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Noncommunication Accelerated Sequential Tripping for Remote-End Faults on Transmission Lines

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Abstract—Short-circuit faults occurring close to either end of a transmission line are normally cleared with some time delay by the distance relay at the opposite end of that line. The pilot relaying schemes require communication media in order to reduce this time delay. This paper presents a noncommunication method that provides high-speed distance relaying over the entire length of transmission lines. Similar to conventional distance relays, the proposed method requires voltage and current signals at the relay location as well as the impedance parameters of the protected line as input. Accelerated sequential tripping (AST) for faults on the end-sections of the line is achieved by using the signals measured from the fault inception to several cycles after the opening of the remote-end circuit breaker (ORCB). A formula is put forward for determining the exact fault distance by using post-ORCB signals. Two indices are also proposed for detecting three- and single-pole ORCB in order to fulfill the prerequisite for accurate fault location and generating a trip command, if needed. The proposed method is validated by conducting more than 10000 simulations on the 39-bus test system using DiGSILENT PowerFactory.

Index Terms—Accelerated sequential tripping, Distance relay, Discrete Fourier transform (DFT), Opening of the remote-end circuit breaker (ORCB).

I. INTRODUCTION

The reach of distance relays is not definite due to several sources of uncertainties, such as inaccuracies of instrument transformers, phasor estimation errors and unknown values of fault resistance. Zone 1 of distance relays is commonly set to cover only a less-than-unity fraction of the protected line to avoid erroneous tripping. The relay operates with no intentional delay if faults occur within Zone 1. The area between the intended reach of Zone 1 and the remote-end of the line is called “end-section”. To clear faults on the end-section of a line, an extended protection zone, i.e., Zone 2, is introduced. To coordinate distance relays on adjacent lines, Zone 2 is graded with an intentional time delay of approximately 400 ms. Accordingly, faults close to either end of a transmission line are cleared instantaneously only from one end of the line and in Zone 2 operating time from the other end.

Non-simultaneous tripping of circuit breakers (CBs) on both line ends is called sequential tripping. During sequential

tripping, the fault remains supplied from one end of the line for more than the Zone 2 time delay considering CB operating time, which may compromise system stability. To avoid this delayed fault clearance, a number of transfer trip schemes have been developed, which implement transmission of a transfer trip signal to the remote-end relay. This is a common practice for tripping the remote-end CB (RCB) more quickly [1]. As a result, faults on the end-sections will be cleared with no intentional time delay from the local-end, and multiple cycles later from the remote-end of the line. This accelerated sequential tripping (AST) is not considered instantaneous tripping due to communication latencies, although it falls under high-speed distance relaying.

Due to signaling-related costs, reliability and technical issues, noncommunication AST methods are considered more attractive than communication ones. Various noncommunication AST methods have been proposed thus far [2]–[16]. Depending on whether the high-frequency or fundamental-frequency components of fault signals are used, these methods can be divided into two groups. Despite providing acceptable performance, methods of the first group require special wide-band measurement devices for extracting the transient characteristics of fault signals [2]–[4]. The methods based on fundamental-frequency phasors are more practical for they only require signals that are traditionally fed to distance relays as input [5]–[15].

AST can be achieved for end-section faults by tracking the change that the currents of sound phases undergo after the opening of the remote-end CB (ORCB) [5], [6]. The variations of symmetrical components of the voltage and current signals at the relay location are used in [7]–[10] to infer ORCB. The presence and magnitude of symmetrical components can be used to determine if the system is in balanced operation. In [11] and [12], the instant and duration of balanced/unbalanced operation of the system after fault inception are used to facilitate AST. The impedance trajectory of the sound/faulted phase(s) is used in [13]–[15] to provide AST. Generally speaking, algorithms based on fundamental-frequency phasors perform well so long as their overlaying assumptions hold. In general, these algorithms and their associated formulas are derived based on one or more of the following assumptions:

- Certain loading condition holds before fault inception.
- The ratio between the zero- and positive-sequence impedances of the system is constrained.
- Post-fault voltage and current signals show no sudden changes apart from those caused by the opening of CBs.
- Fault resistance is either negligible or quite large.
- Mode of opening of CBs, *i.e.*, three-pole and single-pole, is known to the relay a-priori.
- The meshed nature of the system can be disregarded.

The first three items might or might not apply depending on operating conditions and the chain of events the power system undergoes. Fault resistance is a random variable and can take any value and no certain rule applies to it. On the other hand, there is always possibility of incorrect identification of the fault type. Therefore, CBs cannot be guaranteed to always open single-pole for single-phase-to-ground (1-ph-g) faults even if they are enabled to do so. Power systems are meshed to a great extent especially at EHV and UHV levels, where they happen to be more in need of reliable AST due to stability concerns. Therefore, an impedance parallel to the protected line should be considered in developing accurate formulas for the problem.

In this paper, sequential tripping is accelerated by detecting internal faults on the line end-sections and canceling the intentional time delay of Zone 2 for them without using communication. The proposed method places no constraints on the operating point, system parameters or the magnitude of fault resistance. The method can easily be extended to cover all fault types and performs as expected irrespectively of ORCB being three- or single-pole. Two indices are proposed to detect ORCB. If either of these indices implies ORCB while the estimated fault distance lies within the protected line range, a trip command is issued. Accordingly, in the event of an internal fault on the end-sections of the protected line, the relay will open the corresponding CBs with no further time delay.

II. FAULT LOCATION BY DISTANCE RELAYS

In this section, the problem is modeled in sequence domain. Then, a formula is derived for accurate fault location using post-ORCB signals. Fig. 1(a) shows the single-line diagram of a two-source system under normal condition. In this figure, the Thevenin equivalent of the rest of the system from the transmission line viewpoint is deployed. Fig. 1(b) is the same system while a short-circuit fault is applied at distance α from terminal s of the line. The single-line diagram of the system after ORCB is shown in Fig. 1(c). In Figs 1(b) and 1(c), the Norton equivalent of the rest of the system from the transmission line viewpoint is used. Hereinafter, the faulted systems shown in Figs 1(b) and 1(c) are referred to as the pre-ORCB and post-ORCB faulted systems, respectively.

The superscript “*pre*” is used to denote the pre-fault signals, while the signals in the pre-ORCB faulted system are assigned no superscripts. The prime symbol on variables implies they are related to the post-ORCB system. The letter I is used for nodal injection currents and also the current flowing through the fault path, while the letter J represents branch currents.

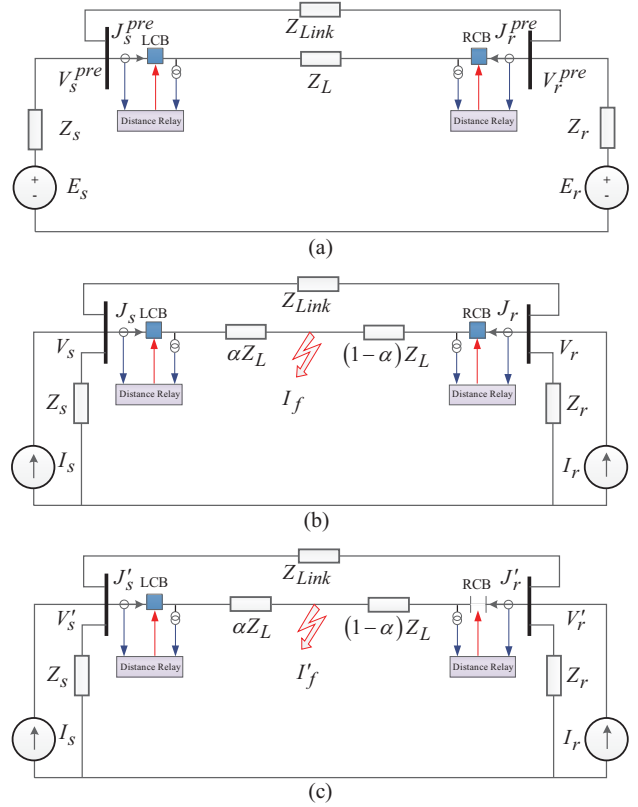


Fig. 1. Single-line diagram of a two-source test system (a) under normal condition, (b) during a fault and before the opening of the remote-end circuit breaker (ORCB), (c) during a fault and after ORCB.

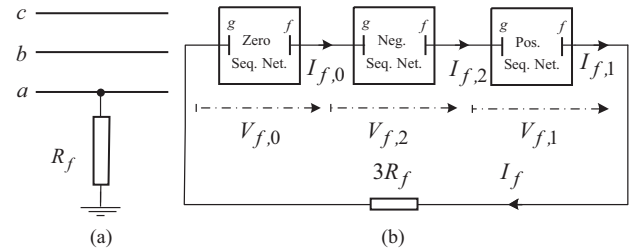


Fig. 2. (a) Basic model of a single-phase-to-ground (1-ph-g) fault. (b) Proper interconnection of the sequence networks for a 1-ph-g fault.

The letters E and V are used to represent voltage source magnitudes and node voltages, respectively.

Distance relays are normally set to clear faults on the first 80% and the remaining 20% of the line instantaneously and with some time delay, respectively. By using distance relays at line ends, simultaneous instantaneous protection from both line ends can be provided on around 60% of every line [17]. Faults on either of the two end-sections of a line are cleared instantaneously from only one side of the line and in Zone 2 operating time from the opposite side.

A. Modeling the Problem in Sequence Domain

The symmetrical components technique was proposed by Fortescue to ease the solution of asymmetrical three-phase networks by turning it into the solution of three decoupled

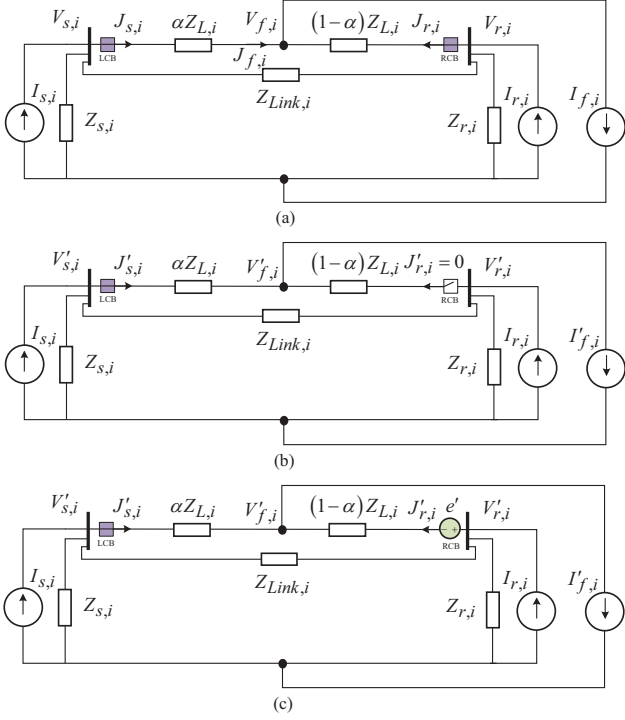


Fig. 3. Sequence network i under a short-circuit fault (a) before ORCB, (b) after three-pole ORCB, and (c) after single-pole ORCB.

symmetrical sequence networks [18]. To this end, the sequence networks and the fault resistance are interconnected with respect to the fault type. Fig. 2(a) shows the basic model of a 1-ph-g fault. The proper interconnection of the sequence networks for this fault is shown in Fig 2(b).

Based on the *Substitution Theorem*, every sequence network can be studied individually provided that the remaining sequence networks and the fault resistance have been replaced by a suitable current/voltage source. Therefore, the sequence network i shown in Fig. 3(a) can be attributed to any fault type, as long as the value of $I_{f,i}$ is set properly. Three-pole ORCB can be easily modeled by opening the line at the RCB location in all sequence networks, as shown in Fig. 3(b). On the other hand, Fig. 3(c) shows how single-pole ORCB can be modeled by inserting an unknown voltage source at the RCB location that is identical in all sequence networks.

The circuit of Fig. 3(c) is solvable in terms of the unknown variable e' . The value of this voltage source can be identified by forming an equation based on the fact that the current of the opened phase “a”, is zero. This means the associated circuit can be solved for bus voltages and line currents. The impedance $Z_{Link,i}$ is put in parallel with the protected line to account for the mesh nature of the transmission system. For simplicity and ease of analysis, the shunt admittance of the protected line is neglected. This introduces no significant adverse impact unless the protected line is excessively long.

B. Fault Location after Opening of the Remote-End CB

The relation between the fault distance and measured voltages and currents are derived here based on the assumptions

that the RCB opens on its three phases (three-pole opening). It is also explained why the obtained formulations remain still valid even with single-pole ORCB.

Three-pole opening of the RCB is represented by an open-circuit in all sequence networks as shown in Fig. 3(a). After three-pole ORCB, the receiving-end current of the protected line becomes zero. Applying KCL at the fault location in all the sequence networks before and after three-pole ORCB gives

$$\begin{cases} I_{f,i} = J_{s,i} + J_{r,i} & \forall i = 0, 1 \text{ or } 2 \\ I'_{f,i} = J'_{s,i} \end{cases} \quad (1)$$

ORCB might be single-pole under 1-ph-g faults. It can be shown that in such a condition, the fault current can still be obtained only by using the sending-end currents as follows

$$I'_{f,i} = \frac{J'_{s,0} + J'_{s,1} + J'_{s,2}}{3} \quad (2)$$

Voltages at the relay and the fault point in the sequence network i are related to each other as below

$$V'_{f,i} = V'_{s,i} - \alpha Z_{L,i} J'_{s,i} \quad (3)$$

With reference to Fig 2(b), it follows from (1) and (2) that after single- or three-pole ORCB under 1-ph-g faults

$$V'_{f,0} + V'_{f,1} + V'_{f,2} = (J'_{s,0} + J'_{s,1} + J'_{s,2})R_f \quad (4)$$

Accordingly, the sending-end voltage and current of the faulted line satisfy the equation below

$$\begin{aligned} (Z_{L,0}J'_{s,0} + Z_{L,1}J'_{s,1} + Z_{L,2}J'_{s,2})\alpha \\ + (J'_{s,0} + J'_{s,1} + J'_{s,2})R_f = V'_{s,0} + V'_{s,1} + V'_{s,2} \end{aligned} \quad (5)$$

C. Identifying the Fault Distance and Resistance

In distance relaying, we are mainly concerned about the fault distance and not fault resistance. For reasons which will be explained in this subsection, the magnitude of the fault resistance would be also obtained using the proposed method. Equation (5), which is based on post-ORCB signals, is used here to calculate both of these unknown variables. Equation (5) can be written in a compact form as

$$U\alpha + J'_{s,a}R_f = V'_{s,a} \quad (6)$$

where

$$U = Z_{L,0}J'_{s,0} + Z_{L,1}J'_{s,1} + Z_{L,2}J'_{s,2} \quad (7)$$

The voltages and current terms appearing in (6) are traditionally fed to distance relays as input. Provided that the line impedance is known, this complex equation in the two real unknowns α and R_f can be resolved into its real and imaginary parts. Accordingly, a system of real linear equations can be formed after ORCB with a general form of

$$\mathbf{H}\mathbf{x} \begin{bmatrix} \alpha \\ R_f \end{bmatrix} = \mathbf{y} \quad (8)$$

The only requirement for building (8) and solving it for its unknowns is to know the instant of ORCB.

III. PROPOSED DISTANCE RELAYING

The solution of (8) readily gives the fault distance on the faulted line for asymmetrical faults. The only problem is that this system of equations is based on variables taken after ORCB (post-ORCB ones). Hence, a prerequisite to forming (8) is to know the instant of ORCB. In practice, the relay is constantly fed with voltage and current signals measured at the sending-end of the protected line. This is the case regardless of whether the RCB has operated or not, yet. For real-time applications, an effective approach is needed to detect ORCB and enable forming a sound system of equations, and to solve that system for its unknowns. Here, two indices are proposed to detect ORCB with respect to its mode of opening, that is single- and three-pole.

A. Three-Pole Opening Index

After three-pole ORCB, all the fault currents pass through the sending-end side of the faulted line in every sequence network. It is possible to calculate the fault current using the sending-end voltage and current phasors at the relay location. Provided that the line is reciprocal and symmetrical, one can write

$$\begin{bmatrix} V'_{f,i} \\ I'_{f,i} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V'_{s,i} \\ J'_{s,i} \end{bmatrix} \quad (9)$$

where ABCD parameters can be approximately calculated for only 80% of the protected line length. The reason is because we do not know the exact fault distance yet and faults at beyond this point are of interest to our proposed relay.

The sequence networks are in series for 1-ph-g faults, which results in the same positive, negative and zero-sequence fault currents. If a fault occurs at 80% of the line, the symmetrical components of the fault current calculated from (9) will be all equal. Otherwise, for faults farther away from the relay, those symmetrical components will no longer be exact, but only close approximations of their true values. An index is defined below to reflect the similarity of the symmetrical components of the fault current as

$$K_{3pole} = \frac{\max(|J'_{f,0}|, |J'_{f,1}|, |J'_{f,2}|)}{\min(|J'_{f,0}|, |J'_{f,1}|, |J'_{f,2}|)} \quad (10)$$

As mentioned, ABCD parameters are calculated for a fault at 80% of the line length. Hence, we expect the magnitudes of the symmetrical components of the fault current to be almost, and not exactly, identical. Therefore, K_{3pole} is expected to be around unity for three-pole ORCB. In this paper, K_{3pole} being smaller than 1.03 is considered an indicator of three-pole ORCB.

B. Single-Pole Opening Index

Let us assume the following relation holds between fault currents before and after single-pole ORCB

$$I'_f = I_f + \Delta I \quad (11)$$

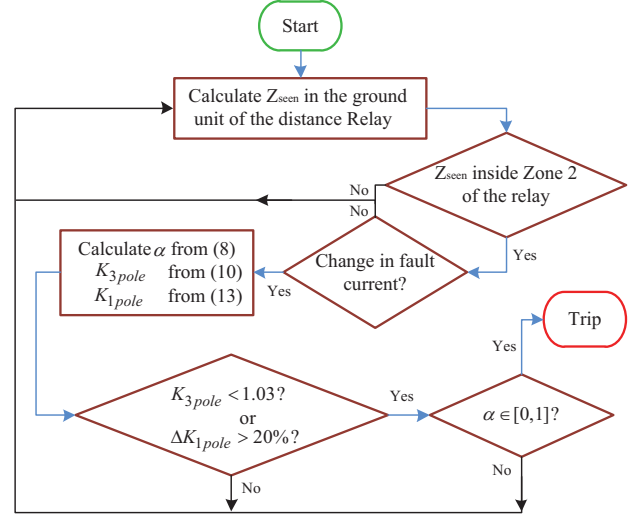


Fig. 4. Flowchart of the proposed distance relaying.

Let us also assume that the fault current is divided proportional to β_i and $1 - \beta_i$ between the left- and right-hand sides of the fault point, respectively. Let $Z_{loop,i}$ denote the impedance of the loop in the sequence network i through which the current produced by e' circulates. Before and after ORCB, the sending-end current of the sequence networks satisfy the following

$$\begin{cases} J_{s,i} = \beta_i I_f \\ J'_{s,i} = \beta_i I'_f + \frac{1}{Z_{loop,i}} e' \end{cases} \quad (12)$$

Since the zero-sequence impedance of a transmission line is normally much larger than its negative-sequence impedance, it is fair to assume $|Z_{loop,0}| > |Z_{loop,2}|$. Thus, the index of single-pole opening can be defined as below

$$K_{1pole} = \frac{|J'_{f,2}|}{|J'_{f,0}|} \quad (13)$$

If K_{1pole} sees a 20% increase over its initial value after the fault inception, single-pole ORCB is certified.

C. Flowchart of the Proposed Distance Relay

Fig. 4 shows the flowchart of the proposed distance relay. If the impedance seen by the relay lies within the Zone 2 reach of the conventional distance relay, the fault distance can be calculated for it using (8). This distance will pinpoint the true fault location only once the RCB has opened. Hence, upon any change in the fault current, the relay starts calculating the indices of three- and single-pole ORCB. If the so-obtained fault distance lies on the protected line (takes a value between zero and unity), and one of the two ORCB indices becomes high and remains so, a trip command is issued.

An important aspect of the proposed method is that the opening indices matter only if a change in the fault current is detected. Such a change can be due to ORCB or any other reasons [15]. In case an abrupt change is detected, and either of K_{3pole} or K_{1pole} indicates ORCB, the estimated fault distance

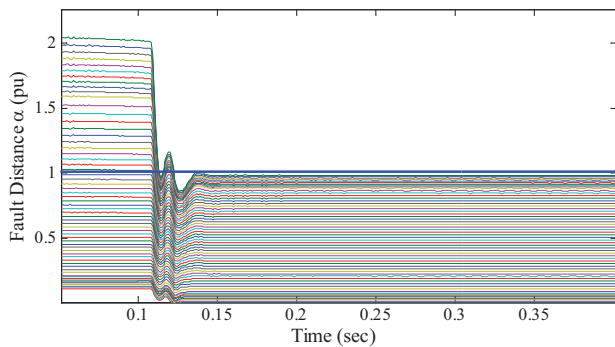


Fig. 5. Estimated fault distance for a 1-ph-g fault with 50Ω resistance at different locations of line 9-8, before and after single-pole ORCB.

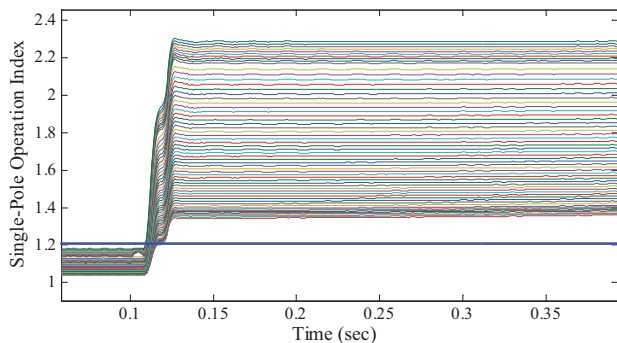


Fig. 6. Single-pole ORCB index for a 1-ph-g fault with 50Ω resistance at different locations of line 9-8.

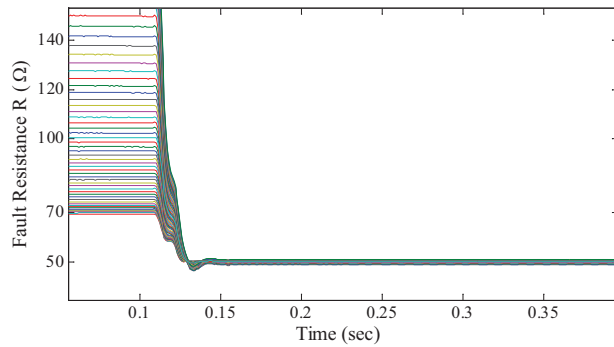


Fig. 7. Estimated fault resistance for a 1-ph-g fault with 50Ω resistance at different locations of line 9-8.

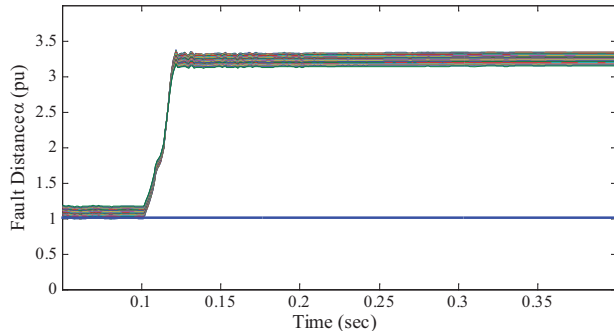


Fig. 8. Estimated fault distance by the relay at bus 9 for external 1-ph-g faults at different locations of line 8-7, before and after the opening of the associated CB.

using (8) is considered reliable. If this distance lies between 0 and 1, it follows that the fault is internal, and hence, the corresponding CB must open with no further delay.

IV. PERFORMANCE ANALYSIS

To evaluate the performance of the proposed relay, the New England 39-bus system modeled in DlgSILENT PowerFactory is selected as test system. This system consists of 34 transmission lines and 12 transformers. Generated waveforms are passed through a second-order Butterworth anti-aliasing filter with a cut-off frequency of 400 Hz. The filtered signals are sampled with a sampling rate of 1000 Hz, *i.e.*, 20 samples per cycle. Afterwards, the discrete Fourier transform (DFT) is applied to those signals to estimate their fundamental-frequency phasors.

As an example, a 1-ph-g fault with fault resistance of 50Ω is applied at 50 different distances on line 8-9. The fault is applied at $t = 0$ sec and the RCB is set to open 100 ms later. The estimated fault distance by the relay before and after single-pole ORCB is shown in Fig. 5. As can be seen, after around 25 ms following ORCB, the estimated fault distance converges to its true value. This time delay accounts for the phasor estimation time and the delay added by the anti-aliasing filter. The single-pole operating index increases more than 20% as shown in Fig. 6. Besides, it can be observed from Fig. 7 that the estimated fault resistance approaches its true value which is 50Ω .

It should be noted that the opposite end of the line (bus 8 side) is also equipped with a distance relay. This means for a large portion of the line length, faults are cleared sequentially from the opposite line ends. By conventional distance relaying, faults on nearly 40% of the line length are cleared in Zone 2 operating time, which is around 400 ms. But using the proposed method, these faults are readily cleared from both line ends after around 125 ms. Providing such AST highly decreases the average fault clearing time on the protected line.

An important aspect of any relaying algorithm is its security. The relay must not operate for faults out of its protection zone. This is guaranteed in the proposed method by checking the fault distance after ORCB is detected. For faults on the neighboring lines, even if the opening indices indicate ORCB, the fault distance would be out of the $[0, 1]$ range. Thus, the relay is not allowed to operate for external faults. This is shown in Fig. 8 for 1-ph-g faults at different locations of line 8-7. The fault distance estimated by the proposed relay at bus 9 moves away from the acceptable range upon opening of the CB of that line.

For a general evaluation of the proposed method, all 34 transmission lines of the 39-bus system are equipped with distance relays. On every transmission line, some 1-ph-g short-circuit faults with resistances of 0, 10, 25 and 50Ω are applied at 50 different spots. The time it takes from fault inception to fault clearance from both line ends are recorded. This whole process is carried out twice, one time for a system equipped

TABLE I
PERFORMANCE COMPARISON BETWEEN THE PROPOSED AND
CONVENTIONAL DISTANCE RELAYS

Average fault clearing time (ms)			IT (%)	GST (%)		AST (%)	
$R_f(\Omega)$	Conv.	Prop.	Both	Conv.	Prop.	Conv.	Prop.
0	154	68	64	34	5	2	31
10	160	77	61	36	6	3	33
25	164	82	59	37	7	4	34
50	167	84	57	37	7	5	36
All	162	78	61	36	6	3	34

IT: Instantaneous tripping from both line ends.
GST: Graded sequential tripping.
AST: Accelerated sequential tripping.

with only conventional distance relays and another time for a system with proposed distance relays. The average fault clearing time, and the range for which AST is provided are rounded to the nearest integer number and listed in Table I.

The extensive simulations conducted show that only for a limited number of cases, the conventional distance relay might operate faster than Zone 2 operating time after ORCB. However, AST is provided on more than 30% of the line length using the proposed method. For faults on the rest portions of the line, i.e., around 6% of the line length, the fault remains to be cleared in Zone 2 operating time. As shown in Table I, AST occurs for faults on approximately 4% of the line length using conventional distance relays. Assuming that the Zone 1 and 2 operating times are respectively 20 ms and 400 ms, the average fault clearing time is reduced to 78 ms by using the proposed method, while it is 162 ms by using conventional distance relays.

V. CONCLUSIONS

In this paper, a method for high-speed distance relaying of the entire length of transmission lines has been proposed. This is achieved by adding an accelerated sequential tripping (AST) logic to conventional distance relays to accelerate the relay decision time for faults on the end-sections of transmission lines. It is shown that the fault distance and resistance can be accurately obtained only using the measurements taken after the opening of the remote-end circuit breaker (ORCB). To provide a sufficient level of security, two indices are introduced to detect the instant of ORCB for both three-pole and single-pole CB opening modes. Contrary to existing AST methods, the proposed method does not place any constraints on the impedance of sources representing the rest of the system from the line viewpoint, or the parallel link between the two line-terminals. Therefore, the proposed method can be easily used to provide high-speed relaying in a wide variety of network conditions.

The proposed AST method is designed to expedite the relay operating time for faults near to the remote ends of the line. In such cases, CT saturations and CVT transients will not be a concern. The results of more than 10000 simulations show

that by using the proposed method, faults on more than 30% of the line will enjoy AST with no need of communication. Providing AST on this portion of the line halves the average relay operating time under 1-ph-g faults. The proposed AST method can be extended to cover other fault types, as well.

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