ω. The results evidently show that the proposed relaying technique maintains a high degree of stability which is almost independent of the fault inception angle.

5) Effects of Source Impedance: Fig. 10 illustrates the simulation results with respect to single-phase (a-phase) ground fault event. In these simulations, the self and mutual impedance of the remote equivalent source (located at bus D) are varied by a factor of five to simulate the impact of severe mismatches between system operating conditions at the occurrences of faults. In these tests, the tripping decision time of the proposed scheme is equally quick and is hardly affected by source-impedance variation.

V. DISCUSSIONS

It is also necessary to consider the design concepts. Several of the more significant aspects are described.

A. Synchronization Error

Accuracy of time synchronization directly translates into the accuracy with phase-angle difference between various phasors that can be measured. This will affect the relay's performance. However, the synchronization accuracy of the proposed GPS and PMU configuration has been demonstrated to remain within 1 μs (equivalent to 0.0126° phase difference at 60 Hz [18]), which more than meets our needs.

B. Settings' Selection

There are only two settings for indices $|M|$ and $|D|$ that need to be selected in the proposed relaying scheme. We adopt two-cycle data prior to the currently moving sampling window as the statistical interval for computing the threshold value of index $|M|$ so that the relaying scheme can online and adaptively update the setting of index $|M|$. The threshold setting of index $|M|$ is computed as follows:

$$|M|_{\text{threshold}} = \mu_M + k \times \sigma_M \tag{10}$$

where μ_M and σ_M are the mean and standard deviation values, respectively. Constant k is a user-determined parameter whose value is proportional to the security and inversely proportional to the response time of the relaying scheme.

Regarding the selection for the threshold value of index $|D|$, we adopt a statistical manner to predetermine it. First, we conduct an extensive series of simulations with respect to all possible fault types, various fault resistance, different fault locations, fault inception angles, operation situations, etc. Then, we collect the fault data of index $|D|$, and use them as sampling events for performing statistical analysis. We have run over thousands of simulation cases and collected a pile of the post-fault data of index $|D|$. It should be noted that these collected data have been expressed in terms of deviation about the true value of fault location index $|D|$. Part of these collected deviation quantities of index $|D|$ is illustrated in Fig. 11. Using these collected data, we perform a lot of examination and evaluation studies with respect to various operation situations including the worse cases to find the threshold value for $|D|$. The result is

$$\begin{cases} D_{th,\alpha-\mathrm{mode}} = 0.0285 \\ D_{th,\beta-\mathrm{mode}} = 0.0208 \end{cases} \tag{11}$$

A selection of the trip threshold depends on the behaviors of the estimated indices $|M|$ and $|D|$, and the desired relay operation time. Conservative selection of the trip threshold results in longer trip decision time and higher security and vice versa. Hence, there is a tradeoff between speed and security of the trip decision.

C. Tripping Condition

In this study, we follow the manner [16] to choose the counter limit. The counter limit (CL) is calculated as

$$CL = \frac{T}{\Delta t} \tag{12}$$

where Δt is the sampling interval. The parameter T is a user-determined parameter that can be interpreted as the shortest time delay for a fault at the beginning of the line. In this study, we have used $T = 1$ ms for all possible fault events. The data are sampled at a sampling rate of 3.84 kHz. Thus, a sampling interval of $\Delta t = 0.26$ ms yields a counter limit of $CL = 3.84 \approx 4$ for all possible faults. It is clearly seen from our investigations that this choice of counter limit is sufficient to perform an excellent relaying task.

D. Safety Considerations for Intermittent Disturbance

To prevent the new designed relay from issuing an incorrect tripping signal during normal system operation and during intermittent external/internal disturbance, the relaying scheme has to be examined with respect to intermittent disturbance. For example, we have performed an extensive series of capacitor tanks switching on/off simulations. With the settings and the counter limit, the results on the security and dependability of the proposed relaying scheme are demonstrated very well.

E. Discrimination Between In-Zone and Out-of-Zone Faults

As described in Section II, the proposed fault discrimination index $|M|$, which is used to make a judgement as to whether a fault occurs in the considered transmission-line system or not, is identical to zero for all healthy conditions. The fault location index D, whose theoretical value is a real number ranging from zero to one, serves as an indicator to distinguish the perceived fault between in zone and out of zone. Therefore, index D can be regarded as a restraint for the proposed relay. The authors have performed a series of EMTP simulations. For example, Fig. 12 shows an extreme case. Inspection of this figure clearly shows the difference of $|M|$ and $|D|$ between internal fault and external fault. For internal fault cases, the indices $|M|$ and $|D|$ indeed behave like the description in Section II; however, both will vary violently for external fault cases. These miracle properties of indices $|M|$ and $|D|$ incorporated with an adaptive threshold setting of $|M|$, a statistical threshold setting of $|D|$, and an elaborately selected counter limit can provide an extremely accurate discrimination between in-zone and out-of-zone faults.

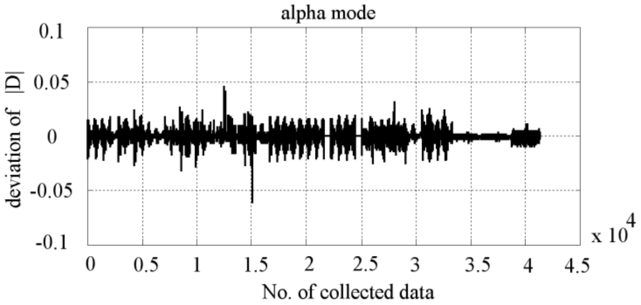

Fig. 11. Collection data of deviations of fault location index D about the true fault locations under various simulated fault events.

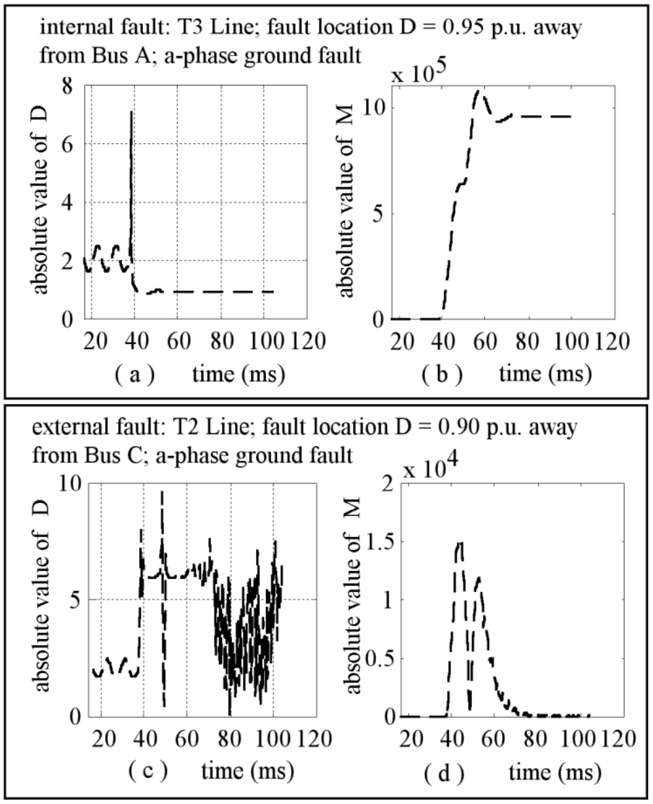

Fig. 12. Comparison between the sensitivities of fault location index $|D|$ and discrimination index $|M|$ with respect to internal and external fault cases.

F. Filtering Considerations

In the proposed algorithm, the real-time voltage and current phasor measurements are obtained throughout the system with the aid of GPS and PMU techniques. These calculations produce very accurate phasor measurements, which can also be used to calculate the local system frequency with the smart discrete Fourier transform (SDFT) [proposed by our lab [17], [21]. Therefore, they are free from errors introduced by system imbalance and harmonics. Especially, the SDFT can resolve the problem due to the dc offset under abnormal operating conditions.

VI. CONCLUSIONS

An adaptive PMU-based protective relaying scheme for EHV/UHV transmission lines is presented. Specifically, a fault discrimination index and a location index in terms of Clarke components of synchronized phasor measurements are derived. The parameter estimation algorithm has also been developed. With the advent of these algorithms, the proposed technique can achieve excellent performance for fault protection of transmission lines. The simulation results show that the proposed relaying scheme correctly discriminates between internal and external faults. Most of the time for identifying an internal fault is less than 6 ms.

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