Adaptive Distance Protection for Line-to-Ground Faults in Networks with Grid-Following Inverters

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***Abstract*—The increasing penetration of inverter-based renewable resources (IBRs) has introduced new challenges to conventional protection practices in modern power systems. This paper investigates the behavior of a Grid-Following (GFL) inverter integrated into the IEEE 14-bus test system and analyzes its impact on distance protection under faulted conditions. Due to current-limiting control and PLL-based synchronization, GFL inverters inject low-magnitude and phase-modulated fault currents, causing traditional distance relays to experience significant underreach or overreach, particularly during high-resistance faults or weak-grid operation. To address these limitations, an adaptive distance protection scheme is proposed that updates Zone 1 reach in real time using locally estimated system impedance and inverter fault-current characteristics. The method also employs a substitution-based formulation at the relay bus to account for inverter internal voltage and variable control actions. Time-domain simulations conducted in PSCAD/EMTDC demonstrate that the proposed algorithm improves fault detection accuracy and reduces misoperation across varying fault resistances, and fault locations, thereby enhancing protection reliability in the presence of GFLs.**

***Index Terms*—Adaptive relaying, distance protection, fault current modulation, renewable energy systems, converter-interfaced sources.**

I. Introduction

Distance relays operate by comparing the apparent impedance at the relay with predefined reach settings and fault–resistance coverage, performing reliably in systems dominated by conventional synchronous generators. In networks with high penetration of inverter-based resources (IBRs), the current-limiting behavior of grid-following inverters reduces the available fault current and alters its phase, diminishing the relay's sensitivity. As a result, the effect of fault resistance due to remote infeed is significantly amplified, producing a larger deviation in the apparent impedance and frequently shifting the impedance trajectory outside the fixed reach boundaries [1]. The variable control of inverters introduces network non-homogeneity, which can compromise the operation of distance relay directional and fault classification elements, reducing the reliability of line protection. Previous adaptive approaches therefore either modify the apparent-impedance calculation to compensate for fault resistance and remote infeed or adapt the relay operating characteristic itself so the supervised reach remains coherent with prevailing system conditions. Methods that compensate the impedance computation rely on estimating fault resistance and/or supplementary impedance terms from local voltage/current measurements or from time-domain solution of overdetermined equations, while alternative schemes adapt zone boundaries based on assessed system operating mode or on post-fault estimation of two-source equivalents [2], [3]. In [4], a control-based scheme was proposed for power electronic-based power plants to coordinate with distance relays during unbalanced grid faults, improving protection accuracy and reliability. To address evolving challenges with inverter-based resources, a source agnostic time domain distance relaying algorithm is proposed in [5]. AI/ML techniques reported in [6] and [7] rely heavily on large volumes of training data, which makes their deployment challenging in real-world power system environments. With the growing penetration of inverter-based resources in modern power grids, traditional line protection schemes face significant challenges. While several solutions have been proposed and provide valuable improvements, further enhancements are still needed to ensure robust and reliable *stepped distance protection* (Zones 1–3) for transmission lines connected to inverter-based resources under these evolving system conditions. In this work, an adaptive Zone-1 setting scheme is proposed for lines connecting grid-following inverters, which accounts for variable inverter voltage and network impedance, does not require network homogeneity, estimates equivalent grid impedance from local pre-fault and fault measurements, and sets adaptive zone boundaries based on the phase angle and magnitude of the fault current.

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II. Problem Formulation

The Two-bus system shown in Fig.1 is used to analyze performance of conventional distance protection scheme. A grid-following (GFL) inverter is connected to the grid through a transmission line of impedance Z_{1L}, and faults are applied at a distance x along the transmission line. Here E_{INV} and Z_{INV} denote the inverter's voltage and impedance, respectively.

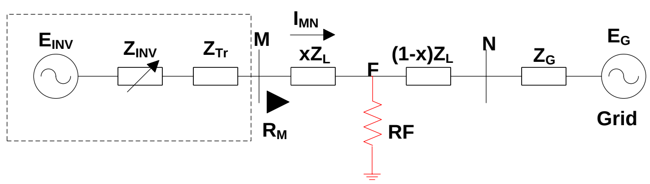

Fig. 1: VSC intergrated to grid.

The apparent impedance measured by a distance relay during a single-phase fault can be expressed as

$$Z_{\text{app}} = \frac{V_a}{I_a + K_0 I_0} = xZ_{1L} + \Delta Z = xZ_{1L} + \frac{3I_{1F}}{I_a + K_0 I_0} R_F \quad (1)$$

Where V_a is the phase-A voltage, I_a is the phase-A current, I_0 is the zero-sequence current, and $K_0 = (Z_{0L} - Z_{1L})/Z_{1L}$ is the zero-sequence compensation factor. Z_{1L} and Z_{0L} are the positive-sequence and zero sequence line impedances respectively. R_F is the fault resistance and I_{1F} is the positive-sequence fault current.

In the presence of GFL inverters with controlled fault current, the deviation impedance ΔZ is larger at times. Major grid codes require inverters to regulate both the magnitude and phase angle of injected current during disturbances. These effects increase the deviation term, distort the apparent impedance trajectory, and frequently cause conventional distance relays to underreach or misclassify in zone and out of zone faults in IBR-dominated grids.

In this work, the sequence-network relationships are used to estimate the grid equivalent impedance Z_{1G} and the fault current I_{1F} from pre-fault and during-fault positive- and negative-sequence measurements. By contrasting the steady-state and faulted conditions, the method captures real-time variations in grid strength and GFL inverter current contribution. In addition, the substitution theorem is applied at the relay bus to account for the variable control actions and the internal voltage and impedance characteristics of the inverter, ensuring that these dynamic effects are properly reflected in the computed quantities.

III. Proposed Method

A. Geometric Construction of the Adaptive Zone-1 Boundary

The adaptive Zone-1 boundary is constructed by translating the analytical expression of the apparent impedance into a geometric representation on the R–X plane. Conventionally, Zone 1 reach is defined considering 80% of the positive-sequence line impedance and resistive coverage. Under GFL-dominated fault conditions, however, the inverter's current-limiting behavior modifies the effective infeed contribution

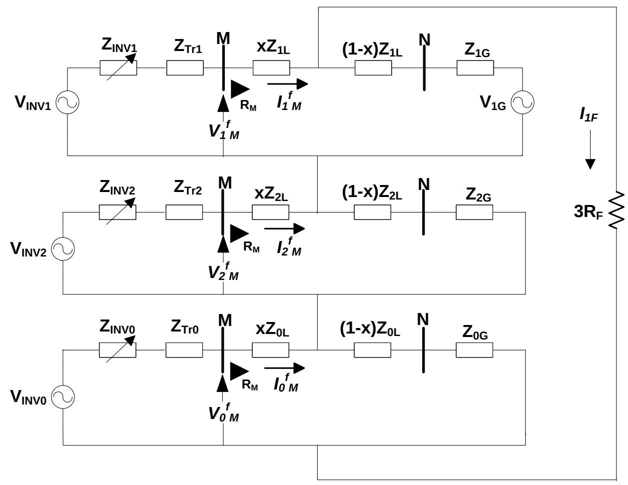

Fig. 2: Sequence-network representation of LG fault.

such that the apparent impedance deviates from this fixed boundary. To capture this shift, the proposed method introduces a second line DE from the $0.8Z_{1L}$ point at a deviation angle α with respect to R axis unlike parallel to this as shown in Fig. 3. The angle α is calculated as

$$\alpha = \angle \Delta Z = \angle I_{1F} - \angle (I_a + K_0 I_0) \quad (2)$$

The physical significance of α can be understood from the R–X plane representation of apparent impedance. In systems dominated by synchronous generators, the relay current $(I_a + K_0 I_0)$ is nearly in phase with the fault current I_{1F}, causing the fault-resistance-induced deviation to lie primarily along the resistance axis. In grid-following inverter-based systems, however, PLL-based synchronization and current control introduce a phase difference between I_{1F} and the relay-measured current, resulting in a rotated deviation impedance ΔZ in the R–X plane. By orienting the adaptive Zone-1 boundary parallel to the angle α, the proposed parallelogram characteristic aligns with the dominant direction of apparent impedance deviation, improving coverage of internal faults while avoiding overreach for external faults. The line length is equal to the maximum deviation impedance magnitude, calculated based on resistance coverage and the maximum fault current magnitude. The adaptive parallelogram relay characteristics are formed by drawing the rest two lines.

The resulting parallelogram-shaped Zone 1 region, therefore, aligns with inverter-modulated impedance behaviour while extending appropriately in the resistive direction. In this way, the adaptive boundary dynamically reflects variations in grid strength, fault resistance, and inverter current-limiting action, mitigating overreach and underreach concerns present in fixed-setting relays. With such settings the apparent impedance falls outside boundaries for higher zone faults as shown in Fig.4.

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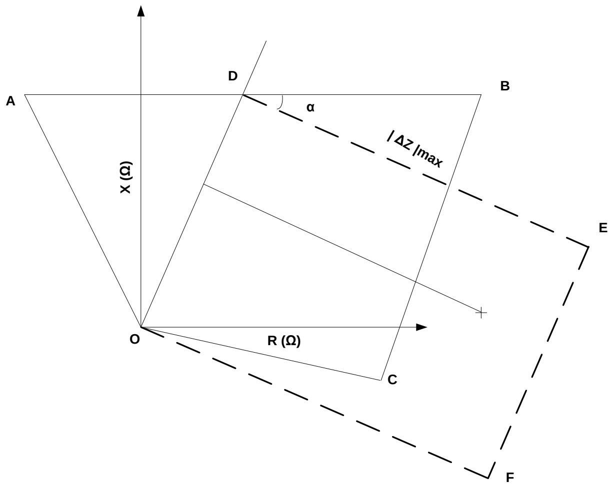

Fig. 3: Performance of Adaptive Zone-1 Boundary setting algorithm for Zone-1 faults.

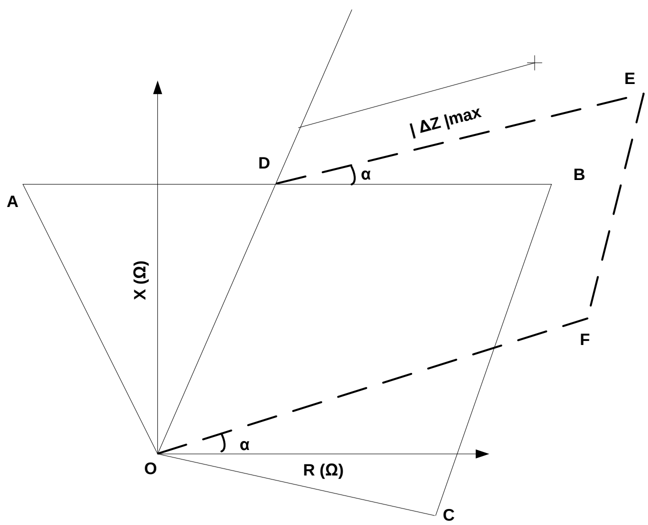

Fig. 4: Performance of Adaptive Zone-1 Boundary setting algorithm for Zone-2 faults.

B. Sequence-Network Formulation for Parameter Estimation

To support the adaptive protection scheme, the pre-fault and during-fault relationships are expressed using the positive- and negative-sequence networks. These expressions enable estimation of the generator positive-sequence impedance Z_{1G} and the fault current I_{1F}, required for real-time computation of the apparent impedance and adaptive Zone-1 reach.

1) Pre-Fault Condition: The steady-state positive-sequence voltage at the relay location M is

$$V_{1M}^{\text{pre}} - Z_{1L} I_{1M}^{\text{pre}} - Z_{1G} I_{1M}^{\text{pre}} - V_{1G}^{\text{pre}} = 0. \tag{3}$$

The superscript "pre" denotes prefault quantities.

2) During-Fault Sequence Equation: When an LG fault occurs at a distance x from the relay, the positive-sequence network as given in Fig.2 satisfies

$$V_{1M}^{f} - Z_{1L} I_{1M}^{f} + [(1-x)Z_{1L} + Z_{1G}]\, I_{1F} - Z_{1G} I_{1M}^{f} - V_{1G} = 0. \tag{4}$$

The superscript "f" stands for during fault quantities. The corresponding negative-sequence expression is derived from the network shown in Fig.2 as

$$V_{2M}^{f} - Z_{1L} I_{2M}^{f} + [(1-x)Z_{1L} + Z_{1G}]\, I_{1F} - Z_{1G} I_{2M}^{f} = 0. \tag{5}$$

3) Grid Impedance Estimation: (3), (4) and (5) yield an estimate of the remote grid side impedance as:

$$Z_{1G} = \frac{\left(V_{1M}^{pre} - V_{1M}^{f} + V_{2M}^{f}\right) - Z_{1L}\left(I_{1M}^{pre} - I_{1M}^{f} + I_{2M}^{f}\right)}{I_{1M}^{pre} - I_{1M}^{f} + I_{2M}^{f}}. \tag{6}$$

4) Fault-Point Current Expression: Solving the sequence network yields the positive-sequence fault current:

$$I_{1F} = \frac{(V_{1G} - V_{1M}) + Z_{1L} I_{1M}^{f} + Z_{1G} I_{1M}^{f}}{Z_{1L}(1-x) + Z_{1G}}. \tag{7}$$

Assuming homogeneity in the grid, the phase angle of the fault-point positive-sequence current is expressed as

$$\angle I_{1F} = \angle\left(\left(V_{1G} - V_{1M}^{f}\right) + (Z_{1L} + Z_{1G}) I_{1M}^{f}\right) - \angle Z_{1L}. \tag{8}$$

Since the Zone 1 reach corresponds to 80% of the line, we set $x = 0.8$ to obtain the maximum internal-fault current within the Zone 1 protection boundary:

$$|I_{1F}|_{\max} = \frac{\left|(V_{1G} - V_{1M}^{f}) + (Z_{1L} + Z_{1G})\, I_{1M}^{f}\right|}{\left|0.2\, Z_{1L} + Z_{1G}\right|} \tag{9}$$

Algorithm 1 Determination of Adaptive Relay Settings

Step 1: Acquire Prefault Measurements: Measure three-phase voltages and currents at the relay location under steady-state (prefault) conditions. **Step 2: Estimate Equivalent Grid Voltage:** Compute grid-side voltage: **Step 3: Detect Fault and Extract Faulted Quantities:** Extract voltage and current phasors at the relay bus during fault: **Step 4: Determine Fault Loop Sequence quantities:** Compute positive- and negative-sequence fault loop currents and voltage: **Step 5: Compute Incremental Impedance:** Determine $|\Delta Z|_{max}$ and $\angle \Delta Z$. **Step 6: Construct Adaptive Quadrilateral:** (a) Draw the first line in the R–X plane representing 80% of the line impedance (xZ_{1L}). (b) From both ends, draw two parallel lines inclined by $\angle \Delta Z$ to the real axis. (c) Each parallel line has length $|\Delta Z|_{max}$. (d) Connect the ends to form a parallelogram defining the adaptive Zone-1 boundary. **Step 7: Decision Logic:** Z_{app} lies inside the adaptive parallelogram Issue **Zone-1 Trip**.

IV. Results

The effectiveness of the proposed distance-protection scheme is evaluated on the IEEE 14-Bus benchmark system, shown in Fig. 5, using PSCAD/EMTDC simulations. The system operates at a nominal frequency of 60 Hz. In this study,

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a grid-following inverter operating under the control strategy illustrated in Fig. 6 replaces the conventional synchronous generator at bus 2. The performance of the distance relay installed at bus 2 is then examined. To assess relay behavior, multiple fault types are applied along line 2–3. Phasor quantities are extracted using a one-cycle DFT, with voltage and current waveforms sampled at 1.8 kHz.

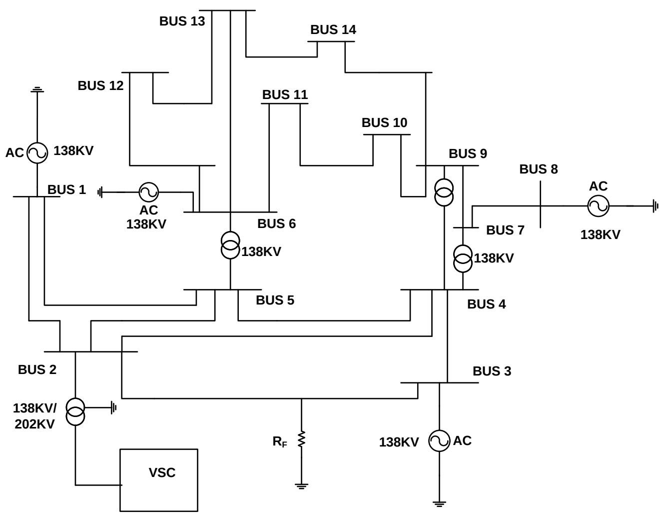

Fig. 5: IEEE 14 Bus system

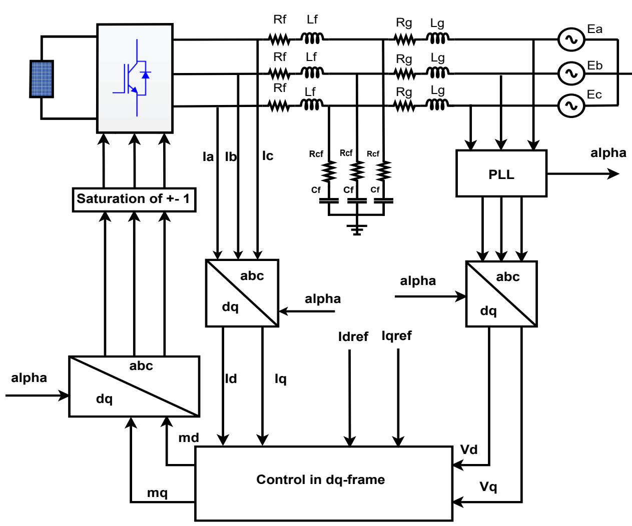

Fig. 6: Overall Control Structure Block Diagram

A. Performance of the proposed method for different fault resistance.

To evaluate the performance of the proposed adaptive boundary distance relaying algorithm, line-to-ground faults of AG type are created at a distance of 0.4 pu from bus 2. Three fault-resistance values—$R_F = 1\,\Omega$, $10\,\Omega$, and $100\,\Omega$—were considered to examine their impact on the proposed algorithm. For each case, the boundaries of the relay were designed based on the parameter $(I_F/I_r)R_F$ and results are shown in Fig.7 (a), (b) and (c) for $R_F = 1\,\Omega$, $10\,\Omega$, and $100\,\Omega$ respectively. In all the three zone-1 fault cases the apparent impedance fell within the adaptive boundary indicating that the distance relay operated correctly as expected.

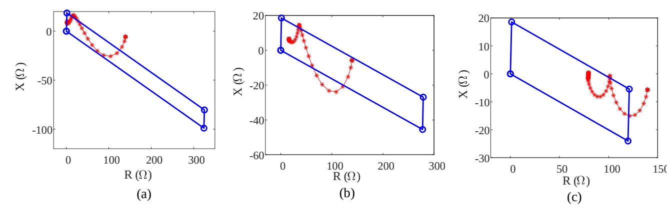

Fig. 7: $x = 0.4$; (a) $R_F = 1\,\Omega$ (b) $R_F = 10\,\Omega$ (c) $R_F = 100\,\Omega$

B. Performance of the proposed method for different fault Location.

Tests were conducted by applying faults at different locations along the transmission line—specifically at 30%, 50%, and 90% of its length—while a constant fault resistance of 75 Ω was maintained. For each case, the apparent impedance observed by the relay was analyzed to determine whether it fell within the adaptive Zone-1 protection boundary. The results showed that faults at 30% and 50% of the line were correctly identified within Zone-1, ensuring instantaneous relay operation. In contrast, the fault at 90% of the line resulted in an apparent impedance outside the Zone-1 boundary, indicating that such a distant fault would not be cleared by Zone-1 and would instead depend on higher protection zones for clearance.

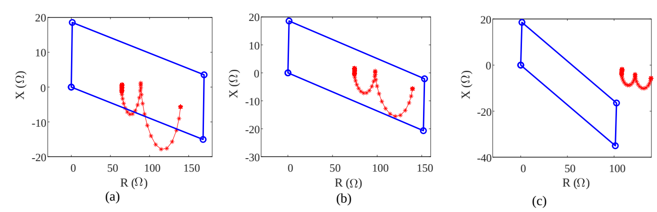

Fig. 8: $R_F = 75\,\Omega$ (a) x=0.3 (b) x=0.5 (c) x=0.9

V. Conclusion

This paper presented an adaptive distance protection scheme for transmission lines connected to grid-following (GFL) inverters under line-to-ground fault conditions. The proposed method dynamically adjusts the Zone-1 reach based on real-time estimation of grid impedance and inverter fault-current characteristics, effectively accounting for current-limiting and phase-modulated behavior of GFL inverters. Time-domain simulations on the IEEE 14-bus system demonstrated that the adaptive boundary accurately captures apparent impedance deviations caused by varying fault resistances and fault locations. For all Zone-1 faults tested, the apparent impedance remained within the adaptive boundary, ensuring correct relay operation, while more distant faults were correctly handled by higher protection zones. The results confirm that the proposed algorithm enhances relay reliability, mitigates underreach and

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overreach issues, and provides robust line protection in IBR-dominated networks. Future work can focus on extending this scheme to multi-terminal lines and incorporating adaptive Zone-2 and Zone-3 settings for comprehensive protection coverage.

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