Distance Protection Methodology for Detection of Faulted Phase and Fault Along With Power Swing Using Apparent Impedance

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ABSTRACT In this paper, a novel distance protection methodology that uses apparent impedance and concentric characteristics to identify faults and faulty phases along with power swing condition is proposed. The rate of change of apparent impedance is used to identify the fault or power swing condition. If a fault is detected, the relative location of the apparent impedance of the six distance elements with respect to their concentric characteristics is used to identify the faulty phases. The distance element(s) that compute the correct apparent impedance is(are) then enabled, which then issues the trip signal if the zone criterion is met. The proposed distance protection methodology is validated in Western System Coordinating Council (WSCC) Nine Bus System in MATLAB/Simulink by simulating various fault and power swing conditions. The results from the case studies proved that the proposed distance protection methodology could enable the right distance elements and issue trip signals during common faults and special kinds of faults like evolving and cross-country faults. Compared to others, the distinguishing feature of the proposed algorithm is its ability to identify the exact faulty phases even during special fault conditions like evolving and cross-country faults. The distance relay using the proposed methodology can issue the trip signal within one cycle for common faults and within one and half-cycle for evolving and cross-country faults.

INDEX TERMS Distance relay, ground distance element, phase distance element, apparent impedance trajectory.

NOMENCLATURE

- \( V_a, V_b, V_c \): Three-phase voltages.
- \( I_a, I_b, I_c \): Three-phase currents.
- AG, BG, CG: Ground Distance Elements or Phase-Ground fault type.
- AB, BC, CA: Phase Distance Elements or Phase-Phase fault type.
- \( Z_{AG} \): Apparent impedance computed by the AG Ground Distance Element.
- \( Z_{BG} \): Apparent impedance computed by the BG Ground Distance Element.
- \( Z_{CG} \): Apparent impedance computed by the CG Ground Distance Element.
- \( Z_{AB} \): Apparent impedance computed by the AB Phase Distance Element.
- \( Z_{BC} \): Apparent impedance computed by the BC Phase Distance Element.
- \( Z_{CA} \): Apparent impedance computed by the CA Phase Distance Element.
- \( \Phi \): Represents phases A, B and C.
- AIT: Apparent Impedance Trajectory.
- \( \text{In}_{\Phi G} \): Status of the apparent impedance trajectory of the Ground Distance Element \( \Phi G \).
- \( \text{In}_{\Phi \Phi} \): Status of the apparent impedance trajectory of the Phase Distance Element \( \Phi \Phi \).
- \( Z3_{\Phi G} \): Status of the apparent impedance trajectory into Zone-3 of the Ground Distance Element \( \Phi G \).
- \( \text{In}_{ABC-Z3G} \): Status indicating entry of all ground distance elements into their Zone-3.
- \( \text{en}_{\Phi G} \): Faulted Phase Selection signal for Ground Distance Element \( \Phi G \). 

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Faulted Phase Selection signal for Phase Distance Element $\Phi\Phi$.

Time taken by the Apparent Impedance Trajectory of the Ground Distance Element $\Phi G$ to cross the concentric characteristics.

Time taken by the Apparent Impedance Trajectory of the Phase Distance Element $\Phi\Phi$ to cross the concentric characteristics.

Minimum of the time taken by the Apparent Impedance Trajectories of those distance elements that crossed their concentric characteristics.

Line to Ground Fault.

Line to Line to Ground Fault.

Zone-1 of the distance relay.

Zone-2 of the distance relay.

Zone-3 of the distance relay.

Power Swing Block signal.

I. INTRODUCTION

Modern transmission system is mainly protected by distance protection. Eleven types of faults can occur in the transmission system with the A-B-C phase sequence: AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABC, and ABCG. The distance relay should be capable to compute the correct positive sequence up to the fault point during all kinds of faults and operate if the apparent impedance is inside the operating region. For a reliable operation, the distance relay deployed in a three-phase transmission system employs three ground distance elements: AG, BG, and CG, and three phase distance elements: AB, BC, and CA. Each distance element is governed by an equation and computes the apparent impedance independently.

All the six distance elements compute the apparent impedance in parallel continuously. The ground distance elements AG, BG, and CG compute the correct positive sequence impedance only during a phase-ground fault in the respective phases. Likewise, the phase distance elements AB, BC, and CA compute the correct positive sequence impedance only during a phase-phase, phase-phase-ground fault in the respective phases and during a three phase fault [1].

For a reliable operation, only those distance element(s) that compute the correct positive sequence impedance during a given fault condition is(are) to be enabled. It can be done by supervising the six distance elements using a logic to identify the faulty phases and enable the right distance element(s).

Leslie N. Crichton introduced the term “Distance Relay” in his paper in 1923 [2]. In this first paper on distance relay, the author mentioned that two sets of relays are required to implement the distance protection scheme to protect the three-phase transmission line against phase and ground faults. However, the intricacies of using the six distance elements were not explored. Hence, the challenge of identifying the faulted phases existed from the birth of the distance relay. Since then, a good quantum of research has been done in this area.

A method to identify the faulted phases based on Wavelet Transforms is proposed by Youssef [3]. The voltage signals are decomposed into wavelets and used to identify the faulted phases. Xinzhou Dong et al. [4] proposed an algorithm to identify the faulted phases based on travelling waves extracted using Wavelet transform and Karenbauer Transform. The accuracy of the wavelet-based methods in [3] and [4] depends on the length of the filters and levels of decomposition. Zou et al. [5] proposed a scheme for identifying the faulted phases using mathematical morphology. The authors extended their work to include phase selection for unbalanced faults during power swing in [6].

Sequence components and correlation theory are used to develop a scheme to identify the faulted phases by Lin et al. [7]. Masoud and Mahfouz [8] proposed a protection scheme with a logic to identify the faulted phases based on alienation coefficients. Alienation coefficients of all the three phases are computed continuously. The value of the coefficient will be between 0 and 1. Faulted phases are identified based on the value of the coefficient for each phase. Eissa et al. [9] proposed a method to identify the faulted phases using auto-correlation coefficients of the current signals.

David Costello and Karl Zimmerman devised a methodology to identify the faulted phases based on the phase angle relationship between the negative and zero sequence currents and the reach computed by each distance element in [10]. Xu et al. proposed a method similar to [10] in [11] which is also based on phase angle relationship between zero and negative sequence current. The presence of the impedance trajectory inside Zone-3 is used as a distinguishing factor between a ground fault and a phase fault. Behnam Mahamedi et al. used the reactive power of symmetrical components to identify the faulted phase in [12]. The zero-sequence and negative sequence reactive power ratio is utilized to identify the faulted phases. Shaoeng et al. proposed a method to identify the faulted phases in [13] for weak infeed conditions. The phase angle of the negative and zero sequence voltages are utilized to identify the probable faulted phases and confirm the faulted phases using superimposed components of voltages to identify the correct faulted phase. Symmetrical component-based faulted phase selection methods reported in [10]–[13] are not tested for different fault inception angles, and their performance is not tested during evolving fault and cross-country fault conditions.

Utsumi et al. [14] proposed a method to identify the faulted phases based on impedance comparison. It was observed that the apparent impedance measured is least for the faulted phases compared to the non-faulted phases. The performance of this method for different fault inception angles is not tested.

A support vector machine (SVM) based classifier was developed using synchronized phase angle of voltage and
current at a generator bus to identify the faulted phases by Gopakumar et al. [15]. The method needs synchronized voltage and current samples for accurate classification. It can be used for post fault analysis in a generating station. Yiqing et al. used convolutional neural network (CNN) in [16] to identify the faulted phases for double circuit lines. Han et al. [17] used gradient similarity and cross-domain adaptation based CNN for identifying the faulted phases. The methods proposed in [15]–[17] are useful only for post fault analysis and cannot be used in the application of faulted phase selection function in a distance relay. Moreover, these methods are not validated for special fault scenarios like evolving and cross-country faults.

Ma et al. [18] proposed a method to identify the faulted phases based on the ratio of the magnitude of the phase currents and the differences in the magnitudes of the other two phase currents. In [19], Taheri et al. proposed a method to identify the faulted phases based on differential power using the decision-tree data mining model. Salehi and Namdari [20] proposed a method to identify the faulted phases using mathematical morphology and travelling waves. Wijekoon et al. [21] used current transients for faulted phase selection in a double circuit line. The same authors developed a transformation matrix to transform the instantaneous three-phase currents and extracted seven current components to identify the faulted phases [22]. Methods proposed in [20]–[22] are dependent on transient currents and can fail during faults with near-zero inception angles and are not validated for special fault scenarios like evolving and cross-country faults.

Most of the methods reported in the literature are for post fault analysis and are unsuitable for integrating into a distance relay for faulted phase selection function. Also, they are not validated for special kinds of faults like evolving and cross-country faults. Hence, a faulted phase selection method for distance protection capable of identifying the faulted phases during all kinds of common faults and special faults like evolving and cross-country faults is developed by analyzing numerous case studies on a Two-Machine Three Bus System. The developed distance protection methodology is validated in WSCC Nine Bus System for various common fault conditions, power swing, and special faults like evolving and cross-country faults. The superiority of the proposed methodology is shown by comparing it with two dominantly used methods in the existing literature.

The specific contributions of this paper to the existing body of knowledge are as follows:

- A distance relaying algorithm that uses an integrated approach of using the concentric characteristics and apparent impedance as the basis for fault detection, faulty phase selection along with power swing detection.
- The proposed algorithm is able to identify the faulty phases even during special faults like evolving and cross-country faults where the methods in comparison failed.

### II. CONVENTIONAL DISTANCE RELAY USED IN UTILITIES

The functional block diagram of a conventional three-phase distance relay used in the utilities is shown in Fig. 1 [23]. The three-phase voltage and current inputs from the potential transformers are fed to the distance relay. The voltage and current signals are pre-processed with analog to digital conversion (ADC), and Phasor Estimation. In Stage-1, the presence of the fault is typically identified using samples of current.

If a fault is identified in Stage-1, Stage-2 is enabled, wherein the phases involved in the fault are identified. A three-phase distance relay consists of three Ground Distance Elements (GDEs): AG, BG, and CG, and three Phase Distance Elements (PDEs): AB, BC, and CA. The apparent impedance equation and the type of fault during which the equation computes the correct positive sequence up to the fault point are given in Table 1 [24].

### TABLE 1. Equations used by the six distance elements to compute the apparent impedance.

| Distance Element | Apparent Impedance | Fault Types for Correct Positive Sequence Impedance |
|------------------|---------------------|-----------------------------------------------|
| AG               | $Z_{AG} = \frac{V_A}{I_A+k_0I_G}$ | AG                                           |
| BG               | $Z_{BG} = \frac{V_B}{I_B+k_0I_G}$ | BG                                           |
| CG               | $Z_{CG} = \frac{V_C}{I_C+k_0I_G}$ | CG                                           |
| AB               | $Z_{AB} = \frac{V_A-V_B}{I_A-I_B}$ | AB, ABG, ABC, and ABCG                       |
| BC               | $Z_{BC} = \frac{V_B-V_C}{I_B-I_C}$ | BC, BCG, ABC, and ABCG                       |
| CA               | $Z_{CA} = \frac{V_C-V_A}{I_C-I_A}$ | CA, CAG, ABC, and ABCG                       |

$k_0 = \frac{Z_0}{Z_1}$  
$Z_1$ = positive sequence impedance of the transmission line,  
$Z_0$ = zero sequence impedance of the transmission line  
$I_{A0} = zero sequence current of phase-A$  
$I_{B0} = zero sequence current of phase-B$  
$I_{C0} = zero sequence current of phase-C$
In Stage-3, the chosen distance element issues a trip signal if the zone criterion of the enabled distance element(s) is met. The method of identifying faulted phases using sequence components in Stage-2 of the conventional distance relay fails to identify the correct faulted phases during some special kinds of faults like evolving and cross-country faults.

A novel methodology for identifying the faulted phases in Stage-2 is proposed and is discussed in the next section.

III. PROPOSED DISTANCE PROTECTION METHODOLOGY

The conventional distance relay fails to identify the faulty phases during special faults like evolving and cross-country faults. This is overcome by using apparent impedance as the basis for identifying the faulted phases during Stage-2.

The block diagram of the distance relay using the proposed methodology is shown in Fig. 2. The voltage and current inputs from the potential transformer and current transformer are fed to the distance relay. The voltage and current signals are pre-processed with operations like scaling, filtering, ADC, and Phasor Estimation.

A. STAGE-1

In Stage-1, the apparent impedance is computed by all the six distance elements using equations defined in Table 1. The apparent impedance is traced in the R-X plane with the protective zone characteristics along with the concentric characteristics as shown in Fig. 3.

B. STAGE-2

The apparent impedance computed by all the six distance elements in Stage-1 is monitored continuously, and if the trajectory of the apparent impedance of at least one of the six distance elements crosses their concentric characteristics, then the time taken to cross the concentric characteristics, \( \Delta t \), of those distance elements is computed and compared with the threshold \( \Delta t_{th} \) as shown in the logic diagram in Fig. 4. If \( \Delta t \) is less than \( \Delta t_{th} \), then it is a fault, and the Fault Identification Logic issues Fault_Id = 1 and disables the Power Swing Detection Logic, indicating the presence of a fault. Else, if any \( \Delta t \) is greater than \( \Delta t_{th} \), then the Power Swing Detection Logic checks that Fault Identification Logic is not enabled (Fault_Id = 0) and issues Power Swing Block signal (PSB = 1) and the relay is blocked from operation.

C. STAGE-3

The function of Stage-3 is to identify the faulted phases and to enable the right distance element(s) among the six distance elements. It is to be emphasized that the function is to identify the phases involved in the fault and not to identify the fault type. A novel method of identifying the faulted phases using the relative location of the apparent impedance computed by the six distance elements with respect to their concentric characteristics is proposed.

The location of the apparent impedance computed by each distance element with respect to its concentric characteristics is called the 'Status of AIT' of that distance element. This status can be logically represented as '0' if the AIT is outside its concentric characteristics and '1' if the AIT is inside its concentric characteristics. The Status of AIT is indicated by In_\( \Phi \)G for GDEs and In_\( \Phi \) for PDEs. Here \( \Phi \) indicates the phases A, B, or C. The status of all the PDEs and GDEs during
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A simulation study is conducted in a Two-Machine Three Bus System shown in Fig. 5 to study the Status Patterns for different types of faults and various fault conditions. The transmission line parameters are considered from a practical 400 kV transmission line used in Indian Power Grid [25] and given in the Appendix. The distance relay (R) is placed at Bus-1 and fed with the voltage at Bus-1 and current through Line-1. The resistive and reactive reach settings for the protective zones of the distance relay are calculated based on the guidelines given in the manual used by the Indian Power Grid [26]. The reach of Zone-1 of the distance relay is set to 80 percent of Line-1 and instantaneous. The Zone-2 reach is set to 120 percent of Line-1, and the timer setting is 350 ms. The Zone-3 reach is set to 120 percent of the total length of Line-1 and Line-2, and the timer setting is 1000 ms. The settings of the concentric characteristics \(Z_1\) and \(t_{th}\) are calculated based on the guidelines given in [27] and set as 20 Ω and 140 ms respectively. The sampling frequency is considered as 2 kHz, and full-cycle Discrete Fourier Transform (DFT) method is used for the phasor estimation. The system is modeled in MATLAB/Simulink environment.

Consider the case of an AG fault at 0 km from Bus-1 with a fault resistance of 0 Ω and fault inception angle of 5°. The apparent impedance computed by the six distance elements during this fault condition is shown in Fig. 6. In Stage-1, the apparent impedance is computed by the six distance elements and traced its trajectory. In Stage-2, the logic shown in Fig. 4 is enabled, and it identified the condition as a fault and issued \(\text{Fault}_\text{Id} = 1\) based on the time taken by the apparent impedance trajectory to cross the concentric characteristics. From Fig. 6, it can be observed that the apparent impedance of AG, BG, CG, AB, and CA distance elements is inside their respective concentric characteristics, and the apparent impedance of BC distance element is outside its concentric characteristics.

In this case, the status of AG distance element \((\text{In}_{\text{AG}} = 1)\), BG distance element \((\text{In}_{\text{BG}} = 1)\), CG distance element \((\text{In}_{\text{CG}} = 1)\), AB distance element \((\text{In}_{\text{AB}} = 1)\), BC distance element \((\text{In}_{\text{BC}} = 0)\) and CA distance element \((\text{In}_{\text{CA}} = 1)\).

Intuitively, it can be understood from the above discussion that the phase distance element associated with those phases which are not involved in the fault did not see the apparent impedance inside its concentric characteristics. With this as an initial observation, several case studies are carried out. The relative position of the apparent impedance computed by the six distance elements with respect to their concentric characteristics in each case is analyzed.

Eight groups of case studies are shown in Table 2, with each group containing eleven case studies: one each for each of the eleven fault types, a total of 88 case studies are carried out, and the Status Patterns are observed.

From the status patterns observed during these 88 case studies, 25 unique status patterns were identified. The distance element(s) that computes the correct positive sequence impedance for that particular fault type is identified. The list of unique status patterns (SPs), each identified with a unique identifier, is shown in Table 3. The distance element(s) that should be enabled for that particular status pattern in a given fault condition is mentioned in the last column of the table.
It can be observed from Table 3 that each GDE and PDE are assigned four sets of SPs. In addition, the SP during a three-phase fault is assigned to all the three phase distance elements.

It is to be noted that the entry of the AIT into Zone-3 of the ground distance elements is to be taken into consideration only if the AITs of all the six distance elements have entered their concentric characteristics. In all other cases, entry of AIT into Zone-3 is a don't care condition represented as X.

The 25 unique status patterns in Table 3 are used to develop the logic for identifying the faulted phases. The developed logic is represented in Fig. 7. The input to the logic is the status of the AITs of the six distance elements and Zone-3 of the ground distance elements. During any fault condition, the status pattern will match with one of the unique status patterns, and the logic will generate an enable signal.

For example, if the faulted phase is phase-A, then en_AG signal is set to ‘1’ and all the others en_BG, en_CG, en_AB, en_BC and en_CA are set to 0. These enable signals will enable the distance elements to issue a trip signal if the apparent impedance is found inside any of their zones and the time criterion of that zone is satisfied, as shown in Fig. 8. The trip signals are sent to the circuit breaker for isolating the faulted section.

The proposed distance protection methodology is validated for its performance through different case studies in WSCC Nine Bus System, and the results are presented in the next section.

IV. RESULTS
Consider the WSCC Three Machine Nine Bus System shown in Fig 9. The transmission line parameters of a practical 400 kV single circuit transmission line used in Indian Power Grid [25] is considered and is given in Appendix. The distance relay (R) that employs the proposed distance protection methodology is located at Bus-7 and set to protect Line-1.
FIGURE 7. Proposed logic to identify the faulted phases in Stage-3.
TABLE 3. Status pattern for different types of faults and the distance elements to be enabled.

| Status Pattern (SP) | In_AG | In_BG | In_CG | In_AB | In_BC | In_CA | Z1_AG | Z2_AG | Z3_AG | Z1_BG | Z2_BG | Z3_BG | Z1_CG | Z2_CG | Z3_CG | DE to be enabled for final relay operation |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------------------------------|
| SP-1                | 1     | 0     | 0     | 0     | 0     | 0     | X     | X     | X     | AG    |       |       |       |       |       |                                |
| SP-2                | 1     | 0     | 0     | 1     | 0     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-3                | 1     | 0     | 0     | 0     | 0     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-4                | 1     | 1     | 1     | 1     | 0     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-5                | 0     | 1     | 0     | 0     | 0     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-6                | 0     | 1     | 0     | 1     | 0     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-7                | 0     | 1     | 0     | 0     | 1     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-8                | 1     | 1     | 1     | 1     | 1     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-9                | 0     | 0     | 1     | 0     | 0     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-10               | 0     | 0     | 1     | 0     | 1     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-11               | 0     | 0     | 1     | 0     | 0     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-12               | 1     | 1     | 1     | 0     | 1     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-13               | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | AB    |       |       |       |       |       |                                |
| SP-14               | 1     | 1     | 1     | 0     | 1     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-15               | 1     | 1     | 0     | 1     | 1     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-16               | 1     | 1     | 0     | 1     | 0     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-17               | 1     | 1     | 1     | 1     | 1     | 1     | 0     | 1     | 1     | BC    |       |       |       |       |       |                                |
| SP-18               | 0     | 1     | 1     | 1     | 1     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-19               | 0     | 1     | 1     | 0     | 1     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-20               | 0     | 1     | 1     | 0     | 1     | 0     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-21               | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | CA    |       |       |       |       |       |                                |
| SP-22               | 1     | 1     | 1     | 1     | 0     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-23               | 1     | 1     | 1     | 0     | 1     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-24               | 1     | 1     | 1     | 0     | 0     | 1     | X     | X     | X     |       |       |       |       |       |       |                                |
| SP-25               | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | 1     | AB & CA |       |       |       |       |       |                                |

Note: X indicates a "Don’t-Care" condition

FIGURE 8. Proposed logic to issue trip signal by the enabled distance elements in Stage-3.

FIGURE 9. WSCC three machine nine bus system.

and Line-2. The sampling frequency is considered as 2 kHz and full cycle DFT is used for the phasor estimation. The resistive and reactive reach settings for the protective zones of the distance relay are calculated based on the guidelines given in the manual used by the Indian Power Grid [26]. The settings of the concentric characteristics $\Delta Z$ and $\Delta t_{th}$ are calculated based on the guidelines given in [27] and set as $20 \Omega$ and 160 ms respectively. The system is modelled in MATLAB/Simulink environment.

The objective of choosing the case studies is to validate the performance of the proposed distance protection methodology during all types of common faults and special kinds of faults like evolving and cross-country faults. With this objective, the following case studies are considered:

1) AG fault
2) ABC fault
3) CA fault
4) BCG fault
5) Evolving Fault (AG to CAG)
6) Cross Country Fault (BG and CG)
7) Stable Power Swing Condition

1) AG FAULT

The performance of the proposed methodology is validated for a single line-to-ground fault in Zone-1 through this case study. An AG fault is simulated at the start of the Line-1 without any fault resistance (a Close-In fault). The fault is incepted at $0^\circ$ and at a time of 14.0162 s. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 10.

It is observed from Fig. 10 that the apparent impedance of the distance elements AG, BG, CG, AB, and CA is inside their concentric characteristics and the apparent impedance of the BC phase distance element is outside its concentric characteristics. In Stage-2, the minimum of the $\Delta t$, $\Delta t_{min}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 0.42 ms. As this is very much less than $\Delta t_{th}$ of 160 ms, the Logic in Stage-2 detected it as a fault condition and issued Fault_Id = 1 and thus enabled the Stage-3.
In Stage-3, the logic identified the faulted phase as A and generated $en_{AG} = 1$. Hence the AG distance element is enabled (indicated by the dotted red line) to issue the trip signal if the apparent impedance is inside any of its Zone. The AG distance element found the apparent impedance in its Zone-1 and issued a trip signal at 14.03026 s. Hence the distance relay using the proposed methodology rightly enabled the AG distance element, and it issued a trip signal within 14.06 ms, as shown in Fig. 11.

2) ABC FAULT IN ZONE-1

The performance of the proposed methodology for a symmetrical fault in Zone-1 is validated through this case study. An ABC fault is simulated in Line-1 at 70 km from Bus-7. An inter-phase fault resistance of 10 $\Omega$ is considered, and the fault inception angle is chosen as 75°. The fault is created at 14.0208 s. In Stage-1, the apparent impedance is computed by the six distance elements during this fault condition and is shown in Fig. 12.

It is observed that the apparent impedance of all the six distance elements is inside their concentric characteristics. In Stage-2, the minimum of the $\Delta t_{max}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 0.76 ms. As this is very much less than $\Delta t_{th}$ of 160 ms, the logic detected it as a fault condition and issued Fault_Id = 1 which enabled the Stage-3.

In Stage-3, the logic identified all the three phases to be faulted and hence generated $In_{ABC\_Z3G} = 1$ and this in turn enabled (indicated by the dotted red line) all the phase distance elements by generating, $en_{AB} = 1$, $en_{BC} = 1$, and $en_{CA} = 1$. These distance elements then sensed the presence of apparent impedance in their Zone-1 and issued the trip signal at 14.03948 s. Hence the distance relay using the proposed methodology operated for a symmetrical fault in Zone-1 within 9.22 ms, as shown in Fig. 13.

3) CA FAULT

To validate the proposed distance protection methodology's functioning for a line-to-line fault in Zone-2, a CA fault is created in Line-2 at a distance of 20 km from Bus-8. An inter-phase fault resistance of 15 $\Omega$ is considered, and the fault inception angle is chosen as 180°. The fault is created at 14.0407 s. It is assumed that the primary protection of Line-2 failed to detect the fault. Hence the distance relay in Line-1 at Bus-7 should see the fault in Zone-2. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 14.

It is observed from Fig. 14 that the apparent impedance of the ground distance elements AG and CG and the apparent impedance of the phase distance element CA are inside their concentric characteristics. In Stage-2, the minimum of
the $\Delta t$, $\Delta t_{\text{min}}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 1.02 ms. As $\Delta t_{\text{min}}$ is very much less than $\Delta t_{\text{th}}$ of 160 ms, the logic detected it as a fault condition and issued $\text{Fault}_\text{Id} = 1$ and thus enabled the Stage-3.

In Stage-3, the logic identified the faulted phases as A and C and generated $\text{en}_\text{CA} = 1$ and enabled (indicated by the dotted red line) the CA phase distance element. The CA distance element then sensed the fault in its Zone-2 and issued the trip signal after the timer expired at 14.41084 s. Hence the distance relay that uses the proposed methodology issued the trip signal in 20.14 ms, as shown in Fig. 15.

4) BCG FAULT

The performance of the proposed methodology for a line-to-line-to-ground fault in Zone-3 is validated through this case study. A BCG fault is created in Line-2 at 50 km from Bus-8 with a fault resistance of 50 $\Omega$. The fault inception angle is chosen as 270° and created at 14.0389 s. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 16.

It can be observed from Fig. 16 that the apparent impedance of ground distance elements BG and CG and phase distance element BC is inside their concentric characteristics. In Stage-2, the minimum of the $\Delta t$, $\Delta t_{\text{min}}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 1.28 ms which is very much less than $\Delta t_{\text{th}}$ of 160 ms. Hence the logic detected as a fault condition and issued $\text{Fault}_\text{Id} = 1$ which enabled the Stage-3. In Stage-3, the logic identified the
faulted phases as B and C and generated $en_{BC} = 1$ and hence enabled (indicated by the dotted red line) the BC phase distance element. The BC phase distance element then sensed the fault in its Zone-3 and issued a trip signal after the timer of Zone-3 expired at 15.05482 s. Hence the distance relay using the proposed methodology rightly enabled the BC phase distance element, and it issued a trip signal within 15.92 ms, as shown in Fig. 17.

Also, it has to be emphasized that the logic proposed for identifying the faulted phases in Stage-3 avoided maloperation by rightly enabling the BC phase distance element. In the absence of such a logic, the BG distance element would have issued a trip signal in Zone-2, whereas the actual fault location is in Zone-3. The maloperation would have happened because the timer setting of Zone-2 is 350 ms and that of Zone-3 is 1000 ms.

5) EVOLVING FAULT
An evolving fault is a special type of fault where the phases involved in a fault change over time [28]. The performance of the proposed methodology for an evolving fault in Zone-1 is validated in this case study. An AG fault is simulated at 100 km from Bus-7 in Line-1 with a fault resistance of 10 $\Omega$. The fault is incepted at 0$^\circ$ at a time of 14.01680 s. At 14.0185 s, a CG fault is simulated with a fault resistance of 5 $\Omega$ at the exact location. Hence, AG fault evolving into CAG fault is simulated. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 18.

It can be observed that the apparent impedance computed by the distance elements AG, CG, AB, BC, and CA is inside their concentric characteristics and the apparent impedance computed by the BG ground distance element is outside the concentric characteristics. In Stage-2, the minimum of the $\Delta t$, $\Delta t_{\text{min}}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 1.36 ms, which is very much less than $\Delta t_{\text{th}}$ of 160 ms. Hence the logic detected it as a fault condition and issued Fault_Id = 1 which enabled the Stage-3.

In Stage-3, the logic identified the faulted phase as A and C and generated $en_{CA} = 1$ and enabled (indicated by the dotted red line) the CA phase distance element. The CA phase distance element then found the apparent impedance in its Zone-1 and issued a trip signal at 14.04012 s. Hence the distance relay using the proposed methodology rightly enabled the CA distance element during the evolving fault, and it issued a trip signal within 21.62 ms, as shown in Fig. 19.

6) CROSS COUNTRY FAULT
A cross-country fault is a simultaneous occurrence of two ground faults involving different phases, and in different line sections [23]. The performance of the proposed methodology for a cross-country fault is validated through this case study. A CG fault is created at 40 km from Bus-7 in Line-1 with a fault resistance of 15 $\Omega$ and is incepted at 60$^\circ$ at a time of 14.0264 s. Simultaneously, a BG fault is created at 60 km with a fault resistance of 0.01 $\Omega$. Hence, a cross-country fault involving the B and C phases is simulated. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 20.

It can be observed that the apparent impedance computed by the distance elements BG, CG, AB, BC, and CA is inside their concentric characteristics, and the apparent impedance computed by the AG ground distance element is outside the concentric characteristics. In Stage-2, the minimum of the $\Delta t$, $\Delta t_{\text{min}}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 1.26 ms. As it is very much less than $\Delta t_{\text{th}}$ of 160 ms and so the logic detected it as a fault condition and issued Fault_Id = 1 which enabled the Stage-3.
In Stage-3, the logic identified the faulted phase as B and C and generated $en_{BC} = 1$ and so enabled (indicated by the dotted red line) the BC phase distance element. The BC phase distance element then found the apparent impedance in its Zone-1 and issued a trip signal in Zone-1 at 14.05808 s. Hence the distance relay using the proposed methodology rightly chose the BC phase distance element, and it issued a trip signal in Zone-1 within 31.68 ms, as shown in Fig. 21.

7) STABLE POWER SWING CONDITION
The performance of the proposed methodology during a stable power swing condition is validated through this case study. A three-phase-to-ground fault is simulated in Line-3 at 70 km from Bus-7, and the faulted line is isolated after ten cycles by opening the breakers B5 and B6. This situation created a stable power swing condition. In Stage-1, the apparent impedance is computed by the six distance elements and is shown in Fig. 22.

It is observed from Fig. 10 that the apparent impedance of all the distance elements AG, BG, CG, AB, BC, and CA are inside their concentric characteristics. In Stage-2, the minimum of the $t_{th}$ of those distance elements whose apparent impedance is inside the concentric characteristics is computed as 361.31 ms which is higher than $t_{th}$ of 160 ms and so the logic detected it as a Power Swing Condition and Fault_Id = 0 and PSB = 1. Hence, the distance relay is blocked from an operation, and so no trip signals were generated, as shown in Fig. 23.

a: ADDITIONAL CASE STUDIES ON WSCC NINE BUS SYSTEM
In addition to the detailed case studies discussed so far, the performance of the proposed distance protection methodology is further analyzed using fourteen case studies and is
After analyzing all the case studies, it is observed that the proposed distance protection methodology identified the faults and faulted phases correctly during all kinds of common faults and special kinds of faults like evolving and cross-country faults. The proposed distance protection methodology is able to operate within one cycle for commonly occurring faults and within a half-cycle for special kinds of faults.

V. SUPERIORITY OF THE PROPOSED METHODOLOGY

The performance of the distance relay that uses the proposed methodology is compared with a distance relay that employed the sequence component-based logic for identifying the faulted phases in Stage-3 and reported in Table 5. The sequence component method mentioned in [29] and the incremental quantity of sequence components based method in [13] are used for comparison with the proposed method. The logic in these two papers is reproduced and compared with the proposed method. Different types of fault scenarios are studied for this comparison.

It is observed from Table 5 that the sequence component-based method in [29] and [30] is able to identify the faulted phases correctly for a single line to ground fault and could not identify the correct faulted phases for a phase-phase-ground fault. The incremental quantity of sequence component-based method in [13] identified the faulted phases correctly in both phase-ground and phase-phase-ground with and without fault resistance. However, both these methods could not identify the faulted phases during evolving fault and cross-country fault scenarios.

Identifying the faulted phases during evolving and cross-country faults is also important. These faults usually start as a single phase to ground fault and lead to a double phase-to-ground fault. Suppose the faulted phase selection identifies only one of them as a faulted phase. In that case, if the distance relay uses single-pole tripping function, it will open only a single pole of the breaker than three-pole, which would lead to further complications. Hence, the fundamental selectivity property of the distance protection scheme will be compromised. Also, failing to identify the faulted phases correctly can lead to maloperation or non-operation. Maloperation and non-operation both are catastrophic and can even lead to a blackout.

| Case Studies | Trip signal of zones of the distance elements | Relay Decision |
|--------------|--------------------------------------------|----------------|
| No fault Condition | AG-Zone 1 | AG-Zone 2 | AG-Zone 3 | BC-Zone 1 | BC-Zone 2 | BC-Zone 3 | CA-Zone 1 | CA-Zone 2 | CA-Zone 3 |
| ABG, 0 km, 0 Ω, 0° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | No trip |
| BC, 10 km, 20 Ω, 30° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | Trip AB in Zone 1 |
| CG, 30 km, 15 Ω, 45° | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip CG in Zone 1 |
| BG, 40 km, 25 Ω, 60° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip BG in Zone 1 |
| CA, 120 km, 15 Ω, 110° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | Trip CA in Zone 1 |
| AB, 150 km, 0 Ω, 120° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | Trip AB in Zone 1 |
| BCG, 180 km, 25 Ω, 150° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip BC in Zone 2 |
| AG, 190 km, 0 Ω, 180° | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip AG in Zone 2 |
| CAG, 200 km, 70 Ω, 120° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip CA in Zone 2 |
| BC, 230 km, 10 Ω, 270° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | Trip BC in Zone 2 |
| CA, 270 km, 0 Ω, 310° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip CA in Zone 3 |
| CG, 280 km, 15 Ω, 330° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Trip CG in Zone 3 |
| BCG, 300 km, 60 Ω, 350° | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | Trip BC in Zone 3 |

FIGURE 23. Trip signals issued by the distance relay using the proposed methodology during power swing condition in Line-1 in WSCC three machine nine bus system.

reported in Table 4. The resistance values mentioned in the first column are the fault resistance, and the angles are the fault inception angles. The fault distance is with respect to the Bus-7.
TABLE 5. Comparison with the published faulted phase selection methods.

| Sl. No. | Fault Scenario         | Trip signal issued by Distance Relay using faulty phase selection |
|---------|------------------------|---------------------------------------------------------------|
|         |                        | Logic in [29], [30] | Logic in [13] | Proposed Method |
| 1       | Close-in L-G fault without Rf | ✓                      | ✓              | ✓              |
| 2       | Close-in L-G fault with Rf  | ✓                      | ✓              | ✓              |
| 3       | Close-in LL-G fault without Rf | ×                      | ✓              | ✓              |
| 4       | Close-in LL-G fault with Rf  | ×                      | ✓              | ✓              |
| 5       | L-G fault in Zone-1 without Rf | ✓                      | ✓              | ✓              |
| 6       | L-G fault in Zone-1 with Rf  | ✓                      | ✓              | ✓              |
| 7       | L-G fault in Zone-2 without Rf | ✓                      | ✓              | ✓              |
| 8       | L-G fault in Zone-2 with Rf  | ✓                      | ✓              | ✓              |
| 9       | L-G fault in Zone-3 without Rf | ✓                      | ✓              | ✓              |
| 10      | L-G fault in Zone-3 with Rf  | ✓                      | ✓              | ✓              |
| 11      | LL fault in Zone-1 without Rf | ×                      | ✓              | ✓              |
| 12      | LL fault in Zone-1 with Rf  | ×                      | ✓              | ✓              |
| 13      | LL fault in Zone-2 without Rf | ×                      | ✓              | ✓              |
| 14      | LL fault in Zone-2 with Rf  | ×                      | ✓              | ✓              |
| 15      | LL fault in Zone-3 without Rf | ×                      | ✓              | ✓              |
| 16      | LL fault in Zone-3 with Rf  | ×                      | ✓              | ✓              |
| 17      | LL-G fault in Zone-1 without Rf | ×                      | ✓              | ✓              |
| 18      | LL-G fault in Zone-1 with Rf  | ×                      | ✓              | ✓              |
| 19      | LL-G fault in Zone-2 without Rf | ×                      | ✓              | ✓              |
| 20      | LL-G fault in Zone-2 with Rf  | ×                      | ✓              | ✓              |
| 21      | LL-G fault in Zone-3 without Rf | ×                      | ✓              | ✓              |
| 22      | LL-G fault in Zone-3 with Rf  | ×                      | ✓              | ✓              |
| 23      | Evolving Fault           | ×                      | ×              | ✓              |
| 24      | Cross Country Fault       | ×                      | ×              | ✓              |

The proposed distance protection methodology that uses the relative location of apparent impedance with respect to their concentric characteristics for identifying the faulted phases is able to identify the faulted phases in all the scenarios, including the evolving fault and cross country fault scenarios.

Hence, the proposed distance protection methodology is competent with the other methods and performs well in special conditions like evolving and cross-country faults where the methods in comparison failed.

VI. CONCLUSION

In a conventional distance relay, the use of concentric characteristics is limited to distinguishing fault and power swing based on the rate of change of apparent impedance. In this paper, a distance protection methodology that uses the concentric characteristics for faulted phase selection in addition to distinguishing fault and power swing is proposed. After identifying the presence of the fault based on the rate of change of apparent impedance, the relative location of the apparent impedance of the six distance elements with respect to their concentric characteristics is used for the identification of the faulty phases and to enable the right distance element to issue the trip signal. The specific contribution of this paper is to provide a unified solution of using the apparent impedance and concentric characteristics for the identification of fault, faulty phases, and power swing condition. The proposed algorithm is validated for all kinds of commonly occurring faults and special kinds of faults like evolving and cross-country faults through case studies in WSCC Nine Bus System.

The robustness of the faulty phase selection function of the proposed algorithm is demonstrated by comparing with those that employ sequence components and incremental quantity of the sequence components widely used by the distance relays used in the utilities. The comparison highlights the ability of the proposed algorithm to identify the faulted phases even during special kinds of faults like evolving and cross country faults where the methods in comparison failed. The proposed distance protection methodology is able to issue the trip signal in the correct zone within one cycle for common faults and within one and half cycle for special kinds of faults like evolving and cross-country faults.

APPENDIX

TRANSMISSION LINE DATA

The transmission line parameters of the 400 kV line in both the Two Machine system and WSCC Nine Bus System is given below:

- Positive Sequence Resistance $= 0.0298 \, \Omega/\text{km}$
- Zero Sequence Resistance $= 0.1619 \, \Omega/\text{km}$
- Positive Sequence Inductance $= 1.0568 \, \text{mH/km}$
- Zero Sequence Inductance $= 3.9470 \, \text{mH/km}$
- Positive Sequence Capacitance $= 11.0414 \, \text{nF/km}$
- Zero Sequence Capacitance $= 7.1301 \, \text{nF/km}$
- Frequency $= 50 \, \text{Hz}$

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