Article:

Azizi, S orcid.org/0000-0002-9274-1177, Sanaye-Pasand, M and Paolone, M (2019) A Modified Formula for Distance Relaying of Tapped Transmission Lines with Grounded Neutrals. IEEE Transactions on Power Delivery, 34 (2). pp. 690-699. ISSN 0885-8977

https://doi.org/10.1109/TPWRD.2018.2884939

A Modified Formula for Distance Relaying of Tapped Transmission Lines with Grounded Neutrals

Sadegh Azizi, *Member*, *IEEE*, Majid Sanaye-Pasand, *Senior Member*, *IEEE,* and Mario Paolone, *Senior Member*, *IEEE*

***Abstract*—Protection of tapped transmission lines with grounded neutrals has been always a challenging problem, usually resulting in compromise solutions. This type of lines may be protected by pilot relaying requiring dedicated and reliable telecommunication links. This paper proposes a modified distance formula for the protection of tapped lines with grounded neutrals against single-phase-to-ground (1-ph-g) faults. The proposed method uses only local measurements similar to conventional distance relays. Nonetheless, it facilitates fast fault clearing from both line-ends over a wider portion of the protected line length. Regardless of whether or not the tapping transformer is in service, the method performs desirably with no need for signaling. The proposed method is extensively tested on a large number of test-systems using the sinusoidal steady-state analysis. It is also implemented into the National Instrument Compact-RIO embedded hardware that has been suitably coupled with the RT-LAB real-time digital simulator by Opal-RT. This setup is used to conduct extensive hardware-in-the-loop (HIL) testing. The improved performance together with simplicity of the proposed distance relaying makes it an attractive option to include in numerical protective relays.**

***Index Terms*—Accelerated sequential tripping (AST), Distance relaying, Operating characteristic, Tapped transmission lines.**

I. Introduction

TRANSMISSION lines may be temporarily tapped in order to supply intermediate loads or to strengthen the underlying network at lower voltage levels [1]-[6]. Such a configuration is generally considered a temporary and inexpensive solution when installation of new substations and/or transmission lines is not economically justifiable [4]. In this context, protection of tapped lines is quite challenging and calls for compromises. It becomes even more complicated in case the line is tapped with a wye-delta transformer with a grounded neutral, i.e., where the star-point of the wye connection of the tapping transformer is grounded [4]-[6].

A theoretical approach for protection of tapped lines is to provide the relay with the Thevenin equivalent circuits of the system from all line terminals [7]. Due to daily/hourly changes in load/generation of the system, such data should be updated often enough to keep the relay performance reliable. The deployment of differential, distance pilot, or PMU-based relaying schemes for protection of tapped lines requires dedicated and highly reliable communication links between the line terminals [8]-[17]. Nonetheless, measurement infrastructure of the tapping branch is normally very poor, and hence, any protection algorithm based only upon local information would be the preferred solution [18]. Despite their merits, travelling-wave based relaying methods may not be applicable either, as they require special wideband measurement devices for extracting the transient features of the fault signals [18]-[21].

The zone settings of distance relays of tapped lines are commonly adjusted in a way that the relay operates securely, regardless of whether the tapping transformer is in service or not [6]. This makes the Zone 1 coverage less than desirable when the tap is in service [3]. The solution to this issue is to enlarge the Zone 1 intended reach or to manually increase the denominator of the distance formula, to compensate for the undesirable reduction of the zero-sequence current measured by the relay. Such approaches require a careful offline study, and moreover, they make the relay unacceptably overreach when the tap is out of service [6]. This means the relay might mal-operate for faults outside the protection zone.

This paper proposes a modified distance formula, which improves the performance of distance relaying on tapped lines. The proposed approach relies on the following observation. Provided that the star point of the tapping transformer wye connection is solidly grounded, the zero-sequence impedance of the tapping branch is much smaller than those of the two other sequences [4], [5]. Hence, the tapping branch shunts a big portion of the zero-sequence fault current [4]. For faults occurring after the tap point, the zero-sequence current measured by the relay does not represent the fault current through the whole path from the relay to the fault point. This makes the relay underreach, *i.e.,* calculate a larger impedance-to-the-fault than the true one [4].

In this work, the ratio of the negative- to zero-sequence currents is used to modify the 1-ph-g distance formula. An appropriate supervision signal is also adopted to confine the amendment only to the distance element of the ongoing fault type. One main advantage of the proposed relaying is that it merely requires locally measured phasors. Moreover, the proposed method performs desirably irrespective of whether the tapping transformer is in or out of service.

Sadegh Azizi and Majid Sanaye-Pasand are with the School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran 14395-515 Iran (e-mail: sadegh.azizi@ut.ac.ir; msanaye@ut.ac.ir).

Mario Paolone is with the Distributed Electrical Systems Laboratory (DESL), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015, Switzerland (e-mail: mario.paolone@epfl.ch).

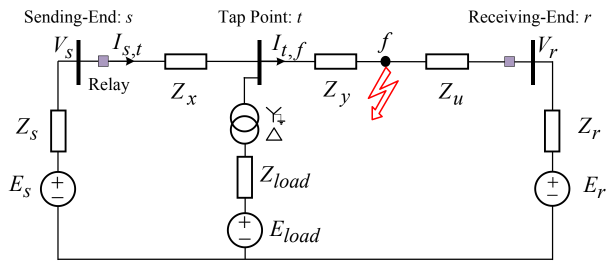

Fig. 1. Single line diagram of a short-circuit fault on a tapped line.

Beside sinusoidal steady-state analysis, the proposed distance relaying is implemented into the National Instrument Compact-RIO embedded hardware in order to show its deployability. The RT-LAB platform by Opal-RT is used as the real-time digital simulator to create a proper test setup for hardware-in-the-loop (HIL) testing of the designed relay. The obtained results confirm the superiority of the proposed distance formula over the one commonly used in conventional distance relays.

The rest of this paper is organized as follows. Section II discusses distance relaying and its underreaching on tapped transmission lines. Section III sets forth the proposed method and discusses its validity before/after opening of the remote-end CB (ORCB). Performance evaluation is carried out in section IV. Finally, Section V concludes the paper.

II. Background and Problem Definition

In the next two sub-sections, graded distance relaying, the relevant terminologies, and underreaching of distance relays on tapped transmission lines are discussed.

A. Graded Distance Relaying

The reach of distance relays is not definite due to several sources of uncertainties such as inaccuracy of instrument transformers and the unknown value of fault resistance [3]. Zone 1 of a distance relay is usually set in a way that it operates instantaneously for faults within the first 80%-90% of the protected line [4]. Faults on the end-section of the protected line are cleared after a certain delay imposed by the Zone 2 settings, *e.g.*, 300 ms. This results in non-simultaneous tripping of the circuit breakers (CBs) at the opposite line ends, which is known as sequential tripping[1] [4].

In the case of sequential tripping, the fault remains supplied from one side of the line for more than Zone 2 time delay considering the CB operating time. System stability and fast auto-reclosing considerations inspire to send, along with the trip signal to the local CBs, a transfer trip signal to the remote-end relay [4]. This is to, directly or with some supervision, have the remote CBs open with no more time delay. Thus, faults on the end-sections are cleared with no intentional time delay from the local end, and several cycles later from the remote end. This accelerated sequential tripping (AST) is not considered instantaneous due to communication latencies, although it falls under the fast fault clearing category.

[1] We define the sequential tripping of a line as the process corresponding to this sequence of events: the CB at one side of the line opens instantaneously but the CB at the other side of the line opens with some time delay as the relay at that side has not seen the fault inside its instantaneous protection characteristic.

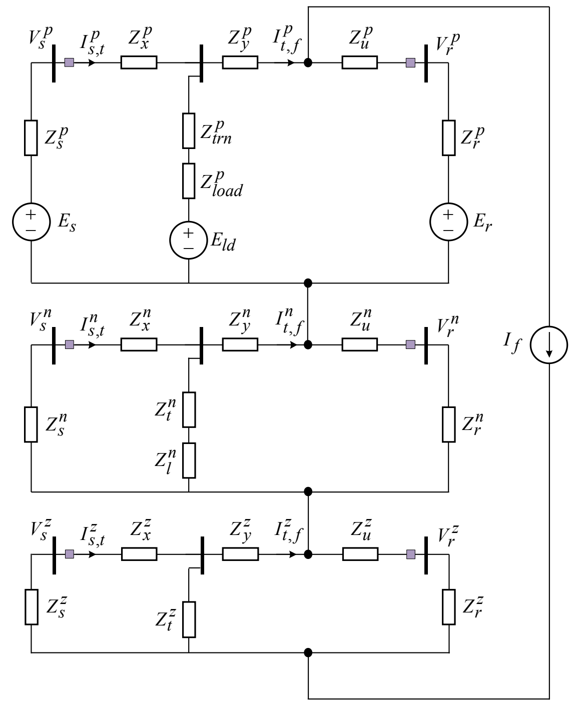

Fig. 2. Interconnection of sequence circuits for a 1-ph-g fault.

B. Underreaching of Distance Relays of Tapped Lines

Fig. 1 shows a short-circuit fault on the tapped line *s*-*r* with length *L*. The tapping transformer is placed at the distance *mL* from terminal *s*. Fault is assumed to occur at the distance *αL* from terminal *s* so that *m*<*α*. To analyze a 1-ph-g fault at this location by using the method of symmetrical components, the three sequence circuits should be interconnected as shown in Fig. 2. Neglecting the fault resistance, the impedance-to-the-fault is calculated to be

$$\alpha Z_L = \frac{V_s^A}{I_{s,t}^A + kI_{s,t}^z} + \frac{\left(I_{s,t}^A - I_{t,f}^A\right) + \left(I_{s,t}^z - I_{t,f}^z\right)}{I_{s,t}^A + kI_{s,t}^z}(\alpha - m) Z_L \qquad (1)$$

where the superscripts *A* and *z* denote phase-*A* and zero-sequence quantities, respectively. Conventional distance relays use the simplified formula below to obtain the impedance-to-the-fault:

$$Z_{seen} = \frac{V_s^A}{I_{s,t}^A + kI_{s,t}^z} \qquad (2)$$

As can be seen, (1) and (2) are not exactly the same. This introduces an error between the true impedance-to-the-fault and what the distance relay measures. It can be shown that the impedance measured by the relay has a larger absolute value than the true impedance-to-the-fault. Thus, distance relays of tapped lines tend to underreach under 1-ph-g faults [4]-[6].

III. Proposed Formula for Use in Distance Relays

In this section, firstly, a new formula is proposed for use in distance protection of tapped lines. This formula performs desirably irrespective of whether or not the tapping transformer is in service. Then, the validity of the proposed formula before and after ORCB is fully discussed. To this end, the power grid is assumed to be composed of linear elements and be operating in sinusoidal equilibrium in pre- and post-fault conditions. Similar to conventional distance relays, it is assumed that line parameters are known to the relay, and the voltage and current signals of the sending-end of the line are fed to the relay as inputs.

A. Key Idea to Resolve Relay Underreaching

A trivial solution to the underreaching problem just described is to multiply the residual current compensating factor k in (2) by a constant coefficient η as:

$$Z_{\text{seen}} = \frac{V_{\text{relay}}^{A}}{I_{\text{relay}}^{A} + k\eta I_{\text{relay}}^{z}} \tag{3}$$

The coefficient η (>1) should be set so as to compensate the overestimation of the fault distance at the reach point of Zone 1. However, such a solution has a major drawback. The relay will overreach if the tapping transformer is disconnected, and thus, this technique might result in undesirable tripping for faults outside the protected zone [4], [6].

When the neutral of the tapping transformer is solidly grounded, the zero-sequence impedance of the tapping branch becomes considerably smaller than its counterparts in the two other sequence circuits [4]. In such a case, the tapping branch shunts a bigger portion of the fault current in the zero-sequence than in the negative- and positive-sequence circuits. The negative-sequence current remains almost identical on both sides of the tap point, contrary to the zero-sequence current.

The above reasoning leads us to the idea of using the ratio of the negative- to zero-sequence currents in order to adjust η, both before and after ORCB. In this way, the denominator of modified distance formula (3) for 1-ph-g faults will be increased when the tapping transformer is in service. On the other hand, this adaptation is reduced/neutralized once the tapping transformer is not in service. Such self-adjustability lends itself very well to the protection of tapped transmission lines.

A tricky problem here is to find a suitable function for η. It has been observed in this research work that a power function of the ratio between the negative-sequence and zero-sequence currents with a less-than-unity exponent, would result in quite desirable outcomes. Mathematically speaking,

$$\eta = \left(\left| I_{\text{relay}}^{n} \middle/ I_{\text{relay}}^{z} \right| \right)^{\zeta} \tag{4}$$

The setting procedure of the exponent ζ will be discussed later in this section. It is most desirable if η takes a value around unity for faults beyond the tap point once the tapping transformer is out of service. This makes the impedance-to-the-fault obtained by (3) matching the one obtained by the conventional formula to a great extent. In practice, this might not be the case, and hence, special care should be taken not to let the instantaneous reach of the relay increases by more than a certain percentage under any circumstance. This can be achieved by setting an upper limit for the exponent ζ.

For instance, let us assume that the ratio between negative- and zero-sequence currents will rise up to the value of 5 in quite extreme conditions. It is also assumed that the reach of Zone 1 is set to 80% of the line length and the residual current compensating factor k is 2. The tapping branch impedance is provided in Appendix. In this example, limiting ζ to 0.2 guarantees that the instantaneous reach of the relay will not exceed 86% of the line length even under these extreme conditions. As mentioned earlier, an instantaneous reach of 80%-90% by Zone 1 is considered quite acceptable [3-5]. It should be noted that the overreaching amount is also affected by the relative zero-sequence impedance of the tapping branch to the transmission line zero-sequence impedance. Therefore, if the tapping transformer is a relatively strong sequence source, there will be more contribution for 1-ph-g faults from the tapping branch, which may overcompensate the underreaching of the relay. The setting procedure that will be presented later in the paper is aimed at dealing with such types of problems.

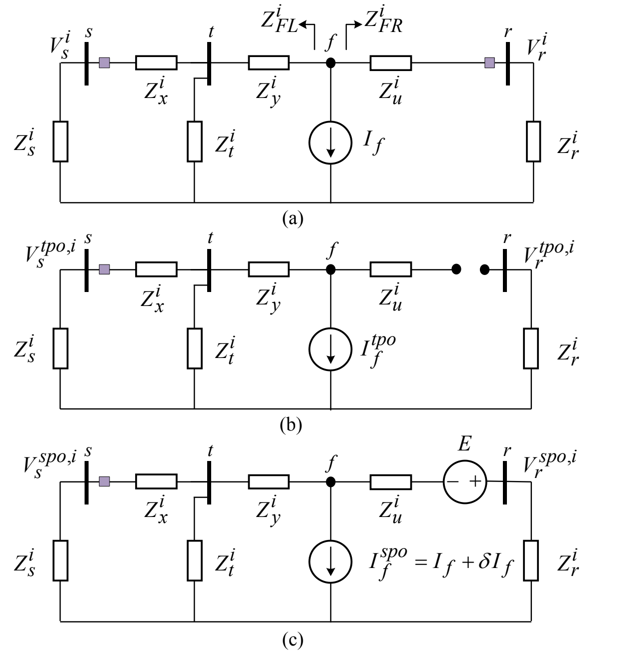

Fig. 3. Individual analysis of sequence circuit i (a) before ORCB, (b) after three-pole ORCB and (c) after single-pole ORCB.

B. Equivalent Faulted Circuit before and after ORCB

In view of the working hypothesis and thanks to the *Substitution Theorem* [22], it is possible to replace the fault resistance and two other sequence circuits by a suitable current source as shown in Fig. 3. This enables the individual analysis of each sequence circuit [23], [24]. Figs 3(a), 3(b) and 3(c) show sequence circuit i prior to ORCB, after three-pole

ORCB, and after single-pole ORCB, respectively. The circuits of Fig. 3 involve no receiving- or sending-end voltage source as they are intended for the individual analysis of negative- and zero-sequence circuits.

The currents passing through the fault resistance during the fault and after three-pole and single-pole ORCB are denoted by I_f, I_f^{tpo} and I_f^{spo}, respectively. Terminals in the simplified circuits of Fig. 3 are labeled '*s*', '*t*', '*f*' and '*r*' from left to right. No particular superscript is used to denote fault signals before ORCB. The superscript '*pre*', '*tpo*' and '*spo*' refer to signals before the fault, and fault signals after three-pole and single-pole ORCB, respectively. The superscript *i* takes a value of *p*, *n* or *z* and refers to the positive-, negative- and zero-sequence circuits, respectively.

From Fig. 3(a), current at the relay location in the sequence circuit *i* can be obtained by applying the current division rule. Let us denote the ratio between the equivalent impedances of the left- and right-hand sides of the fault point *f* by β^i as below

$$\beta^i = \frac{Z_{FL}^i}{Z_{FR}^i} \tag{5}$$

The ratio of the current at the relay to that of the branch between the fault and tap point is denoted by ρ^i as below

$$\rho^i = \frac{Z_t^i}{Z_s^i + Z_x^i + Z_t^i} \tag{6}$$

The fault current at the relay location can be calculated from

$$I_{relay}^i = I_{s,t}^i = \rho^i \frac{1}{\beta^i + 1} I_f \tag{7}$$

Once the tap is in service, the first factor on the right-hand side of (7), that is ρ^i, is larger in the negative-sequence circuit than in the zero-sequence circuit.

After three-pole ORCB, the fault current will be supplied from only the left-hand side of each sequence circuit. In this case, the sending-end current of the faulted line in the sequence circuit *i* can be obtained from

$$I_{s,t}^{tpo} = \rho^i I_f^{tpo} \tag{8}$$

It follows from (8) that subsequent to three-pole ORCB, the current at the relay is a certain fraction of the fault current, irrespective of the exact fault location. This is the case once the tap is in service. This holds for any 1-ph-g fault at beyond the tap point. The fractional factor ρ^i on the right-hand side of (8) is greater in the negative-sequence than that in the zero-sequence circuits. It follows that the negative-sequence current at the relay is always greater than the zero-sequence current at that location,

In Fig. 3(c), the voltage source *E* is used to model the single-phase operated CB at the remote-end of the line. Let us define δI_f as the difference between I_f^{spo} and I_f. Subtracting the nodal equations of the circuit in Fig 3(a) from their corresponding nodal equations of the circuit in Fig. 3(c)

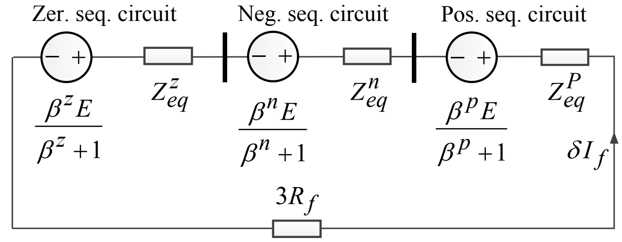

Fig. 4. Equivalent superimposed circuit accounting for changes in voltage and current signals after single-pole ORCB.

produces some superimposed nodal equations that can be attributed to a virtual circuit, called the superimposed circuit. This superimposed circuit is identical with the circuit of Fig. 3(c), except for the fact that the amount of its current source is changed to δI_f. If the δ sign is used to refer to the voltage and current phasors in the superimposed circuit *i*, one can obtain

$$\begin{cases} \delta I_{t,f}^i = \dfrac{1}{\beta^i + 1} \delta I_f + \dfrac{E}{Z_{loop}^i} \\ \delta I_{r,f}^i = \dfrac{\beta^i}{\beta^i + 1} \delta I_f - \dfrac{E}{Z_{loop}^i} \end{cases} \tag{9}$$

where Z_{loop}^i is the sum of Z_{RF}^i and Z_{LF}^i.

Superimposed voltages and currents in different sequence circuits all result from single-pole ORCB, which is modeled by the voltage sources *E*. The residual current source δI_f represents the connection of the remaining sequence circuits in series with the fault resistance. The series connection of the superimposed sequence circuits in loop with the fault resistance is simplified in Fig. 4. The equivalent voltage source in this circuit is obtained from

$$E_{eq} = \sum_{\forall i} \frac{\beta^i}{\beta^i + 1} E = KE \tag{10}$$

If Z_{eq}^i is the equivalent impedance of the parallel combination of Z_{RF}^i and Z_{LF}^i, the superimposed current δI_f can be calculated as below

$$\delta I_f = \frac{-E_{eq}}{\sum_{\forall i} Z_{eq}^i + 3R_f} = \frac{-K}{\sum_{\forall i} Z_{eq}^i + 3R_f} E = -cE \tag{11}$$

Single-pole ORCB makes the sum of three sequence currents passing through the remote-end CB drop to zero. Neglecting the pre-fault current, it follows that

$$\sum_{\forall i} I_{r,f}^{spo,i} = \overbrace{\sum_{\forall i} \frac{\beta^i}{\beta^i + 1}}^{K} I_f^{spo} - \sum_{\forall i} \frac{E}{Z_{loop}^i} = 0 \tag{12}$$

Given $I_f^{spo} = I_f + \delta I_f$, *E* is obtained from (11) and (12) as

$$E = \frac{K}{Kc + \sum_{\forall i} \frac{1}{Z_{loop}^i}} I_f \tag{13}$$

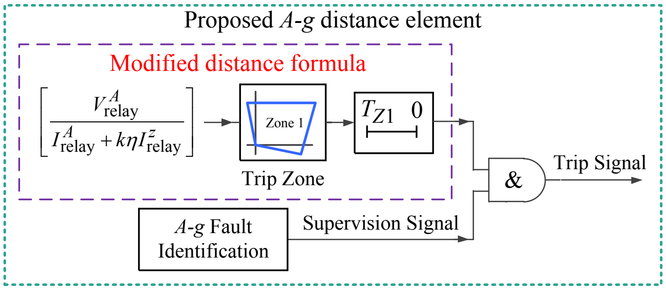

Fig. 5. Logic diagram of Zone 1 of the implemented distance relay.

With reference to (11), (13) and Fig. 3(c), the fault current at the relay location after single-pole ORCB is obtained from

$$I_{s,t}^{spo,i} = h\rho^{i}\left[\frac{1}{\beta^{i}+1}+\frac{h'}{Z_{loop}^{i}}\right]I_{f} \quad (14)$$

where h and h', being identical in all sequence circuits, are

$$h = \frac{\sum_{\forall i}\frac{1}{Z_{loop}^{i}}}{\sum_{\forall i}\frac{1}{Z_{loop}^{i}}+Kc}, \qquad h' = \frac{K}{\sum_{\forall i}\frac{1}{Z_{loop}^{i}}} \quad (15)$$

After single-pole ORCB, the negative-sequence and zero-sequence fault currents at the relay location can be obtained from (14).

C. Logic Diagram and Setting Procedure of the Proposed Distance Relay

In this part, firstly the logic diagram of the proposed distance relay is explained. Next, the procedure that has to be followed to properly set the relay is put forward.

1) Logic diagram: The logic diagram of Zone 1 of the *A-g* element of the proposed distance relay is shown in Fig. 5. The *B-g* and *C-g* elements of the relay have analogous structures. The only difference is that the "Fault Type Identification" block, and variables involved in the distance formula should change with respect to the faulted phase. For other protection zones, the operating characteristic inside the associated "Trip Zone" block has to be updated appropriately.

The proposed distance relay is essentially designed to overcome overreaching of conventional distance relays under 1-ph-g faults, only. To prevent *A*-g, *B-g* and *C-g* distance elements from responding to other fault types, a supervision logic is embedded into the logic diagram of the proposed relay as shown in Fig. 5. The addition of the supervision logic may prolong the relay decision time by several milliseconds. For this reason, the output of the conventional ground element may be merged with that of the proposed ground element through an "OR" gate. In this way, the proposed distance relay is guaranteed to respond to 1-ph-g faults inside its operating zone, under no circumstances, later than a conventional distance relay.

2) Setting procedure: This part is aimed at presenting a setting procedure to be followed in case the proposed relay is used for protection of tapped transmission lines. This procedure is pursued for setting the relays used in the performance evaluation section of the paper.

The values of source impedances are not constant and may vary within a wide range in various operating conditions. Besides, transmission angle, which is the difference between the phase-angles of the sending- and receiving-end sources would change depending on the loading of the tapped line. The forgoing factors will result in a variation range for the ratio of negative- to zero-sequence currents, which is of concern to the proposed relay. Therefore, it is required to set the proposed relay in a way that it performs acceptably under those possible conditions, without compromising security of the protection scheme.

In this paper, transmission angle is denoted by δ and is considered to vary between -30° to 30°. The procedure for setting the proposed relay can be described as below:

i. A solid 1-ph-g fault is simulated at 80% of the tapped line in condition where the ratio between negative- and zero-sequence currents at the relay lies in the middle of the corresponding variation range. A value of exponent ζ is sought that makes the impedance seen by the relay equal to $0.8\,Z_L^p$. This value is referred to as ζ_{tap_in}. It is also checked to ensure that with ζ_{tap_in}, the instantaneous reach does not exceed 0.85% of the line length once the ratio between negative- to zero-sequence currents is maximum.

ii. A 1-ph-g fault is simulated at the beginning of next neighboring lines with a reasonably large fault resistance, say 20 Ω. The maximum value of the exponent ζ is sought that does not make this fault be cleared instantaneously, thereby preserving security. This exponent value is called $\zeta_{security}$.

iii. A number of solid 1-ph-g fault are simulated at 85% of the tapped line once the tap is out of service. The maximum value of ζ is sought that will not result in instantaneous operation of the relay in none of the simulated cases. This value is referred to as ζ_{tap_out}.

iv. The exponent ζ in (4) is set to the minimum of ζ_{tap_in}, $\zeta_{security}$ and ζ_{tap_out}.

Setting the relays as described above can increase the instantaneous reach of the relay. The relay is also guaranteed not to maloperate for external 1-ph-g faults with reasonably high resistances. Besides, the instantaneous reach of the relay for solid 1-ph-g faults will not exceed 85% of the line length in any operating conditions. It should be noted that the setting procedure for lines with more than one tap remains the same as the procedure described above.

IV. Performance Assessment

The performance of the proposed method is evaluated in this section. This is firstly carried out by using an extensive number of steady-state simulations. To validate the proposed method in more realistic conditions and to show its deployability on existing hardware platforms, the proposed method is implemented into an industrial-grade microcontroller. This device is then suitably coupled with a real-time power grid simulator in an HIL testing setup.

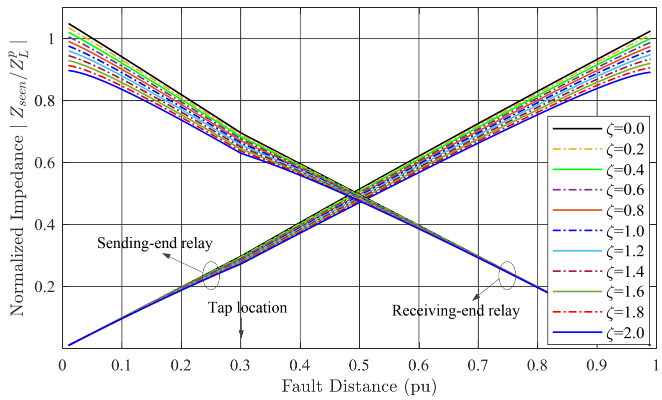

Fig. 6. Impedance seen from both line ends using the proposed formula, once the tapping transformer is in service.

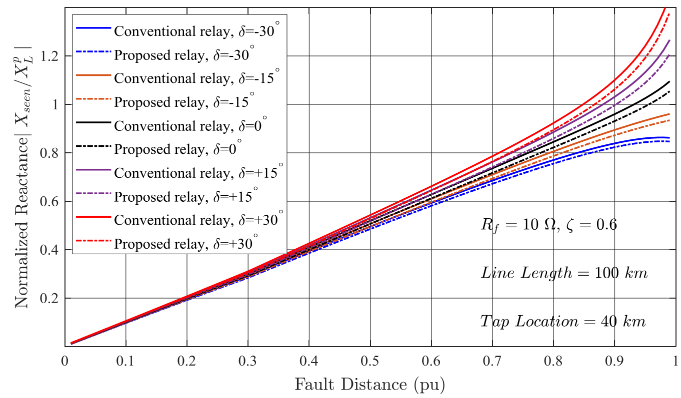

Fig. 8. Reactance seen by the proposed distance formula, once the tapping transformer is in service.

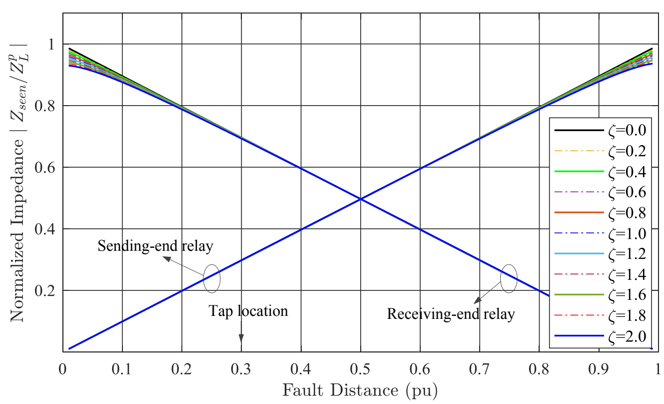

Fig. 7. Impedance seen from both line ends using the proposed formula once the tapping transformer is out of service.

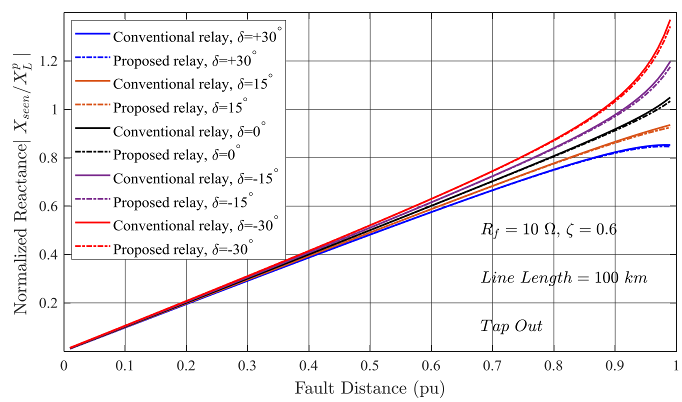

Fig. 9. Reactance seen by the proposed distance formula, once the tapping transformer is out of service.

The operating characteristics of protection zones of distance relays used for simulation studies are provided in Appendix. To ensure apparent impedance is located inside the tripping zone, a time delay of 5 ms is considered. This is to increase the relay security against noise and transient components of input signals. Furthermore, the intentional time-delays of the distance relay for faults inside Zone 1, Zone 2 and Zone 3 are set to zero, 300 ms and 600 ms, respectively. The time between issuing a trip command and the opening of the associated CB is considered to be 30 ms.

A. Sinusoidal Steady-State Analysis

In view of the working hypothesis introduced earlier, the sinusoidal steady-state response can be obtained most efficiently by the phasor method [22]. This facilitates the evaluation of the proposed method performance using an extensive number of test cases; some merit that is practically beyond the capability of time-domain simulation studies.

1) Sensitivity of the proposed method to different factors: Let us consider a 100 km transmission line tapped by a solidly grounded transformer at distance 30 km on the line. The source impedance ratio at the two line-ends is considered to be 0.2. A number of solid 1-ph-g faults are simulated at different locations of this transmission line. Figs 6 and 7 show the impedance seen by the relay at each line ends, once the tapping transformer is in and out of service, respectively. It is worth noting that in these figures, ζ=0 corresponds to impedance seen by the conventional distance formula. It can be observed that when the tapping transformer is out of service, the estimated fault distance by the proposed and conventional formulas become closer. The increase of the instantaneous fault clearing range for different values of ζ can be easily seen from Fig. 6. The setting procedure proposed in Section III enables setting ζ in a way that the security of distance relaying is not degraded, either.

To study the effect of fault resistance on the proposed formula, a number of 1-ph-g faults are applied at different locations of the protected line. The transmission angle is set to -30, -15, 0, 15 and 30 degrees and the exponent ζ is set to be 0.6. The obtained results are shown in Figs. 8 and 9. It can be seen that the fault resistance makes the relay overreach/underreach depending on the transmission angle. This behavior is quite similar to that of the conventional distance relay. The larger the fault resistance, the larger the difference of the true fault distance with what the relay estimates. It can be seen from Fig. 9 that the response of proposed and conventional relays become closer when the tapping transformer is not in service.

As pointed out in the third item of the setting procedure, the exponent ζ should be constrained to prevent the relay from maloperation in case of external faults. Fig. 10 shows the maximum allowable exponent meeting this requirement for different fault resistances and transmission angles. It can be

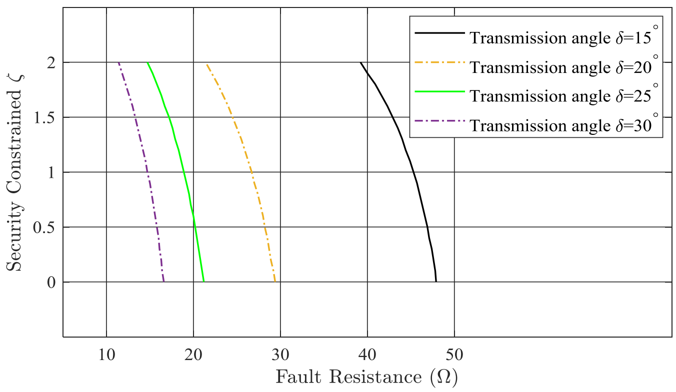

Fig. 10. Security constrained ζ to avoid instantaneous operation for external 1-ph-g faults.

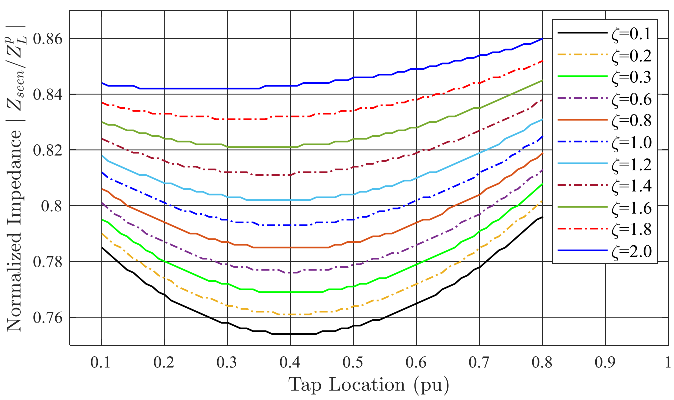

Fig. 11. Impedance seen by the relay for different tap locations.

observed from this figure that the larger the exponent, the more likely that the relay maloperates for the same fault resistances. It can also be concluded that ζ should be set to lower values if the transmission angle varies within a wider range. Conversely, if the transmission angle does not exceed a certain value, say 10° for instance, the probability of relay's maloperation for external faults falls down to negligible levels.

The studies carried out in the foregoing parts have all been devoted to a tapped transmission line, with tap location fixed at 30% of the line length. Here, the effect of varying tap location along the line is investigated. Fig. 11 demonstrates the impedance seen by the relay for different exponents and locations of the tapping transformer along the line. As can be seen, for the same ζs, the instantaneous reach of the relay further decreases as the tap is moved closer to the middle of the line. This means the farther the tap is placed from either of the line-ends, the more effective becomes the compensating factor η in modified distance formula (3). In practice, it is usually less likely to use a tap near the line ends.

2) General evaluation of the proposed method: For general evaluation of the proposed method, 10000 different test systems are randomly created here for any certain tap point, as detailed in Appendix. This enables examining the relay under a large number of system conditions, as is the case in practice.

With a reasonable variation range for fault resistance, four different modes of fault clearing can be distinguished regarding 1-ph-g faults on the protected line. The first mode is instantaneous tripping (IT) of the line from its both ends. This mode essentially occurs when distance relays at the two line-ends see the fault inside their Zone 1 operating characteristics. For faults on the line end-section, the remote relay sees the fault inside its Zone 1, whereas the local relay may see the fault inside its Zone 2. After ORCB, the impedance seen by the local relay would vary. If this new impedance moves inside Zone 1 of the relay, accelerated sequential tripping (AST) will be the fault clearing mode. Nonetheless, the impedance seen by the local relay may still reside in Zone 2, following the ORCB. This will result in normal sequential tripping (NST), i.e., Zone 1 tripping of the remote end of the line and Zone 2 tripping of its local end. If the fault resistance is sufficiently large, both relays will see the fault inside their Zone 2 operating characteristics. In this condition, the fault will be cleared in Zone-2 operating time from both line-ends. In this paper, this mode of fault clearing is referred to as time-delayed tripping (TDT) from both ends. Among these different tripping modes, only instantaneous tripping and AST falls under the fast fault clearing category [4].

TABLE I
FAULT CLEARING MODES BY THE PROPOSED AND CONVENTIONAL RELAYS

CB Opening	Relay	Average Coverage of Line Length			
		Fault Clearing Mode			
		IT from Both Ends	AST	NST	TDT from Both Ends
Single-Pole	Prop.	42.9 %	38.2 %	18.6 %	0.3 %
	Conv.	37.8 %	20.4 %	41.5 %	0.3 %
Three-Pole	Prop.	42.9 %	19.1 %	37.7 %	0.3 %
	Conv.	37.8 %	18.6 %	43.3 %	0.3 %

Here, the tapping transformer is placed at 30% of the line length. Using the setting procedure presented earlier, the exponent ζ is set to 0.5. The fault resistance is altered between 0 to 25 Ω. The transmission angle is randomly changed between -30° to 30°. Applying faults at 100 different locations on the protected line, a total of more than 1000 fault cases are examined on every single test system. Table I provides the average portion of the line for which faults are cleared in one of the fault-clearing modes presented earlier. As can be seen, the instantaneous tripping happens on a larger range of the line by the proposed relay compared to that by the conventional relay. The proposed relay facilitates fast fault clearing, through instantaneous or accelerated sequential tripping, for faults on a larger portion of the protected line. This superiority is more prevalent once CBs are set to open single-pole for 1-ph-g faults. Such desirable performance is achieved without compromising security, thanks to more accurate estimation of the fault distance by the proposed approach.

In this part, the sensitivity of the relay to the magnitude of fault resistance is demonstrated by an example. The line length is assumed to be 100-km and the tap is placed at 40% of the line length. The exponent ζ of the proposed relay at each line end is again set to 0.5. Fig. 12 shows portions of the protected line for which faults are cleared in instantaneous and AST modes. To this end, 1000 randomly created systems are

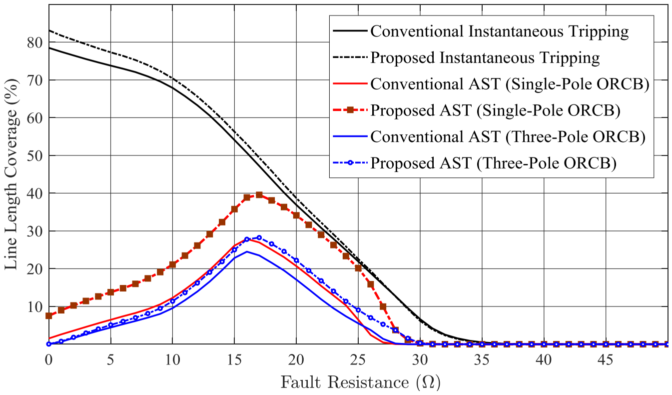

Fig. 12. Portions of line-length for which the relay provides fast fault clearing through instantaneous tripping and accelerated sequential tripping (AST) modes.

TABLE II
PERFORMANCE OF THE PROPOSED RELAYING METHOD IN TERMS OF INCREASE OF ITS INTENDED INSTANTANEOUS REACH

Tap Location m (%)	ζ	Line Length (km)				
		50	100	150	200	250
		Increase of Intended Reach (pu)				
0.20	0.3	0.01	0	0	0	0
	0.4	0.02	0.01	0.01	0	0
	0.5	0.03	0.03	0.02	0.01	0
	0.6	0.06	0.04	0.03	0.02	0.01
0.35	0.3	0	0	0	0	0
	0.4	0	0	0	0	0
	0.5	0.01	0	0	0	0
	0.6	0.03	0.01	0	0	0
0.50	0.3	0	0	0	0	0
	0.4	0	0	0	0	0
	0.5	0.01	0	0	0	0
	0.6	0.03	0	0	0	0

studied for each specific fault resistance. As can be seen, the instantaneous tripping range by the proposed relay is always larger than that by the conventional relay. The same holds for AST range provided by the proposed relay, as well.

Enlarging the fault resistance magnitude reduces the portions of the line for which the fault is seen in Zone 2 by the local relay. Nonetheless, after instantaneous tripping of the other end of the line, the fault will be supplied only from the local end, which reduces the current passing through the fault resistance. Accordingly, the impedance seen by the relay shrinks after the ORCB and may move inside Zone 1. It can be seen from Fig. 12 that the AST coverage increases until the fault resistance rises up to around 17 Ω. Further increment of the fault resistance magnitude results in reduction of the Zone-1 coverage of the remote relay. Therefore, from this point onward, the AST coverage of the local relay starts decreasing, as the fault resistance is gradually increased. Accordingly, 1-ph-g faults on an increasing portion of the protected line will be cleared in Zone-2 operating time from both line-ends.

The exponent ζ of the proposed relay should be set as detailed in Section III-C. Accordingly, the value of this parameter is chosen such that it does not result in more than five percent increase in the instantaneous reach of the relay even in worst-case scenarios. Here, this increase is calculated for a large number of randomly created test systems with different values for ζ. The obtained results are averaged and tabulated in Table II. As expected, larger exponents are more likely to result in more increase in the intended instantaneous reach of the relay. Thus, it is recommended to set ζ to smaller values if the variation range of the source impedances is not known. This is to ensure security of the protection scheme is not degraded under no conditions.

B. Hardware-in-the-Loop (HIL) Testing

The derivations of the proposed method are all obtained based on the sinusoidal steady-state assumptions mentioned earlier. However, phasor extraction techniques implemented in the hardware of relays do not have an ideal behavior. This is due to many factors such as the inclusion of fault decaying DC components, noise, potential presence of harmonics and electromagnetic transients associated to the fault inception. To

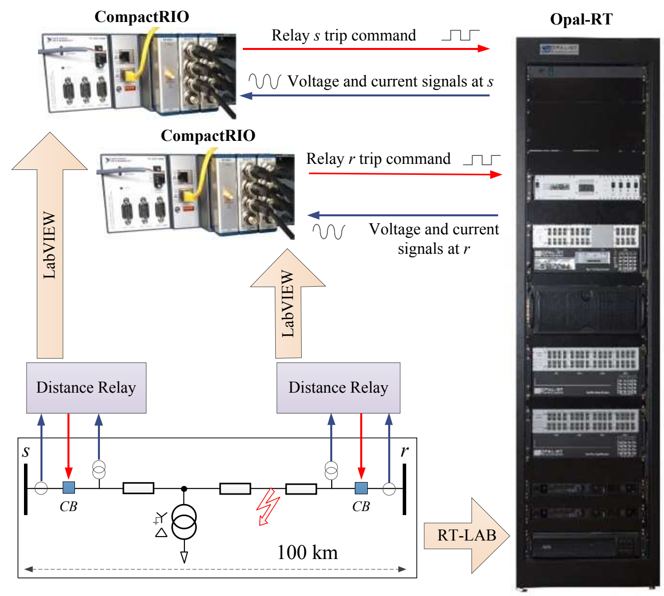

Fig. 13. Test setup used for hardware-in-the-loop (HIL) testing of the implemented distance relay.

validate the proposed method in more realistic conditions and to show its deployability, a tapped transmission line is modeled here using the SimPowerSystem (SPS) toolbox of MATLAB as shown in Fig. 13. This setup is used for hardware-in-the-loop (HIL) testing of the designed relay.

Transmission line models, voltage and frequency dependent load, instrument transformers and noise are modeled as in [25]. The RT-LAB software package is used to read the MATLAB/Simulink test-model, and compile and download it onto the Opal-RT eMEGAsim power grid real-time digital simulator. The proposed relay is implemented into the National Instrument CompactRIO hardware programmed with LabVIEW RT. The Opal-RT simulator generates three-phase time-domain waveforms that are available as analog output signals in dedicated ports. The CompatRIO hardware platform samples these waveforms by means of 16bits A/D converters operating at 1 kHz sampling rate. Then, the relays

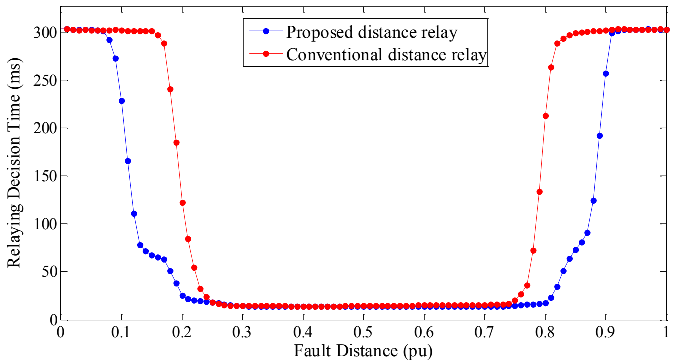

Fig. 14. Average relaying decision time using proposed and conventional distance relays while single-pole tripping is enabled for 1-ph-g faults.

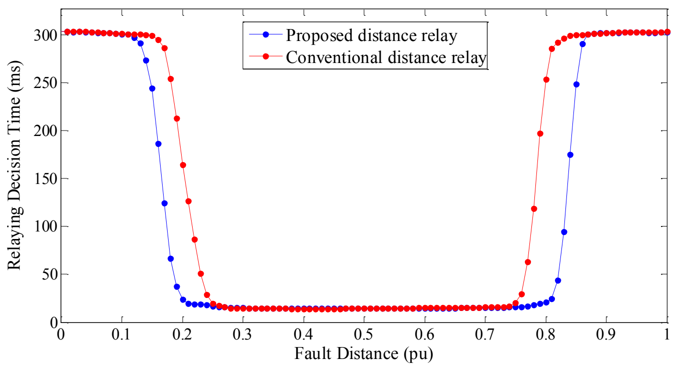

Fig. 15. Average relaying decision time using proposed and conventional distance relays while single-pole tripping is not allowed for 1-ph-g faults.

calculate their corresponding fundamental phasors using a full-cycle DFT algorithm.

In distance relaying, as explained earlier, the instantaneous reach of the relay is limited, for example, to 80% of the line length. Not to mistake internal faults with external faults, some intentional time delay, e.g., 300 ms, is applied for clearing faults on the end-section of the line. This is a common practice for preserving security of the relaying scheme. The proposed and conventional relays will have a fairly identical operating time, if they see the fault in the same protection Zone. Otherwise, for instance, if the proposed relay sees a fault inside Zone 1 and the conventional relay sees the same fault inside Zone 2, the operating times of the proposed and conventional distance relay will be totally different. By improving the accuracy of estimated fault distance, the proposed approach facilitates instantaneous fault clearing on, ideally the entire and practically a large portion of the 80% permissible instantaneous range. However, the instantaneous reach of the conventional relay will be smaller than that of the proposed relay due to the underreaching problem addressed earlier. Accordingly, the conventional relay will unnecessarily apply an intentional Zone-2 time-delay for clearing faults on some noticeable portion of the instantaneous range.

Here, the above-mentioned difference between the proposed and conventional distance relays is demonstrated. To this end, the tapped line length is set to 100 km and the tap is placed at 40 km ahead of the sending-end terminal. Two fault resistances of 0 Ω and 10 Ω are examined. The transmission

TABLE III
VARIATION RANGE OF THE PARAMETERS OF THE 230 KV TEST SYSTEMS

Variable description and unit	range	
magnitude of voltage source (p.u.)	0.98	1.02
voltage source impedance magnitude (p.u.)	0.1	0.3
angle of impedance behind the voltage source (°)	78	82
magnitude of pos. seq. impedance of line (p.u.)	0.30	0.42
line pos. seq. impedance angle (°)	84	86
line zero seq. impedance magnitude (p.u.)	0.9	1.2
angle of zero seq. impedance of line (°)	73	77
magnitude of pos. seq. impedance of parallel link (p.u.)	0.9	1.1
angle of pos. seq. impedance of parallel link (°)	84	86
magnitude of zero seq. impedance of parallel link (p.u.)	4	6
angle of zero seq. impedance of parallel link (°)	73	77
load apparent power at tapping transformer (p.u.)	0.04	0.08
load phase angle at tapping transformer (°)	-8	8

angle is set to vary between -15° to 15° in 5° steps. Impedances of the faulted line and load are set equal to middle values of their corresponding rang listed in Appendix. Load power factors of unity, 0.9 lagging and leading are examined. Figs 14 and 15 show the average decision time of the relay in 100 fault cases examined at each specific location. The obtained results confirm that instantaneous fault clearing by the proposed relay happens on a larger portion of the line middle-section compared to that by the conventional relay. Instantaneous tripping, however, does not happen for faults on the line end-sections, which verifies security of the method. It follows from Fig. 14 that sequential tripping is also accelerated for 1-ph-g faults on around 15 % of the line length, after single-pole ORCB.

V. CONCLUSION

A modified distance formula was set forth in this paper for protection of tapped transmission lines with grounded wye connections against single-phase-to-ground (1-ph-g) faults. The proposed distance formula takes advantage of the ratio of the negative-sequence to zero-sequence currents at the relay to accurately estimate the impedance-to-the-fault. Normally, the ratio of the negative-sequence to zero-sequence currents for faults occurring beyond the tap point is larger than unity. Not only does this hold during a 1-ph-g fault, but also after three- or single-pole opening of the remote-end CB (ORCB) as justified through analytical discussions and extensive simulations studies.

Using the proposed distance relay, the instantaneous tripping of tapped lines can be facilitated for 1-ph-g faults over almost the entire middle-section of the protected line. This is achievable where the negative-sequence current that the relay measures is larger than its zero-sequence current, as is normally the case once the neutral of the tapping transformer is solidly grounded. Protection of tapped lines based on the proposed distance formula also accelerates sequential tripping for 1-ph-g faults on around 15% of the protected line. This is the case when single-pole tripping of CBs is allowed. No further calculations are needed for such desirable reduction in average fault clearing time. It has been

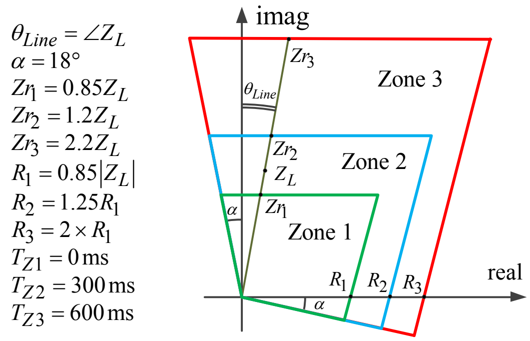

Fig. 16. Operating characteristics of distance relays.

also shown that the proposed relay can be used for distance relaying of transmission lines with more than one taps.

Appendix

Test System Data: Data of the 230 kV test systems created for sinusoidal steady-state analysis of the proposed distance relaying are given in Table III. The parameters of the tapped test system used in the HIL testing are set equal to the middle values of the corresponding ranges in this table. The base power and base voltage on the high voltage side of the 230/63 kV tapping transformer are considered to be 400 MW and 230 kV, respectively. The tapping transformer leakage impedance is set to be a random value between 10% and 14% in its nominal power base, *i.e.,* 40 MW.

Distance Relay Operating Characteristics: The operating characteristics of protection zones of distance relays used for simulation studies are set as shown in Fig. 16. In this figure, Z_L is the positive-sequence impedance of the protected line.

References

[1] A. G. Phadke, J. S. Thorp, *Computer Relaying for Power Systems,* John Wiley & Sons, 2009.

[2] W. A. Elmore, *Protective Relaying: Theory and Applications*, CRC Press, 2003.

[3] S. H. Horowitz, A. G. Phadke, J. K. Niemira, *Power system relaying*, John Wiley & Sons Inc, 4th ed, 2014.

[4] P. M. Anderson, *Power System Protection*. New York: IEEE Press, 1999.

[5] Areva, *Network Protection & Automation Guide*. 1st ed. 2002.

[6] G. Ziegler, *Numerical Distance Protection: Principles and Applications*, 4th ed. 2011.

[7] A. Esmaeilian, P. J. Salamati, M. Salay Naderi, "Distance protection algorithm for three terminal transmission lines using local measurements," *International Review on Modelling and Simulations*, vol. 5, no. 5, pp. 2205-2213, Oct. 2012.

[8] M. T. N. Dinh, M. Bahadornejad, A. S. A. Shahri, and N. K. C. Nair, "Protection schemes and fault location methods for multi-terminal lines: A comprehensive review," in *2013 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia),* pp. 1–6, Nov. 2013.

[9] B. Bhalja and R. P. Maheshwari, "New differential protection scheme for tapped transmission line," *IET Gen., Transm. Distrib,* vol. 2, no. 2, pp. 271–279, Mar. 2008.

[10] M. A. Redfern, J. Lopez, and R. O'Gorman, "A flexible protection scheme for multi-terminal transmission lines," in *IEEE Power Engineering Society General Meeting,* pp. 2678–2682 Vol. 3, Jun. 2005.

[11] A. Saber, A. Emam, and H. Elghazaly, "A backup protection technique for three-terminal multisection compound transmission lines," *IEEE Trans. Smart Grid,* vol. PP, no. 99, pp. 1–1, 2017.

[12] N. A. Al-Emadi, A. Ghorbani, and H. Mehrjerdi, "Synchrophasor-based backup distance protection of multi-terminal transmission lines," *IET Gen., Transm. Distrib,* vol. 10, no. 13, pp. 3304–3313, Oct. 2016.

[13] A. Ghorbani, H. Mehrjerdi, N. A. Al-Emadi, "Distance-differential protection of transmission lines connected to wind farms", *International Journal of Electrical Power & Energy Systems*, vol. 78, no. 11, pp. 11–18, Jul. 2017.

[14] T. Zheng, Y. Zhao, J. Li, X. Wei, Y. Wang and Z. Wang, "A new pilot distance protection scheme for teed lines," *12th IET International Conference on AC and DC Power Transmission (ACDC 2016),* Beijing, pp. 1-5, 2016.

[15] Q. Jiang, B. Wang, and X. Li, "An efficient PMU-based fault-location technique for multiterminal transmission lines," *IEEE Trans. Power Del.,* vol. 29, no. 4, pp. 1675–1682, Aug. 2014.

[16] P. K. Nayak, A. K. Pradhan and P. Bajpai, "A three-terminal line protection scheme immune to power swing," *IEEE Trans. Power Del.,* vol. 31, no. 3, pp. 999-1006, Jun. 2016.

[17] A. Y. Abdelaziz, M. A. Rahman, M. S. Moussa, "Distance protection for multi-terminal transmission lines", *2nd International Conference on Electric Power and Energy Conversion Systems (EPECS),* 15-17 Nov. 2011

[18] P. Jafarian and M. Sanaye-Pasand, "High-frequency transients-based protection of multiterminal transmission lines using the svm technique," *IEEE Trans. Power Del.,* vol. 28, no. 1, pp. 188–196, Jan. 2013.

[19] M. Khodadadi and S. M. Shahrtash, "A new noncommunication based protection scheme for three-terminal transmission lines employing mathematical morphology-based filters," *IEEE Trans. Power Del.,* vol. 28, no. 1, pp. 347–356, Jan. 2013.

[20] M. da Silvaa, M. Oleskoviczb, and D. V. Couryb, "A hybrid fault locator for three-terminal lines based on wavelet transforms," *Elect. Power Syst. Res.,* vol. 78, no. 11, pp. 1980–1988, Nov. 2008.

[21] A. Ahmadimanesh and S. M. Shahrtash, "Employing s-transform for fault location in three terminal lines," in *10th International Conference on Environment and Electrical Engineering,* pp. 1–4, May 2011.

[22] Desoer and E. S. Kuh, *Basic Circuit Theory*, New Delhi: Tata McGraw-Hill, 2009.

[23] A. S. Dobakhshari and A. M. Ranjbar, "A wide-area scheme for power system fault location incorporating bad data detection," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 800–808, Apr. 2015.

[24] S. Azizi and M. Sanaye-Pasand, "From available synchrophasor data to fault identity: Formulation and feasibility analysis," *IEEE Trans. on Power Systems,* vol. 32, no. 3, pp. 2062-2071, May 2017.

[25] S. Sarri, M. Pignati, P. Romano, L. Zanni, and M. Paolone, "A hardware-in-the-loop test platform for the performance assessment of a PMU-based real-time state estimator for active distribution networks," in *PowerTech 2015, IEEE, Eindhoven*, pp. 1–6, Jun. 2015.