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

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***Abstract*—Short-circuit faults close to each end of a transmission line are normally cleared with some time delay by the distance relay at the opposite end of that line. To reduce this time delay, the pilot relaying schemes use communication links. This paper presents a non-communication method that provides high-speed distance relaying over the entire transmission line length. 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 inputs. 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 operation of the remote-end circuit breaker (ORCB). The results show that the use of post-ORCB signals would accurately yield the fault distance. Two indices for detecting three- and single-pole ORCB are proposed so as to fulfil the prerequisite for accurate fault distance estimation and generating a trip command, if needed. The proposed method is successfully validated by conducting more than 10000 simulation cases on the 39-bus test system using DIgSILENT PowerFactory.**

***Index Terms*—Accelerated sequential tripping, Distance relays, Discrete Fourier transform (DFT), Remote-end circuit breaker operation (ORCB).**

I. INTRODUCTION

The reach of distance relays is not definite due to several sources of uncertainties, such as inaccuracies in 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 an end-section. To clear faults on the end-sections of the line, an extended protection zone, i.e., Zone 2, is used. To coordinate distance relays on adjacent lines, Zone 2 is graded with an intentional time delay of approximately 400 ms. Accordingly, faults on either end of a transmission line are cleared instantaneously only from one end of the line and in Zone 2 time delay 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, potentially compromising 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) with less time delay [1]. As a result, faults on the end-sections are cleared with no intentional time delay from the local-end, and multiple cycles later from the remote-end of the line if signaling is successful. 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, non-communication AST methods attract more consideration than communication ones. Various non-communication AST methods have been proposed thus far [2-16]. Depending on whether the high-frequency components or fundamental-frequency components of fault signals are used, these methods can be divided into two groups. Despite providing acceptable performance, methods of the former group require special wideband measurement devices for extracting the transient characteristics of the fault signals [2-4]. The methods based on fundamental-frequency phasors are more practical for they only require signals that are normally fed to distance relays as inputs [5-15].

AST under end-section faults can be achieved by tracking the change that the currents of sound phases undergo after operation of the remote-end CB (ORCB) [5-6]. The variation of symmetrical components of 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 conclude whether the system is in balanced operation.

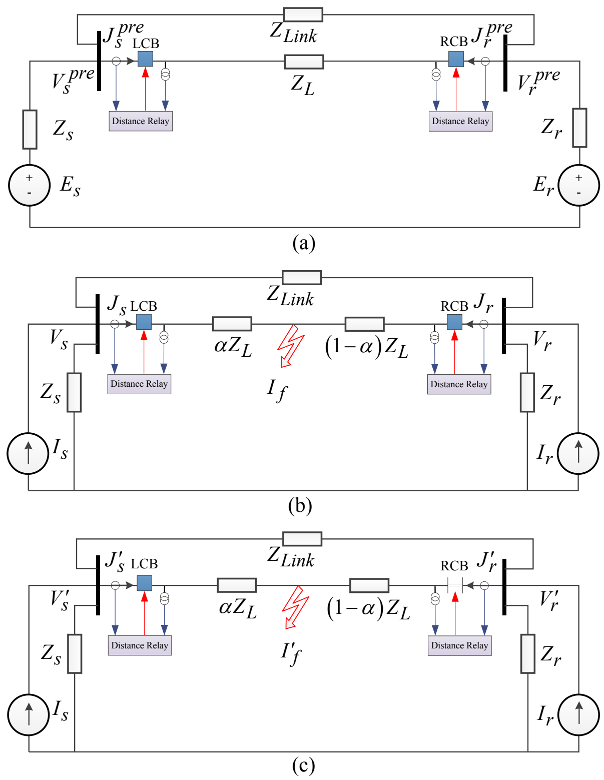

Fig. 1. Single-line diagram of a two-source test system (a) under normal condition (b) During a fault and before the operation of the remote-end circuit breaker (ORCB) (c) During a fault after ORCB.

In [11-12], the instant and duration of balanced/unbalanced operation of the system after fault inception are used to facilitate AST. Impedance trajectory of the sound or faulted phase(s) is used in [13-15] to provide AST.

The algorithms based on fundamental-frequency phasors perform well so long as their overlaying assumptions hold. 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 should contain no sudden changes apart from those caused by the operation of CBs in the system.
- Fault resistance is negligible or quite large.
- Mode of operation 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 networks 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 is needed to 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 annulling 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 cope with 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 length, a trip command is issued. Accordingly, in the event of internal faults on the end-sections of the protected line, the relay will open the associated CBs with no further time delay.

II. Accurate Fault Location by Distance Relays

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 used. Fig. 1(b) is the same system while a short-circuit fault is applied at distance α from terminal s on 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) and their respective signals are referred to as the pre-ORCB and post-ORCB faulty systems.

Distance relays are 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 both line ends, simultaneous instantaneous protection from both line ends can be provided on around 60% of the line length. Faults on either of the two end-sections are cleared instantaneously from only one side of the line and in Zone 2 time from the other side.

The superscript "pre" is used to denote the pre-fault signals, while the signals in the pre-ORCB faulty 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. The letters E and V are used to represent voltage source magnitudes and node voltages, respectively.

A. Modeling the Problem by Symmetrical Components

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 symmetrical sequence networks. 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 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 with 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 the single-pole ORCB can be modeled by 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 is 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 Operation of the Remote-End CB

Here, the relation between the fault distance and measured voltages and currents are derived based on the assumptions that the RCB opens on its three phases (three-pole operation). It is also explained why the obtained formulations remain valid after single-pole ORCB under 1-ph-g faults. Three-pole operation 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

$$\begin{cases} I_{f,i} = J_{s,i} + J_{r,i} \\ I'_{f,i} = J'_{s,i} \end{cases} \quad \forall\ 0 \le i \le 2 \tag{1}$$

ORCB might be single-pole under 1-ph-g faults. From Fig. 3(c), it follows that in such condition, the fault current can be still obtained from only sending-end currents as follows

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

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

$$V'_{f,i} = V'_{s,i} - \alpha Z_{L,i} I'_{s,i} \tag{3}$$

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

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

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

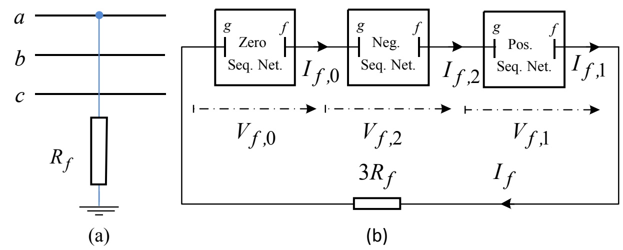

Fig. 2. (a) Basic model of a single-phase-to-ground (1-ph-g) fault, (b) Proper interconnection of the sequence networks for a 1-ph-g fault.

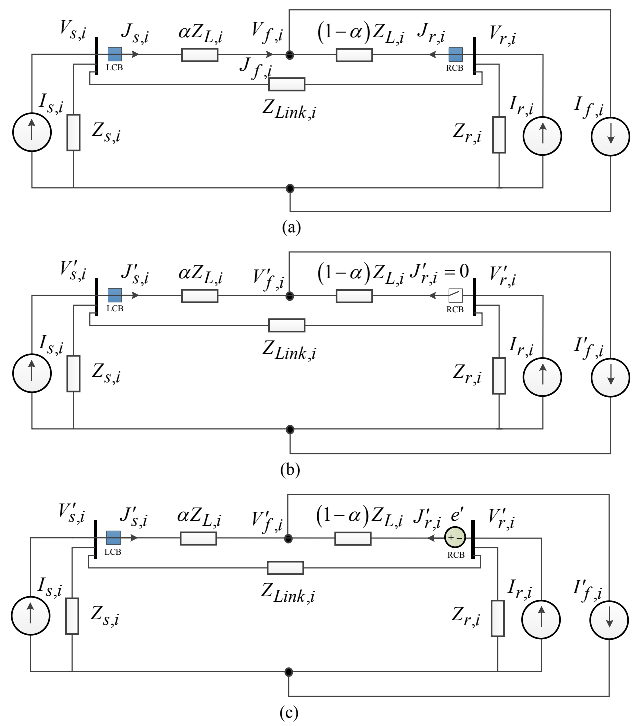

Fig. 3. Sequence network i under a short-circuit fault (a) Before ORCB, (b) After three-pole ORCB, and (c) After single-pole ORCB.

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

C. Obtaining 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 part, the magnitude of the fault resistance would be also obtained using the proposed method. Equation (5), which is built based on post-ORCB signals, is used here to calculate both of these unknown variables.

Equation (5) can be written in compact form as

$$U\alpha + R_f I_{s,a} = V_{s,a} \tag{6}$$

where

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

Voltages and currents appearing in (6) are conventionally 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 in α and R_f can be formed after ORCB with a general form of

$$\boldsymbol{Hx}\begin{bmatrix}\alpha \\ R_f\end{bmatrix} = \boldsymbol{y} \tag{8}$$

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

III. Proposed Distance Relaying

Solution of (8) readily gives the fault distance on the protected 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 no matter the RCB has operated or not yet. For real time applications, an 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 depending on its mode of operation.

A. Three-Pole Operation Index

After three-pole ORCB, all the fault currents pass through the sending-end side of the protected line in every sequence network. On the other hand, sequence networks are in series under 1-ph-g faults. It is possible to calculate the fault current using the sending-end voltage and currents at the relay location. Provided that the line is reciprocal and symmetrical, one can write

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

where ABCD parameters are obtained for 80% of the protected line length. The reason is because faults at that and farther locations are of major interest to our algorithm.

If the fault is located on 80% of the line, symmetrical currents are all identical. However, we are also interested in faults at locations of the line for which (9) is not exact, but only a good approximation. An index is defined to reflect similarity of symmetrical components of fault current as

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

As just mentioned, ABCD parameters are not built for the exact fault location, but for 80% of the line length. Hence, we expect magnitude of symmetrical components of current to be almost, and not exactly, identical. Therefore, K_{3pole} is expected to be around unity for three-pole ORCB. Practically speaking, K_{3pole} smaller than 1.03 can be considered to be an indicator of three-pole ORCB.

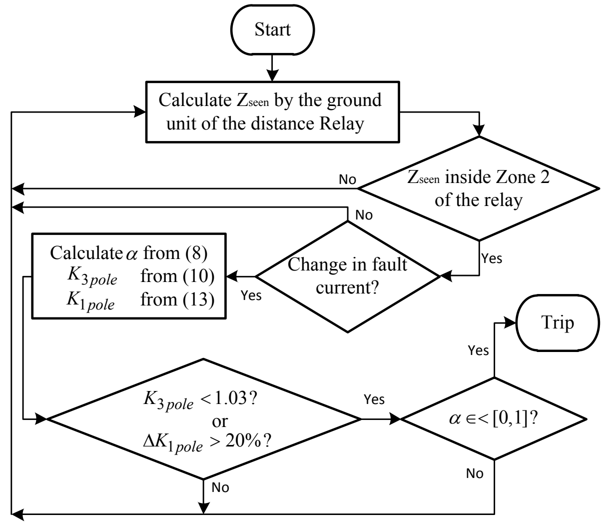

Fig. 4. Flowchart of the proposed distance relaying.

B. Single-Pole Operation Index

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

$$I'_f = I_f + \delta I \tag{11}$$

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

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

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

$$K_{1pole} = \frac{\left|J'_{f,2}\right|}{\left|J'_{f,0}\right|} \tag{13}$$

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

C. Flowchart of Proposed Distance Relaying

Fig. 4 shows the flowchart of the proposed distance relaying. If a fault is located inside Zone 2 of the conventional distance relay, the fault distance can be calculated for it using (10). This distance will be the true fault location only once the RCB has operated. Hence, upon any change in the fault current, indices of three- and single-pole ORCB are begun to be calculated. If the so-obtained fault distance lies on the protected line (takes a value between zero and unity), and one of these two ORCB indices becomes high and remains so, the trip command is issued.

An important aspect of the method is that the operation indices matters only if a change in the fault current is detected. Such a change can be due to the ORCB or any other reason [15]. In case an abrupt change is detected, and K_{3pole} or K_{1pole} constraint holds true, the estimated fault distance using (10) is considered reliable. Hence, if this distance is between 0 and 1, if follows that the fault is internal, and hence, the related CB must be opened with no further delay.

IV. Performance Analysis

To evaluate the performance of the proposed relaying method, the New England 39-bus system modeled in DIgSILENT PowerFactory is selected to be studied. 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 extract their fundamental-frequency components.

As an example, a 1-ph-g fault with fault resistance of 50 Ω is applied at 50 different distances on line 8-9. The fault is applied at t=0 s 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 from ORCB, the fault distance converges to its final value. This time includes the phasor estimation time and the delay added by the anti-aliasing filter. The single-pole operation 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 50 Ω.

It should be noted that the other 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 line ends. By conventional distance relaying, faults at nearly 30% of the line remote-end are cleared in Zone 2 time-delay, which is around 400 ms. But using the proposed method, these faults are readily cleared from both ends after around 125 ms. AST, therefore, 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 neighboring lines, even if the operation indices hold true, the fault distance would be out of [0,1] range. Thus, the relay is not allowed to mal-operate for irrelevant faults. This is shown in Fig. 8 under a 1-ph-g fault at different locations on line 8-7. The fault distance estimated by the proposed relay at bus 9 side of line 9-8 moves away from the acceptable range upon operation of CB of that line.

Here, all transmission lines in 39-bus system are equipped with distance relays. On every transmission line, 1-ph-g

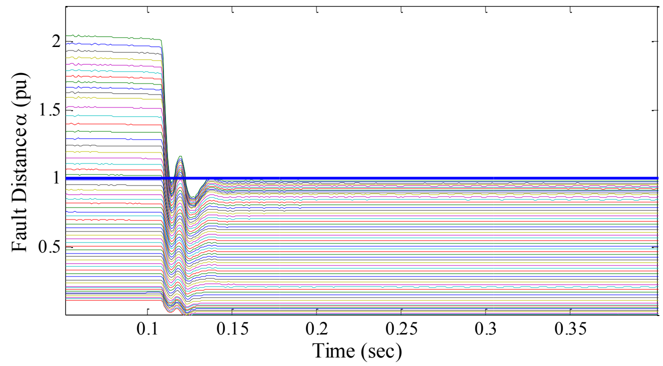

Fig. 5. Estimated fault distance for a 1-ph-g fault with 50 Ω resistance at different locations of the protected line 9-8, before and after single-pole ORCB.

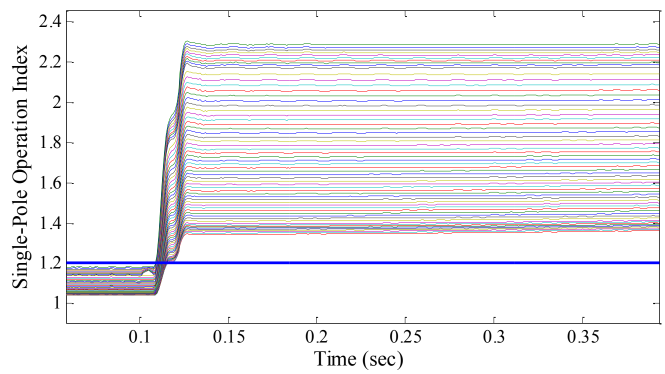

Fig. 6. Single-pole ORCB index, for a 1-ph-g fault with 50 Ω resistance at different locations of the protected line 9-8.

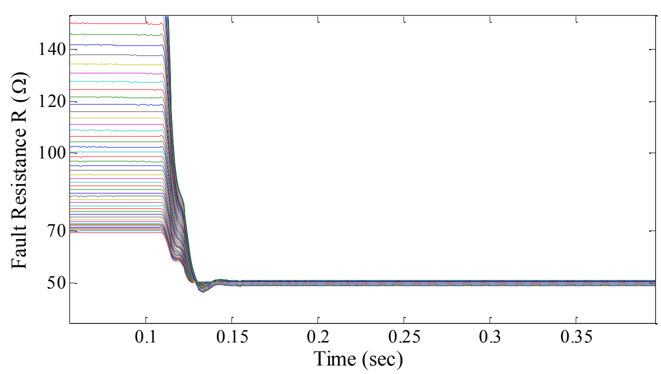

Fig. 7. Estimated fault resistance for a 1-ph-g fault with 50 Ω resistance at different locations of the protected line 9-8.

short-circuit faults with resistances of 0, 10, 25 and 50 Ω are applied at 50 points. The time it takes from fault inception to fault clearance from both ends are obtained. This is carried out once for a system equipped 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 operation time after ORCB. However, AST is provided on more than 30% of the line length using the proposed method. For faults on the rest

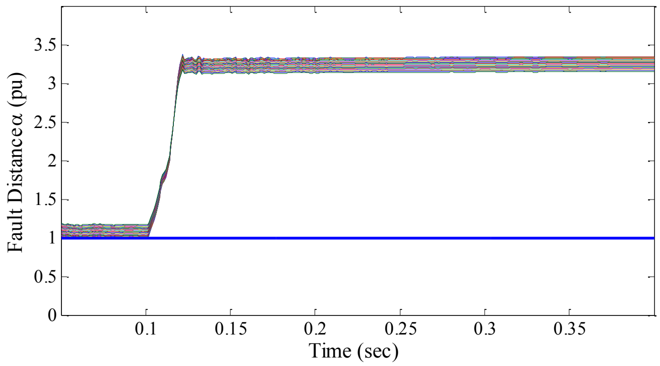

Fig. 8. Estimated fault distance for a 1-ph-g fault at different locations on line 8-7, before and after operation of the associated CB.

TABLE I COMPARISON OF THE PROPOSED AND CONVENTIONAL DISTANCE RELAYS

Average fault clearing time (ms)			Simultaneous tripping from both sides	Graded sequential tripping		Accelerated sequential tripping	
(Ω)	Conv.	Prop.	Conv.	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%

portions of the line, i.e., around 6% of the line length, the fault remains to be cleared in Zone 2 time-delay. As shown in the table, AST occurs for faults on approximately 4% of the line length using conventional distance relays. Compared to conventional distance relays, the proposed ones provide AST for faults occurring on a quite larger portion of transmission lines. Assuming Zone 1 and 2 time-delays are respectively 20 and 400 ms, the average fault clearing time is reduced to 79 ms using the proposed method, while it is 161 ms using conventional distance relays.

V. CONCLUSIONS

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

The proposed AST method needs to expedite the relay operation time for faults near to the remote ends of the line. In such cases, CT saturations and CVT transients are not deemed a real concern. Results of more than 10000 simulated case show that on average, faults on more than 30% of the line enjoy AST with no need for communication thanks to the proposed method. Overall, providing AST on this portion of the line halves the average relay operation time under 1-ph-g faults. Using the exact approach, the proposed AST method can be extended to cover other fault types, as well.

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