Adaptive Fault Type Classification for Transmission Network Connecting Converter-Interfaced Renewable Plants

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Abstract—Fault ride through compliance as imposed by the grid codes (GCs) prevents the inadvertent disconnection of the renewable plants from the network even during faults. Control algorithms applied in the converters associated with such plants modulate the fault characteristics significantly and result in malfunction of available fault type classifiers at times. In this article, an adaptive fault type classification technique is proposed for transmission network connecting converter-interfaced renewable plants. The method calculates sequence current angles in the faulted loop by determining pure-fault impedance of the plant at every instant during fault using local voltage and current data for fault type identification. The proposed method is tested for different fault situations on renewable integrated standard systems using PSCAD/EMTDC. The performance of the proposed method is found to be accurate in the presence of different types of renewable plants and complying different GC requirements. Comparative assessment reveals its superior performance.

Index Terms—Fault type classification, power system faults, renewable energy power plant.

I. INTRODUCTION

A. Motivation and Incitement

PRESENT environmental concern compels large-scale converter-interfaced renewable plants (CIRPs) to be integrated to high-voltage transmission networks [1], [2]. In order to maintain required reliability of a power system with variable renewable sources (like solar and wind farms), different control schemes are being applied through the converters connected to CIRPs [3]. To satisfy the fault ride through (FRT) requirement as imposed by different grid codes (GCs), CIRPs are to be connected even during fault [4], [5]. Presence of such converter interfaced sources in the network modulates the voltage and current signals significantly during fault. Such a different fault characteristic impels available protection schemes to be under scrutiny where fault type classification is an important task [6], [7]. Identification of fault type is an integral part of relay decision process in transmission networks with applications such as single pole tripping, distance relaying, etc. [8]. Diversified control

schemes in the presence of CIRPs, different GC requirements and system nonhomogeneity ask for a revisit on the available fault type classification techniques.

B. Literature Review

The methods available for fault classification tasks can be classified into different categories and are highlighted in the following section.

1) *Commercial Approaches*: Phase angles associated with sequence current and voltage components are generally utilized in commercially available relays for fault type classification [8]–[10]. The relay compares the relative angles between pure-fault sequence currents available at the local end and identifies the fault type in the network [9]. Such approach remains unaffected from fault resistance and load imbalance issue and classifies the fault types fast and accurately. Adverse effect of phase angle variation in positive sequence current is avoided in some relays by utilizing the angle difference between negative and zero sequence currents only [10]. In this technique, fault resistances are estimated for discrimination between single-line-to-ground and double-line-to-ground faults. Phase angle difference of superimposed sequence voltages are utilized in some of the relays along with current angle feature for fault type classification in weak-infeed situation [8], [11]. These techniques consider homogeneity in the system and work properly for power networks connecting synchronous generators (SGs). However, with CIRP modulating the voltage and current signal during fault and system homogeneity consideration being no more valid, such fault type classification techniques find limitations.

2) *Data Driven Approaches With/Without Advanced Signal Processing Tools*: Several training-based techniques using artificial neural network, fuzzy logic, decision tree, and their hybrid combinations are proposed for fault classification in transmission network [12]–[17]. Some of those approaches use features extracted from voltage and current using signal processing tools like discrete wavelet transform, S-transform [18], [19]. Diversified control schemes associated with renewable plants change the voltage and current patterns significantly during fault compared to a conventional synchronous generator-based system. Therefore, the performance of such pattern-based classification techniques are under scrutiny for networks with renewables. In addition, such approaches require large number of training data sets, which are very difficult to obtain in real power system.

3) *Modification in Control Schemes*: One control-based solutions is provided in [6] for proper fault type classification

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using conventional technique. Dual current controller is used to regulate the negative sequence current in the CIRP imitating synchronous generator fault current signature. Such modification in the controller embedded in the inverter is difficult to generalize for different control schemes with different type of sources, in particular for a large grid.

4) *Miscellaneous Approaches*: A time domain fault classification technique is proposed in [7] for wind power system based on the waveform correlation of transient voltage, which requires high sampling frequency for its operation. Some improved fault type classification techniques are proposed for microgrids in the presence of renewable generations [20], [21]. The technique in [21] is developed assuming very small phase angle difference between the positive sequence voltages at both ends of the protected line. Such assumption holds good for microgrids and is not valid for long transmission lines connecting large-scale CIRPs. Fault classification technique utilizing system wide data obtained through phasor measurement units are proposed in [22], [23]. Communication of data during fault results delay in decision and makes the technique unsuitable for fast protection requirements.

C. Contribution

In this article, an adaptive fault type classification technique is proposed for transmission network connecting converter-interfaced renewable plant. For a CIRP integrated nonhomogeneous system, the proposed method uses local voltage and current data to determine the phase angles of sequence currents in the faulted loop by calculating the pure-fault sequence impedances of the renewable plant during fault and are updated at every measurement instant following fault detection. The calculated sequence current angles are applied for fault type identification. The proposed method is tested for different fault situations with change in system conditions on renewable integrated different standard systems using PSCAD/EMTDC. The performance of the proposed method is also tested in the presence of different renewable plants complying different GC requirements and found to be accurate. Comparative assessment with available techniques establishes the superior performance of the proposed method.

The main contributions of this article can be summarized as follows.

- 1) A pure-fault sequence network is obtained for a CIRP integrated transmission system by modeling the CIRP with a fixed voltage source and variable series impedance. Such a model of CIRP is adaptive to different control operations and variability associated with it.
- 2) The pure-fault sequence impedances of the CIRP are determined using local voltage and current data measured during fault and prefault and are updated continuously with every set of measurements available during fault.
- 3) The calculated pure-fault sequence impedances of the CIRP are used to determine the sequence current angles in the faulted loop, applied for fault type classification. In case of unavailability of negative sequence current from CIRP even during asymmetrical fault, local voltage data are used to obtain the phase angle of negative sequence current in the faulted loop.

Fig. 1. CIRP integrated modified 39-bus New England system.

D. Organization

The article is organized as follows: Section II introduces the renewable integrated test system used in this article with description on the control scheme applied for the CIRPs. The issues associated with fault classification techniques available in commercial relays and algorithms recommended for weak-infeed conditions are analyzed in Section III. The proposed adaptive fault classification technique is formulated in Section IV. Results evaluating the performance of proposed method at different situations and the real-time validation are provided in Sections V and VI. The observation on the results obtained for different conditions is discussed in Section VII and finally Section VIII concludes the article.

II. SYSTEM DESCRIPTION

A 345 kV, 60 Hz, 39-bus New England system [24] integrating renewable plants, as shown in Fig. 1, is considered in this article for defining the problem and testing the proposed method. Simulations are carried out using EMTDC/PSCAD. Voltage and current phasors at relay bus are estimated using 1-cycle discrete Fourier transform (DFT) with a data sampling rate of 3.84 kHz. Digital mimic filter is used to eliminate the decaying-dc component of fault current [25].

The generator connected at bus 33 is replaced by a 300 MW solar photovoltaic (PV) plant [26]. The solar plant consists of multiple PV units, each connected to the common coupling bus (33) through a dc/ac inverter and dYg type transformer. The solar-based CIRP is controlled in synchronous reference frame, which regulates the fault current along with the filter of the converter, as shown in Fig. 2 [27]. The grid side and converter side voltages are denoted by V_{grid} and V_{inv} , respectively. Feedforward compensation is provided, as shown in Fig. 2, to decouple the converter operation from the disturbances occurred in the grid side. This maintains the voltage across the filter to be balanced even during unbalanced situation in grid side and consequently generates balanced current in output.

The solar plant is modeled satisfying North American grid codes (NA-GCs) and operates close to unity power factor [28]. As to the GC, the solar plant rides through the low voltage situation during fault without imposing any regulation on active and

Fig. 2. Control scheme applied to the solar-based CIRP.

Fig. 3. Current angle-based fault type classifying logic. (a) δ_I^+ comparator. (b) δ_I^0 comparator

reactive components of fault current [28]. For verification of the impact of different renewable sources, the solar plant is replaced in some cases with Types-III and IV wind farm consisting of standard control schemes [29], [30]. A 300 MW Type-III wind farm is also connected at bus 38 with the existing synchronous generator, sharing its total generation. The performance of the fault type classification techniques are also tested in the presence of renewable plants complying European grid codes (EU-GCs) regarding FRT requirement.

Performance of the fault type classification algorithms are tested for the relay at bus 19 for faults in line 16–19. For emphasizing the issue in the presence of CIRPs, bus 20 is disconnected from bus 19, which isolates the generator at bus 34 and load at bus 20 from rest of the system. In order to maintain proper generation and load balance, bus 15, 16, and 24 loads are modified suitably.

III. PROBLEM STATEMENT

This section reviews the sequence current angle-based fault type classifier used in most of the commercial relays associated with a voltage-based algorithm, recommended for fault classification in weak-infeed situation and makes an assessment of their performances in the presence of CIRP.

A. Current Angle-Based Fault Type Classification

Many available relays use current angle-based comparison for fault type classification [8], [9]. In the approach, relay classifies the fault types using the phase angle relationship of the sequence currents in the faulted loop as in Fig. 3 [8]. The letters A, B, and C in the figure represent the respective phases of a 3-phase system and G indicates the ground. In the figure, δ_I^+ and δ_I^0

Fig. 4. Performance of conventional current angle-based classification with SG and solar-based CIRP.

represent the angle difference of negative sequence fault current with the positive and zero sequence fault currents, respectively. Subscripts 0, 1, and 2 represent the zero, positive, and negative sequence components, respectively. System connecting only SGs maintains homogeneity in the network and thereby the fault currents on both ends of the protected line possess similar phase angle relationship. This allows the current angle-based fault type classifier to operate correctly in conventional power systems using only local current measurements.

On the other hand, the CIRPs are modeled as controlled current sources. Thus, the sequence currents during faults are modulated according to the control schemes associated with the CIRPs. This makes the sequence currents from CIRP to be of different phase angle relationship compared to that in the faulted loop. This results in malfunction of current angle-based fault type classifier at times in such a scenario. This is demonstrated in Fig. 4 for the performance of relay at bus 19 for a phase-A-to-ground fault (AG) in line 19–16. The fault is created at 5 s at a distance of 0.3 pu from bus 19 with a fault resistance of 0.5 Ω . As shown in Fig. 4, the relay calculates $\delta_I^+ = -1.3^\circ$ and $\delta_I^0 = 1.2^\circ$ in the presence of synchronous generator at bus 33 of 39-bus system (as in the nonmodified system). Thus, the relay identifies the fault type correctly with the relation shown in Fig. 3. On the other hand, the relay calculates $\delta_I^+ = -40^\circ$ and $\delta_I^0 = 90.4^\circ$ in the presence of solar-based CIRP. Thus, the relay cannot identify any fault type using δ_I^+ comparator of Fig. 3, whereas δ_I^0 comparator identifies the AG fault as CG or ABG fault. This demonstrates the incorrect operation of such fault type classifier in the presence of CIRP. Fault type misidentification by δ_I^0 also results in maloperation of the relays using fault resistance estimation along with the angle difference of negative and zero sequence currents for the purpose [10].

B. Voltage Angle-Based Fault Type Classification

Relays also use the phase angle relationship between superimposed sequence voltage components for fault type classification, when the current-based approach fails to identify any particular fault type, especially for weak-infeed situation [8]. In this technique, the relay uses similar angle comparators, as in Fig. 3, but with superimposed sequence voltage angles. Superimposed voltage at a bus connected to a plant depends on superimposed current and equivalent plant impedance, which get modulated with the applied control schemes in the plant. Thus, the relay using superimposed voltage angle based classifier may also maloperate in the presence of CIRP.

Fig. 5. Performance of voltage angle-based classifier in the presence of CIRP.

Fig. 6. Transmission network integrating solar-based CIRP to grid.

Fig. 7. Two bus equivalent model of CIRP integrated transmission network.

Such a maloperation is observed for voltage-based classifier for the same fault, as discussed in Section III-A, where the current angle-based classifier failed. Results are shown in Fig. 5, where δ_V^+ and δ_V^0 represent the angle difference of negative sequence superimposed voltage with the positive and zero sequence superimposed voltages, respectively. In this case, the relay finds $\delta_V^+ = 28^\circ$ and $\delta_V^0 = -5.8^\circ$. Results in Fig. 5 show that δ_V^+ calculated by the relay is outside the detection zone for AG fault. Thus, the relays fail to identify the fault type even using current and voltage angle-based classifier concurrently.

With such limitations of available fault type classification techniques, there is a need for an alternative technique to identify fault types in the transmission networks connected to CIRPs.

IV. PROPOSED FAULT TYPE CLASSIFICATION TECHNIQUE

To mitigate the issues associated with available fault classifiers in the presence of CIRP, a local voltage and current data-based adaptive fault type classification technique is proposed. Fig. 6 shows a transmission line connecting solar-based CIRP. The solar plant consists of multiple solar PV units with each one connected to the collector bus through dc/ac inverter and a step-up transformer as mentioned in Section II.

Fig. 7 shows the equivalent diagram of the system of Fig. 6, considering MN as the protected line with an impedance Z_L , for the following analysis. A fault in the line is considered at a distance of $x pu$ from bus M. The positive sequence model of conventional power grid connecting only SGs is represented

Fig. 8. Equivalent model of a CIRP integrated network. (a) Prefault. (b) Fault situations.

Fig. 9. Pure-fault network of a CIRP integrated transmission network.

using a voltage source (E_G) with an impedance (Z_G) in series. A grid connected solar plant is considered as a voltage controlled current source [31]. This is represented in Fig. 7 with a current source (I_{PV}) and a parallel variable admittance (Y_{PV}) in series with the transformer impedance (Z_{Tr}) [6]. I_{PV} and Y_{PV} are functions of solar irradiance, number of operating units and their control scheme at that instant. At any particular instant, a current source can be converted to an equivalent voltage source (E_{PV}) with an equivalent impedance in series (Z_{PV}) [32]. Such a voltage source-based representation is shown in Fig. 7. Z_{PV} changes at each measurement instant, in accordance with the variation of solar irradiance, plant status, and control operation. Such a representation satisfies the controlled voltage and current output at the terminal of CIRP [33]. Equivalent impedance of the solar plant consisting of Z_{PV} and Z_{Tr} in series is represented as Z_{SP} further in the analysis.

Representation of such a network during prefault and fault situations consists of different equivalent impedances, as shown in Fig. 8 (a) and (b), respectively. Z_{SPpre} and Z_{SPf} represent the equivalent impedances of solar plant during the prefault and fault, which vary with the measurement instances depending on the control scheme and system condition.

Using Kirchhoffs current law for the circuit in Fig. 8 (b), the current through the faulted loop can be expressed as follows:

$$I_F = I_{MF} + I_{NF} \quad (1)$$

where, I_{MF} and I_{NF} represent the fault currents at bus M and N, respectively.

Currents at both ends during prefault are equal in magnitude, but opposite in phase, as shown in Fig. 8 (a). Thus, (1) can be rewritten as follows:

$$I_F = \Delta I_M + \Delta I_N \quad (2)$$

where incremental current, $\Delta I_{(M,N)}$ at each end are represented as in (3).

$$\Delta I_{(M,N)} = I_{(M,N)F} - I_{(M,N)pre} \quad (3)$$

Using the property of (3), a pure-fault sequence network for a CIRP integrated system is represented in Fig. 9. Note that pure-fault impedance of solar plant (Z_{SPpf}) is different from

Fig. 10. Pure-fault sequence network for (a) AG. (b) BC. (c) BCG fault with solar-based CIRP connected at bus M.

Z_{SPpre} and Z_{SPf} . The excitation voltage (E_F) is the fault point voltage during prefault.

Applying current distribution property in Fig. 9, incremental current at bus M (ΔI_M) can be expressed as follows:

$$\Delta I_M = \frac{(1-x)Z_L + Z_G}{Z_{SPpf} + Z_L + Z_G} I_F \quad (4)$$

Using the property obtained from (1) in (4), Z_{SPpf} can be represented as in (5).

$$Z_{SPpf} = \frac{(I_{MF} + I_{NF})((1-x)Z_L + Z_G)}{I_{MF} - I_{Mpre}} - (Z_L + Z_G) \quad (5)$$

Using equivalent internal voltage of grid (E_G), (5) can be rewritten as follows:

$$Z_{SPpf} = \frac{(E_G + I_{Mpre}(Z_L + Z_G)) - (E_G - I_{NF}((1-x)Z_L + Z_G) + I_{MF}xZ_L)}{I_{MF} - I_{Mpre}} \quad (6)$$

With the equivalent networks during prefault and fault situations, as shown in Fig. 8, Z_{SPpf} in (6) can be expressed as follows:

$$Z_{SPpf} = \frac{V_{Mpre} - V_{MF}}{I_{MF} - I_{Mpre}} \quad (7)$$

With the concept as derived above-mentioned, the pure-fault sequence diagrams of the system in Fig. 7 for AG, BC, and BCG faults are shown in Fig. 10 representing all three asymmetric fault types. R_{ph} represents the phase-to-phase arcing resistance. Solar plant controlled in synchronous reference frame and with feedforward compensation is set to generate balanced current output, as described in Section II. Thus, the negative sequence network for solar plant in Fig. 10 is represented by an open circuit. dYg connection of the transformer connecting solar plant results in zero sequence current at bus M to flow through only transformer and line impedances, as shown in Fig. 10 (a).

Series connection of the sequence networks in Fig. 10 (a) for an AG fault results in the sequence currents through R_F (I_{1F} , I_{2F} , and I_{0F}) to be equal in magnitudes and phases. Similarly, Fig. 10 (b) shows the antiphase relationship between I_{1F} and I_{2F} for BC fault. I_{2F} and I_{0F} in Fig. 10 (c) are not influenced

Fig. 11. Pure-fault sequence current distribution for AG fault with solar plant at bus M. (a) ΔI_{1M} . (b) ΔI_{2M} . (c) ΔI_{0M} . (d) ΔI_{1N} . (e) ΔI_{2N} . (f) ΔI_{0N} . (g) I_{1F} . (h) I_{2F} . (i) I_{0F} .

by the solar plant due to the control scheme generating balanced current output and dYg type transformer connection. Thus, the phase angle difference of negative and zero sequence impedances being very small for a conventional transmission network [34], I_{2F} and I_{0F} remain in phase with each other for BCG fault. This results in I_{1F} and I_{2F} to be in phase opposition for BCG fault also. Such phase angle relationship is used in the conventional current angle-based classifier in identifying the particular fault types in the network [8]. Due to the inequality and nonhomogeneity in the equivalent sequence impedances of solar plant, sequence currents in the faulted loop are distributed at both the line ends with unequal signatures. This is demonstrated in Fig. 11 for a AG fault created in line 16-19 of Fig. 1. The figure shows that the phase angle relationship used in the current angle-based fault classifier is not followed by the pure-fault sequence currents at bus M, whereas it is properly maintained in the faulted loop. A fault classification technique is proposed in the next section by applying the sequence current angles in the faulted loop determined using local measurements.

A. Proposed Technique to Determine Sequence Current Angles in the Faulted Loop

Using the current distribution property in Fig. 10 (a), I_{1F} can be expressed in terms of ΔI_{1M} as follows:

$$I_{1F} = \Delta I_{1M} \frac{Z_{1SPpf} + Z_{1L} + Z_{1G}}{(1-x)Z_{1L} + Z_{1G}}. \quad (8)$$

Homogeneity in a conventional transmission network allows the grid equivalent impedance (Z_G) to be expressed in terms

of protected line impedance (Z_L) with real valued multiplier ($K_{1,2,0}$) for each sequence component, as in (9).

$$Z_{(1,2,0)G} = K_{(1,2,0)} Z_{(1,2,0)L}. \quad (9)$$

Grid strength being sufficiently large compared to solar plant, Z_{1G} is much smaller than Z_{1L} and Z_{1SPpf} . Thus, neglecting Z_{1G} in the numerator of (8) and using (9), I_{1F} can be approximated as follows:

$$I_{1F} \approx \Delta I_{1M} \left(\frac{Z_{1SPpf} + Z_{1L}}{(1-x + K_1)Z_{1L}} \right) \quad (10)$$

With Z_{1SPpf} obtained from (7), the phase angle of I_{1F} can be determined from,

$$\arg(I_{1F}) = \arg \left(\left(1 + \frac{Z_{1SPpf}}{Z_{1L}} \right) \Delta I_{1M} \right) \quad (11)$$

Negative sequence network being considered as an open circuit for the solar plant, V_{2M} in Fig. 10 becomes equal to V_{2F} . I_{2F} is only contributed from the grid side and can be expressed as follows:

$$I_{2F} = -\frac{V_{2F}}{(1-x)Z_{2L} + Z_{2G}} \approx -\frac{V_{2M}}{(1-x + K_2)Z_{2L}} \quad (12)$$

Thus, the phase angle of I_{2F} can be determined as follows:

$$\arg(I_{2F}) = \arg \left(\frac{V_{2M}}{Z_{2L}} \right) - \pi \quad (13)$$

Note: I_{2M} may be available at the renewable connected bus in the presence of other types of sources and associated control schemes. Some of the available standards reveal that the CIRP interfacing inverters are being configured to be capable of providing negative sequence current [35]. For such a situation in the presence of I_{2M} , the relay calculates the phase angle of I_{2F} in a similar way to (11).

$$\arg(I_{2F}) = \arg \left(\left(1 + \frac{Z_{2SPpf}}{Z_{2L}} \right) \Delta I_{2M} \right) \quad (14)$$

Where Z_{2SPpf} can be calculated similarly as in (7) using negative sequence voltage and current. Phase angle of I_{2F} calculated using (14) is valid whenever I_{2M} is available, even for a short duration of time with rapid modulation [36]. In case the control action inhibits the negative sequence current afterwards, the angle can be calculated using (13).

Due to dYg connection of transformer, I_{0M} in Fig. 10 flows only through the transformer and homogeneity is maintained for zero sequence current distribution at both the ends. Thus, the phase angle of I_{0F} can be determined as follows:

$$\arg(I_{0F}) = \arg(\Delta I_{0M}) \quad (15)$$

I_{0M} may even become negligible in case of different types of connections of the interfacing transformer (like, ygYg or ygD). In such a situation, the relay calculates the angle associated with I_{0F} similar to (13) as for negative sequence current angle calculation.

B. Proposed Method

Steps associated with the proposed fault type classification technique are provided in Fig. 12. Following fault detection, the relay determines Z_{1SPpf} using local voltage and current

Fig. 12. Flow diagram of proposed fault type classification technique.

measurements. Utilizing this, the proposed method calculates the angle associated with I_{1F} using (11). Absence of both negative sequence voltage and current confirms a balanced fault situation. In case of balanced current output from a CIRP even during asymmetric fault, the proposed method calculates the angle of I_{2F} using negative sequence voltage data available to the relay using (13). In the presence of I_{2M} (with different control schemes associated with different types of sources and also for conventional system), the proposed method calculates the angle of I_{2F} using (14), similar to the approach used in calculating the angle of I_{1F} . Following identification of ground fault by the presence of I_{0M} , the relay calculates the angle of I_{0F} using (15). As the relative angles of the sequence currents in the faulted loop hold unique relationship with each other for different fault types in the network, the calculated angles of I_{1F} , I_{2F} , and I_{0F} are applied in the current angle-based classifier for fault type identification. Fault current limitation of a renewable plant results drop in positive sequence voltage (V_1) to be significant during fault, which is used in this article for fault detection. As shown in Fig. 12, the presence of negative sequence voltage (V_2) is also used for the purpose to provide high sensitivity to the fault detection unit for asymmetrical faults with high R_F . Thresholds (V_{1th} and V_{2th}) used in fault detection unit are selected considering maximum steady-state voltage deviation and voltage unbalance for a transmission network.

V. RESULTS

Performance of the proposed fault type classification technique is tested on renewable integrated modified 39-bus New England system as in Fig. 1. The proposed method is evaluated using the local data available at the renewable connected bus in the system. Results are provided for different fault types with variations in fault resistance, fault location, system condition in the presence of different renewable sources with changes in associated control scheme, GC requirement, and plant output, as summarized in Table I. The performance of the proposed method is also tested for some critical fault conditions and with different standard test systems.

TABLE I
LIST OF FAULT CASES

Fault types	AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABC
R_F (Ω)	0.5, 1, 5, 10, 30, 50, 100
x (pu)	0.05, 0.1, 0.3, 0.5, 0.7, 0.9, 0.95, external
$ Z_{1G} $ (pu)	0.1, 1, 2, 5, 10
$(X/R)_{Z_{1G}}$	5, 15, 25, 40
Variability of CIRP	25, 50, 75, 100 (% of plant capacity)
Grid code	NA-GC, EU-GC
CIRP type	Solar, Type-III wind, Type-IV wind
Sampling frequency	0.96 kHz, 1.92 kHz, 3.84 kHz, 7.68 kHz
Test systems	WSCC 9-bus, 39-bus New England, IEEE 118-bus
Other cases	Presence of measurement noise, with CT saturation, Fault during power swing, no line flow condition

Fig. 13. Relative angles for AG fault.

TABLE II
COMPARATIVE ANALYSIS WITH RECENT AVAILABLE METHODS

Parameters	Available Methods				Proposed Method
	[37]	[7]	[13]	[15]	
Data required (single/both end)	Single end	Single end	Single end	Both end	Single end
Tested for CIRP end	No	Yes	No	Yes	Yes
Adaptive to control schemes of CIRP	No	Yes	No	Yes	Yes
Tested with different CIRPs	No	Yes	No	No	Yes
Sampling rate	1 kHz	10 kHz	1-16 kHz	1.2 kHz	0.96-7.68 kHz
Data Volume	Online	Online	Volume of training data	Volume of training data	Online
Response time	11 ms	6 ms	6-10 ms	45ms	4-10 ms

A. Performance Evaluation With Comparative Assessment

Performance of the relay at bus 19 in Fig. 1 is evaluated for a AG fault created at 5 s in line 19-16 at a distance of 0.25 pu from bus 19, with a fault resistance of 0.5 Ω . Result in Fig. 13 shows that the relay using conventional current angle-based classification approach [8] obtains $\delta_I^+ = -40^\circ$ and $\delta_I^0 = 90.4^\circ$. Thus, the method fails to identify any fault type using δ_I^+ comparator of Fig. 3, whereas δ_I^0 comparator identifies the AG fault as CG or ABG fault. Even with voltage-based approach of [8], the relay calculates $\delta_V^+ = 28^\circ$, which is out of the identification zone for AG fault, as shown in Fig. 13. Thus, it clearly demonstrates the malfunctioning of both current and voltage-based approaches. The proposed fault type classification method calculates $\delta_I^+ = -0.9^\circ$ and $\delta_I^0 = -1.8^\circ$ by applying the steps as in Fig. 12 and identifies the fault type correctly.

A comparative assessment of proposed method with recently available techniques is summarized in Table II. The transient monitoring index-based approach of [37], voltage wave

TABLE III
PERFORMANCE EVALUATION FOR VARIATION IN FAULT RESISTANCE

Fault Type	Classifier Zone (Fig. 3)	R_f (Ω)	Conventional		Proposed	
			δ_I^+	δ_I^0	δ_I^+	δ_I^0
AG	$\delta_I^+: 0 \pm 15$	5	-7.3	99	0.24	-0.12
	$\delta_I^0: 0 \pm 30$	100	-153	147.8	-0.1	-0.05
BCG	$\delta_I^+: 180 \pm 15$	5	156.8	72.5	-179.2	1.03
	$\delta_I^0: 0 \pm 30$	100	54	168.2	180	0.2
CA	$\delta_I^+: -60 \pm 15$	1	-85.1	—	-59.8	—

(Angles in degree)

correlation-based method of [7], fast discrete orthonormal s-transform (FDOST)-based approach of [13], and data mining-based technique of [15] are considered for this assessment. The table clearly depicts that the adaptive faulted-loop current angle estimation-based proposed method is superior compared to the recently available methods for a CIRP integrated system.

B. Performance of Proposed Method for Different Fault Types With Variation in Fault Resistance

Relative angles of the sequence currents in the faulted loop change with the fault types and are independent of fault resistance. Thus, the proposed method can identify the fault types accurately in the presence of fault resistance. Performance of both conventional and proposed classification method are provided in Table III for identification of different fault types with variation in fault resistance. Results show that δ_I^+ and δ_I^0 calculated by the proposed method are within the correct classification zones as mentioned in column II of Table III, whereas the conventional approach fails to identify the fault types correctly at times. For the case of BCG fault with a R_F of 100 Ω (Second row of Table III), the conventional approach calculates $\delta_I^+ = 54^\circ$ and $\delta_I^0 = 168.2^\circ$, which lie outside the classifier zones of $180^\circ \pm 15^\circ$ and $0^\circ \pm 30^\circ$, respectively. On the other hand, the relay using proposed method calculates $\delta_I^+ = 180^\circ$ and $\delta_I^0 = 0.2^\circ$ and identifies the fault type correctly. This clearly demonstrates the superiority of the proposed method compared to the conventional method.

C. Performance for Faults at Different Locations With Change in System Condition

Grid strength is considered to be sufficiently large compared to the solar plant in the formulation of the proposed method. Wide margins provided for fault classification zones ($\pm 15^\circ$ for δ_I^+ , $\pm 30^\circ$ for δ_I^0) in the method ensure correct identification of fault types even for weak grid condition. This is demonstrated through an evaluation, where faults are created in line 16-19 of Fig. 1 with variation in grid equivalent impedance (Z_{1G}) from 0.1 to 10 pu of the earlier considered value. The required Z_{1G} is obtained by replacing the system connected at bus 16 with its Thevenin equivalent. The distribution of faulted loop current being dependent on Z_{1SPpf} and x [as observed in (8)], simultaneous variation in those parameters are also considered for this demonstration. Solar plant output directly affects Z_{1SPpf} . Therefore, the output of the plant is varied from 25% to 100% by changing the number of operating units in the plant. The

Fig. 14. Performance of the proposed method for AG faults at different locations with change in system conditions.

Fig. 15. Performance of the proposed method for AG faults at different locations with change in grid impedance characteristics.

performance of the proposed method is evaluated for AG faults at different locations (0.1 to 0.9 pu) in line 16-19. Results are provided in Fig. 14, where the relative angles calculated by the proposed method are presented by color mapping. Results show that δ_I^+ and δ_I^0 obtained for all the cases are well within the margin provided in the proposed method. It is also observed that the relative angles computed by the proposed method deviates more from their ideal values (0° for both δ_I^+ and δ_I^0 for AG fault) for high Z_{1G} situations, whereas high Z_{1SPpf} obtained for reduced plant output situation results in lower deviation. This shows the robustness of the proposed method in identifying fault types in different system conditions.

D. Performance of the Proposed Method for Change in Grid Impedance

In the formulation of proposed method, grid strength is considered to be sufficiently large and with Z_{1G} and Z_{1L} be homogeneous. As the proposed technique accommodates a wide margin for fault classification zones ($\pm 15^\circ$ for δ_I^+ , $\pm 30^\circ$ for δ_I^0), it can perform correctly even for a large deviation from the two considerations. This is demonstrated through an evaluation, where AG faults are created in line 16-19 of Fig. 1 with variation in magnitude and (X/R) ratio of Z_{1G} . The required Z_{1G} is obtained by replacing the system connected at bus 16 by its Thevenin equivalent, similar to the Section V-C. The magnitude of Z_{1G} is varied from 0.1 to 5 times of the earlier considered value and (X/R) ratio of Z_{1G} is varied from 5 to 40. Simultaneous variation in x is also considered for this article. Results are shown in Fig. 15. δ_I^+ and δ_I^0 obtained for all the cases are represented with color mapping, which are well within the margin provided for corresponding classification zone. This verifies the robustness of the proposed method under such situations.

TABLE IV
PERFORMANCE WITH DIFFERENT TYPES OF GC COMPLIANCE

Fault Type	Classifier Zone (Fig. 3)	Grid Code	Conventional		Proposed	
			δ_I^+	δ_I^0	δ_I^+	δ_I^0
CG	$\delta_I^+ : -120 \pm 15$	NA-GC	-73.9	-115.7	-119.84	119.9
	$\delta_I^0 : 120 \pm 30$	EU-GC	37.8	116.7	-121.4	119.8
BCG	$\delta_I^+ : 180 \pm 15$	NA-GC	156.8	72.5	-179	1.03
	$\delta_I^0 : 0 \pm 30$	EU-GC	-2.7	-20.2	-171	-2.8
AB	$\delta_I^+ : 60 \pm 15$	NA-GC	69.2	—	60.2	—
		EU-GC	-135.6	—	52.4	—

(Angles in degree)

E. Performance With Different GC Compliance

Grid integrated CIRPs must satisfy the FRT requirements imposed by GCs. Such requirement enforces regulation on active and reactive power generation criteria during fault. FRT requirement varies with the GCs imposed by different countries and its results in modulation of the fault current differently. Impact of two popular GCs on fault type classification is discussed in this section.

- 1) NA-GC enforces the FRT compliance on CIRP without imposing any specific regulation on active and reactive fault current component and operates the CIRP close to unity power factor even during fault.
- 2) EU-GC imposes higher priority on reactive power support to improve the voltage profile at common coupling point [28].

Performance of both conventional and proposed classification method is tested for the relay at bus 19 of Fig. 1 for different faults in line 16-19, while the solar plant satisfies both the GCs, each at a time. Results are provided in Table IV. As in the first row of Table IV, for a CG fault the conventional approach calculates $\delta_I^+ = -73.9^\circ$ and $\delta_I^0 = -115.7^\circ$ for the solar plant satisfying NA-GC, whereas it calculates $\delta_I^+ = 37.8^\circ$ and $\delta_I^0 = 116.7^\circ$ for EU-GC compliance by the plant. In both the cases, the conventional method cannot find the relative angles within the respective classifier zone, as mentioned in column II and misclassifies the fault type. On the other hand, the proposed method finds the relative angles within the set classifier zones for both cases and identifies the fault type correctly. Results provided for BCG and AB faults in Table IV also have similar conclusions. This demonstrates the capability of the proposed method in identifying fault types in the presence of CIRPs complying different GCs.

F. Performance Evaluation With Different Types of CIRP

Control schemes and converter arrangements associated with CIRPs vary with the source types. Thus, the modulation of fault current differs significantly with the types of CIRP. The proposed technique determines the pure-fault plant impedance independent of the source types and associated control schemes and identifies the fault types accurately in the presence of different types of CIRP. This is demonstrated with the performance of the relay at bus 19, for faults in line 16-19. The solar plant connected at bus 33 is replaced by type-III wind farm first and then by type-IV. Results in Fig. 16 show that for AG fault the relay using conventional current angle approach calculates $\delta_I^+ =$

Fig. 16. Performance evaluation of proposed method for different types of CIRP with comparative assessment.

Fig. 17. Performance of proposed method for fault in a no line flow condition.

$-168.0^\circ, 58.5^\circ, 116.4^\circ$, and $\delta_I^0 = 144.0^\circ, 8.7^\circ, 58.2^\circ$ in the presence of solar plant, Type-III wind farm and Type-IV wind farm, respectively. This shows the fault current modulation diversity in the presence of different types of CIRP resulting malfunction of the available fault classification technique. On the other hand, the relay using proposed method finds the relative angles within their classification zones, as shown in Fig. 16 and identifies the fault type correctly. This demonstrates the adaptability of the proposed method for different types of sources with different control schemes.

G. Performance of the Proposed Method With no Line Flow Condition

The incremental current (ΔI), calculated in (3), uses current during fault and prefault condition. The prefault current for a no line flow situation contains only line-charging current. A fault in such a situation may be critical to classify. The proposed method is tested for such an event. To achieve no line flow situation in line 19-16, the loads at bus 19 and bus 16 are adjusted suitably. A phase-B-to-ground (BG) fault is created in line 16-19 at a distance of 0.3 pu from bus 19 with $R_F = 5 \Omega$. It is evident from the results shown in Fig. 17 that the method applied at bus 19 identifies the fault type correctly even for such a case.

H. Performance of the Proposed Method for Faults Near Local and Remote Buses

Faults close to local bus with negligible R_F and near remote bus with high R_F are considered as two critical cases for a transmission line protection scheme. In the first case, a CAG fault is created at 5 s in line 16-19 at a distance of 0.05 pu from bus 19 with a R_F of 0.5Ω . In the second case, a BG fault is created at 5 s in line 16-19 at a distance of 0.95 pu from bus 19 with a R_F of 100Ω . Results for both the cases are shown in Fig. 18.

Fig. 18. Performance of the proposed method for faults close to line ends.

Fig. 19. Performance of the proposed method for an external ABG fault.

It is observed that δ_I^+ and δ_I^0 calculated by the proposed method are inside their corresponding fault classification zones, which demonstrate the correct performance of the proposed method even for such critical fault events.

I. Performance of the Proposed Method for External Fault

Homogeneity in a conventional transmission network allows the proposed method to perform correctly even for external faults. This is demonstrated for an ABG fault created in line 16-17 at a distance of 0.1 pu from bus 16 with a R_F of 10Ω . Results shown in Fig. 19 demonstrate the correct operation of the proposed method applied at bus 19 for such an external fault situation.

J. Performance in the Presence of Measurement Noise

1-cycle DFT and the antialiasing low-pass filter can mitigate the effect of noise in the proposed method. In order to evaluate the performance of the proposed method under noisy condition, voltage, and current signals are contaminated with uniform distribution noise with zero mean and a standard deviation of 3% [38]. δ_I^+ and δ_I^0 calculated by the proposed method for such a situation are shown in Fig. 20 along with the voltage and current signals. Results demonstrate the effectiveness of the proposed method even with measurement noises.

K. Performance Assessment for CT Saturation

There is a low probability of current transformer (CT) saturation in case the line is only connected to CIRP because of the fault current limiting property. Presence of parallel infeed from a conventional source may result in CT saturation. Such a situation changes the incremental current from its actual value. The adaptive approach used in the proposed method for calculating faulted loop current by determining pure-fault plant impedance at every instant during fault reduces the impact of CT saturation

Fig. 20. Performance of the proposed method in the presence of measurement noises. (a) Voltage and current with noise and (b) angles.

Fig. 21. Performance of the proposed method in case of CT saturation showing (a) phase currents and (b) angles.

on the performance. A CAG fault is created in line 16-19, at 5 s at a distance of 0.1 pu from bus 19 with a R_F of 0.5Ω . The parallel infeed at bus 19 from generator connected at bus 34 in Fig. 1 is considered to be present for this case and CT burdens are selected such a way that CT saturation is observed at bus 19 for the fault case. Results in Fig. 21 show δ_I^+ and δ_I^0 computed by the proposed method for such a situation along with the phase current waveforms. This demonstrates the robustness of the proposed method even for CT saturation situation.

L. Performance Assessment During Power Swing

Power swing being a symmetrical event, it is detected as a nonfault situation by the negative sequence voltage threshold used in the fault detection unit applied in the proposed method. An asymmetrical fault during power swing may put challenge for the fault classification unit due to the dynamic variation in voltage and current measurements. However, proposed method has no issue for such condition as it calculates current in faulted loop by determining pure-fault plant impedance and updates for every each set of measurements available during fault. Performance of the proposed fault classification method is tested for fault during power swing.

A 300 MW Type-III wind farm is connected at bus 38 of the 39-bus New England system of Fig. 1 sharing the total generation of the existing synchronous generator. A three phase fault is created in line 26-29 at 7.3 s, which is cleared by opening the circuit breakers at both ends of the line at 7.35 s. As a result, a power swing is observed in the system. An ABG fault is created in line 26-28 at 8 s with a R_F of 10Ω . Fig. 22 (a) shows the voltages at bus 28 and currents in line 26-28. Following the detection of fault, the proposed method determines the equivalent pure-fault impedance of the source side for every available measurement

Fig. 22. Performance of the proposed method for fault during power swing.

Fig. 23. Performance of the proposed method with different sampling frequencies.

sets and calculates δ_I^+ and δ_I^0 for fault type classification. Results in Fig. 22 (b) demonstrate that the proposed method can identify the fault type correctly even for a fault during power swing.

M. Performance Assessment With Different Sampling Rates

Renewable plants are integrated to the system through power converters, which use high switching frequency and generate more harmonics. The higher sampling frequency provides better representation of the signal and also eases the low-pass filter design. The proposed method requiring only fundamental components for its operation can perform accurately even with a sampling frequency of 960 Hz (16 samples/cycle). This is demonstrated below in Fig. 23 for a sampling rate of 16, 32, 64, and 128 samples/ cycle representing sampling frequencies of 960, 1920, 3840, and 7680 Hz, which are common for the commercial relays used in a 60 Hz system. BG faults created in line 16-19 with a R_F of 10Ω are considered for the case.

N. Performance Evaluation of the Proposed Method for Different Standard Systems

The performance of the proposed method is tested for other two standard systems integrating CIRP. First one is a WSCC 9-bus system integrating a 100 MW solar plant at bus 9, as in [27]. Second one is an IEEE 118-bus system [39], where a 100 MW solar plant is connected at bus 112. The proposed method is tested at the solar plant connected bus for faults in line 8-9 for 9-bus system and line 110-112 for the 118-bus system with variation in fault type, fault resistance, and fault location. Results of the cases are provided in Table V, which demonstrate that the relative angles computed by the proposed method are within the corresponding classification zones. Thus, the proposed method performs correctly for different power systems.

TABLE V
PERFORMANCE EVALUATION FOR DIFFERENT STANDARD SYSTEMS

Fault Type (Classification Zones)	x (pu)	R_F (Ω)	WSCC 9-bus		IEEE 118-bus	
			δ_I^+	δ_I^0	δ_I^+	δ_I^0
AG $(\delta_I^+ : 0 \pm 15)$ $(\delta_I^0 : 0 \pm 30)$	0.05	1	1.27	-0.39	0.14	-0.01
		100	-0.50	-0.28	0.02	0.07
	0.95	1	0.63	-2.38	0.05	-0.02
		100	0.05	-1.41	2.02	3.13
BCG $(\delta_I^+ : 180 \pm 15)$ $(\delta_I^0 : 0 \pm 30)$	0.05	1	-178.73	0.88	-179.40	0.97
		100	178.71	-11.23	174.44	-10.40
	0.95	1	-176.53	5.54	-175.77	14.30
		100	179.07	-1.17	177.75	-1.07
BC $(\delta_I^+ : 180 \pm 15)$	0.05	1	-181.9	-	-181.7	-
	0.95	1	-179.4	-	-180.1	-

(Angles in degree)

Fig. 24. Real-time simulation (OPAL-RT) experimental setup.

TABLE VI
PARAMETERS ASSOCIATED WITH OPAL-RT SIMULATOR

Parameters	Description
Time step	100 μs
Operating system	Linux based Redhat OS
Simulator	OP5607 (RCP/ HIL vitex7 FPGA processor)

VI. REAL-TIME VALIDATION

The proposed method is validated using OP5607 (OPAL-RT) real-time simulator. Fig. 24 shows the real-time simulation experimental setup used for this article. Parameters associated with real-time simulator are provided in Table VI. The renewable integrated 39-bus New England system (see Fig. 1) and the proposed fault type classification method are first modeled in MATLAB integrated with OPAL-RT. Then, those are compiled with RT-LAB to run as an effective platform for developing and testing real-time operation of the proposed method for the system under consideration.

A BG fault is created in line 19-16 at a fault distance of 0.4 pu from bus 19 with a R_F of 20 Ω . Results are provided in Fig. 25. It is observed that the relative angles computed by the proposed method applied at bus 19 are within the corresponding classification zones and the fault type is identified correctly. Fault is detected at 4 ms following fault inception applying the voltage drop principle used in the proposed method and the classification unit identifies the fault type immediately following the detection.

Fig. 25. Real-time performance of the proposed scheme.

VII. DISCUSSION

The observations on the results can be summarized as follows.

- 1) The proposed fault classification method can identify the fault types correctly within 10 ms even for any critical fault event in a CIRP integrated transmission network.
- 2) The proposed classification technique is adaptive to the change in control scheme associated with different CIRPs and complied GCs.
- 3) The proposed method is found to be robust against the significant variation in grid impedance characteristics and also resilient against the measurement inaccuracies such as presence of noise and CT saturation.
- 4) The fault classifier is triggered by a fault detection unit, which discriminates the nonfault events such as load switching, power swing, etc, from faults and prevents maloperation of classifier for such situations.
- 5) Real-time validation using OP5607 (OPAL-RT) demonstrates the efficacy of the proposed classification method for practical implementation.

VIII. CONCLUSION

The different control schemes adopted in the renewable plants affect the homogeneity of fault currents contributed from both ends of a line. This leads to the performance of available fault classification techniques based on local current and voltage data to be erroneous. An adaptive fault type classification technique is proposed for such a nonhomogeneous situation in the presence of renewables. Using local voltage and current data, the sequence current angles in the faulted loop are calculated by determining the pure-fault impedance of the renewable plant at every instant following the fault detection and applied for fault type classification. In case of unavailability of negative sequence current from CIRP even for asymmetrical fault, voltage data are used for the required phase angle calculation. The proposed method performs correctly in the presence of any control scheme applied for different types of sources in the network. The performance of the proposed method is demonstrated for different fault types with change in fault resistance and fault location. Results provided in the presence of different renewable sources with variation in associated control schemes, GC requirements, plant output, and grid condition validate the adaptability of the proposed method with different fault characteristics variation, even in weak grid condition. Accurate performance for challenging situations like power swing, CT saturation, and presence of measurement noises demonstrate the robustness of the proposed method. Comparative assessment with the available techniques reveals its superiority.

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