Assessment of Directional Elements for Power Networks Connected to Inverted Based Renewable Resources: Problems and Mitigation Approach

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***Abstract*— The existing commercially available directional methods require angles of voltage, current, line, and source impedances to determine the direction of the fault. In presence of inverter-based renewables resources (IBRs) the voltage, current, and source impedance angle deviates, and it depends on the inverter controls. The inverter controls are dictated by the grid codes and interconnection agreements. Therefore, the existing methods may be mal operating for networks connected with IBRs. In this paper, a detailed study of existing methods is provided, and a mitigation approach is also proposed using only the current signal. The proposed approach is tested using EMTDC simulation of a 220kV, 200 km transmission line connected with IBRs. The proposed method is validated with field data which confirms the accuracy of the proposed mitigation approach.**

Keywords—Transmission line protection, directional relay, Clarke's transformation, inverter-based resources

I. INTRODUCTION

Large-scale integration of renewables is taking place due to environmental concerns. With the integration of the inverter-based resources (IBRs), the fault voltage and currents are modulated due to which voltage and current angles may shift [1]. The angle/phase shift may affect the conventional line protection principles using local end information such as line distance and directional protection. The directional relay algorithms are classified into time-domain, frequency domain, and time-frequency domain-based methods [2]. The frequency-domain-based methods depend on the phase shift polarizing quantity (reference) and operating quantity (current).

The positive, negative, and zero sequence-based methods requires the three sequence voltages respectively as polarizing quantity and the three sequence currents during a fault, respectively, as the operating quantity to determine the direction of fault [3]. The positive sequence-based methods may not work well for lines connected with IBRs as abnormal phase angle shifts are introduced by converter controls [4]. The negative sequence-based directional elements may not work for full converter-based renewable resources as these systems are not provided with negative sequence currents due to converter feedforward compensation [5]. Moreover, the negative and zero sequence-based directional methods require source impedances which are varied during the fault continuously which may result in the mal-operation of these methods for lines connected with renewables.

To mitigate the issues due to renewable integration, only current-based methods are proposed [6]-[7] and [9]. A time domain-based directional method is proposed in [6] using only fault current signal. The fault direction is determined by comparing the generated reference signal with the fault current signal. The success of the method depends on correct reference signal generation which depends on the fault inception and current zero-crossing time. The zero-crossing detection is not easy and is impacted by the fault inception time, transients and DC offset present in the fault signals. Also, the directionality detection using only the current phasor is presented in [7]. The methods [6] and [7] require knowledge of fault type. The fault type identification for the networks with renewables is difficult [8] and the performance of these methods may be affected. The phase difference between the pre-fault and fault current is used to determine the direction of the fault [9]. The performance of the method requires power flow direction.

A review of the existing literature reveals that the existing voltage-based polarizing quantity directional elements depend on both voltage and current angle information which might not be reliable for IBRs. The only current-based method without dependency on the angles of voltage, and source impedance is reliable for the networks with IBRs. In this paper, a detailed analysis of the existing methods is reviewed, and a mitigation approach is proposed using only the current signal to eliminate the dependency on fault type. The proposed method is illustrated through numerical simulations using PSCAD/EMTDC environment and is validated with field data which confirms the accuracy of the proposed method.

The paper is organized as follows: Section II analyses the existing voltage based polarizing methods, Section III describes the proposed solution approach, Section IV explains the simulation results and analysis, Section V presents the validation of proposed method with field data and Section VI presents the conclusion of this paper.

II. ANALYSIS OF VOLTAGE-BASED POLARISING METHODS

Two scenarios are analyzed to investigate the potential issues with voltage-based polarizing methods in the presence of IBRs: (1) both sides have conventional sources, and (2) one side is a wind park as shown in Fig. 1 and Fig. 2, respectively. The analysis uses a 100 MW synchronous generator and a 400 MW Type IV wind turbine generator connected to a 200 km transmission line.The line parameters and power flow details are maintained the same for both cases. The inverter modeling details are taken from the recent literature [11, 12].

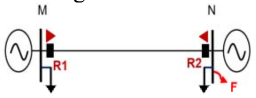

Fig.1. Single line diagram for Scenario 1.

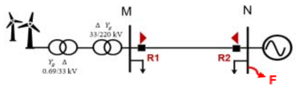

Fig.2.Single line diagram for scenario 2.

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A. Positive Sequence Directional Method [3]

The method requires the positive sequence angle $\emptyset_1$ which is expressed in terms of positive sequence voltage V_{1M} and positive sequence current I_{1MN} as in (1).

$$\emptyset_1 = \angle I_{1MN} - \angle V_{1MN} = -\angle Z_{MF1} \quad (1)$$

where, Z_{MF1} is the positive sequence impedance of line MN. The zones of the direction of fault in terms of Z_{MF1} can be expressed as in (2).

$$\emptyset_1 = \begin{cases} -\angle Z_{MF1} < \emptyset_1 < 0, & Forward\ fault \\ \angle Z_{MF1} < \emptyset_1 < 180°, & Reverse\ fault \end{cases} \quad (2)$$

Let us consider ABC-g fault on Bus N with R_f of 0.01 Ω as shown in Fig. 1. The voltage and current waveforms measured by R_1 for scenario 1 and scenario 2 as shown in Fig. 3. The V_{1M} and I_{1MN} measured by relay R_1, R_2 are as shown in Table I. Table II shows the direction of fault detected using the positive sequence method for both scenarios.

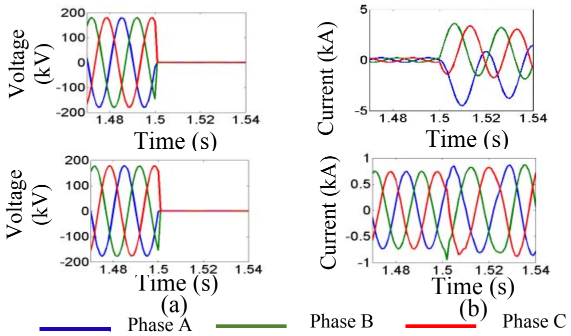

Fig. 3. Voltage and Current waveforms for ABCG fault on Bus N with R_f 0.01 ohms seen by R_2 (a) scenario 1 and (b) scenario 2.

TABLE I
POSITIVE SEQUENCE COMPONENTS FOR SCENARIO 1 AND SCENARIO 2

Relay	Scenario 1		Scenario 2	
	$V_1(kV)$	$I_1(kA)$	$V_1(kV)$	$I_1(kA)$
R_1	$0.06\angle-79.6$	$2.045\angle 43.26$	$0.02\angle-168$	$0.844\angle 35.54$
R_2	$105\angle-75.3$	$2.53\angle-135$	$22\angle-59.21$	$0.801.\angle-154$

TABLE II
POSITIVE SEQUENCE DIRECTION FOR SCENARIO 1 AND FOR SCENARIO 2

Relay	$\angle I_1 - \angle V_1$		Actual Direction	Scenario 1 Direction	Scenario 2 Direction
	Scenario 1	Scenario 2			
R_1	122.89	-156.85	Reverse	Reverse	Out of zone
R_2	-59.5	-96.21	Forward	Forward	Out of zone

Fig. 4(a) shows that the method works well for conventional systems but is not reliable for IBR-connected systems as seen from Fig. 4(b). For both R_1, R_2 the directional element was out of the zone (Table II). This is because of the abnormal phase angle shifts observed due to converter controls in the case of IBR-connected systems.

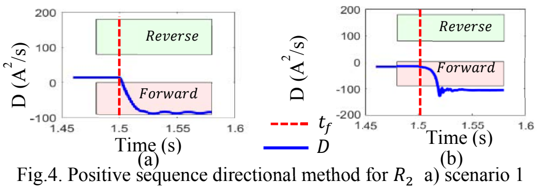

Fig.4. Positive sequence directional method for R_2 a) scenario 1 b) scenario 2

B. Negative Sequence Directional Method [3]

The method requires the negative sequence angle $\emptyset_2$ which is expressed in terms of negative sequence voltage V_{2M} and negative sequence current I_{2MN} as in (3).

$$\emptyset_2 = \angle I_{2MN} - \angle -V_{2MN} = -\angle(Z_{SL2} + Z_{LM2}) \quad (3)$$

where, Z_{SL2} is the negative sequence impedance of source 1 and Z_{LM2} is the negative sequence impedance of line MN. The zones of the direction of fault can be expressed as in (4).

$$\emptyset_2 = \begin{cases} -\angle(Z_{SL2} + Z_{LM2}) < \emptyset_2 < 0, & Forward\ fault \\ \angle(Z_{SL2} + Z_{LM2}) < \emptyset_2 < 180°, & Reverse\ fault \end{cases} \quad (4)$$

For a BC-g fault on Bus N for the system shown in Fig.1 and Fig. 2, Table III shows V_{2M} and I_{2MN} measured by relay R_1,R_2 for scenarios 1 and scenario 2. Table IV shows the direction of fault detected using the negative sequence method for both scenarios.

Fig.5 and Table IV shows that for both R_1, R_2,the directional element was out of zone for IBR connected system. This is because of the continuous variation of source equivalent in case for IBR connected systems during fault.

TABLE III
NEGATIVE SEQUENCE COMPONENTS FOR SCENARIO 1 AND FOR SCENARIO 2

Relay	Scenario 1		Scenario 2	
	$V_2(kV)$	$I_2(kA)$	$V_2(kV)$	$I_2(kA)$
R_1	$74.4\angle-79.7$	$1.21\angle-145$	$75.2\angle-71.9$	$0.07\angle-8.6$
R_2	$30.9\angle-79.9$	$1.10\angle 14.72$	$76.6\angle-72.7$	$0.050.\angle 154.8$

TABLE IV
NEGATIVE SEQUENCE DIRECTION FOR SCENARIO 1 AND FOR SCENARIO 2

Relay	$\angle I_2 - (\angle V_2 - 180)$		Actual Direction	Scenario 1 Direction	Scenario 2 Direction
	Scenario 1	Scenario 2			
R_1	94.57	−116.7	Reverse	Reverse	Out of zone
R_2	-65.32	47.57	Forward	Forward	Out of zone

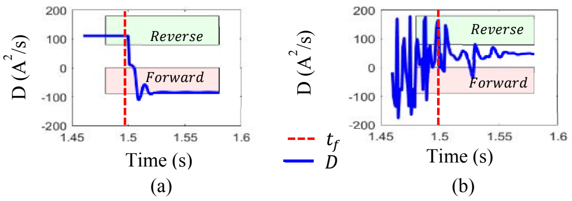

Fig.5. Negative sequence directional method for scenario 1 and scenario 2 for relay a) R_1 b) R_2

C. Zero Sequence Directional Method [3]

The method requires zero sequence angle $\emptyset_0$ which is expressed in terms of zero sequence voltage V_{0M} and zero sequence current I_{0MN} as in (5).

$$\emptyset_0 = \angle I_{0MN} - \angle -V_{0MN} = -\angle(Z_{SL0} + Z_{LM0}) \quad (5)$$

where, Z_{SL0} is the zero sequence impedance of source 1 and Z_{LM0} is the zero sequence impedance of line MN. The zones of the direction of fault can be expressed in terms of Z_{LM0} and Z_{SL0} as below:

$$\emptyset_0 = \begin{cases} -\angle(Z_{SL0} + Z_{LM0}) < \emptyset_0 < 0, & Forward\ fault \\ \angle(Z_{SL0} + Z_{LM0}) < \emptyset_0 < 180°, & Reverse\ fault \end{cases} \quad (6)$$

For the system shown in Fig. 1 and Fig. 2, Table V shows the V_{0M} and I_{0MN} for R_1 and R_2 for BC-g fault for scenarios 1 and scenario 2. Table VI shows the directions detected.

Fig. 6(a) confirms that the zero-sequence method works well for conventional systems but not for systems connected to IBR (Fig. 6 (b)). This is because of the varying zero-sequence equivalent in the case of IBR systems during fault. Most offshore wind farms are connected through subsea cables. The zero-sequence impedance angle can be very less in cases of subsea cable which might reduce the zone available for forward faults because of which this method might fail.

TABLE V
ZERO SEQUENCE VOLTAGE AND CURRENT FOR SCENARIO 1 AND SCENARIO 2

Relay	Scenario 1		Scenario 2	
	$V_0(kV)$	$I_0(kA)$	$V_0(kV)$	$I_0(kA)$
R_1	$74.5\angle-79.8$	$1.05\angle-153.4$	$76.9\angle-64.8$	$0.47\angle-159$
R_2	$20.6\angle-80.1$	$0.456\angle6.24$	$28.9\angle-59.3$	$0.48.\angle31.33$

TABLE VI
ZERO SEQUENCE DIRECTION FOR SCENARIO 1 AND SCENARIO 2

Relay	$\angle I_0-(\angle V_0-180)$		Actual Direction	Scenario 1 Direction	Scenario 2 Direction
	Scenario 1	Scenario 2			
R_1	106.4	96.13	Reverse	Reverse	Reverse
R_2	-53.65	-99.36	Forward	Forward	Out of zone

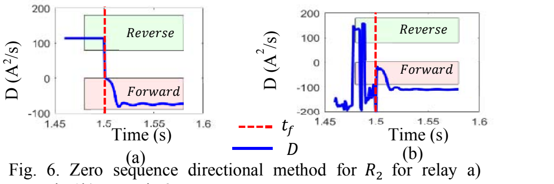

Fig. 6. Zero sequence directional method for R_2 for relay a) scenario 1b) scenario 2.

D. Results Summary of Existing Practical Methods for Conventional and IBR Connected Systems

A 2-bus system of a 200 km transmission line with both sides conventional source (Fig. 1) and one side conventional and one side IBR source (Fig. 2). Four fault types (A-g, BC-g, BC, ABC-g) are considered for two different fault resistances (0.01 Ω and 10 Ω).Four different fault locations i.e., Fault on bus M, 25% of the line from bus M, 75% of the line from bus M and on bus N are considered for analysis.

A total of 64 cases are considered for both conventional systems and IBR-connected systems for relays R_1 and R_2. The positive and zero sequence impedance of the line considered for the system in Fig.1 and Fig.2 are 0.543 + 29.72i Ω and 39.38+129.35iΩ respectively.

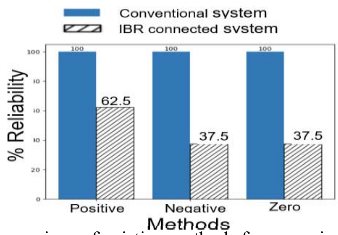

Fig.7. Comparison of existing methods for scenario 1 and 2.

Fig. 7 shows the comparison of the direction of fault obtained from existing methods for scenario 1 and scenario 2. From Fig. 7, only 62.5%, 37.5% and 37.5% of cases correctly identified the direction using positive, negative and zero sequence based methods respectively. Therefore, the commercially available methods are not reliable for IBR connected systems and there is a scope for improvement.

III. Proposed Solution Approach

To mitigate the limitations of the existing commercially available methods, we proposed a time domain based directional method using only current signals. This method will eliminate the problem of transients and dependency on fault type, and a Clarke transformation approach is proposed. Here, the alpha component of the fault current is used to generate the reference signal using the zero-crossing detected technique proposed in [6]. The alpha and beta components of Clarke transformation are obtained as in (7) and (8).

$$I_\alpha = \frac{2}{3}\left(I_a - \frac{I_b}{2} - \frac{I_c}{2}\right) \tag{7}$$

$$I_\beta = \frac{2}{\sqrt{3}}(I_b - I_c) \tag{8}$$

The alpha component (7) is used to generate the reference using the zero crossing detection technique as in (9).

$$i_r = \begin{cases} (i_\alpha'[n])^2 & 0 < n < Z_1 \\ -(i_\alpha'[n])^2 & Z_1 < n < Z_2 \\ (i_\alpha'[n])^2 & Z_2 < n < N-1 \end{cases} \tag{9}$$

where, i_α' is the differentiation of I_α, N is the number of samples per cycle and Z_1, Z_2 are the samples where $i_\alpha = 0$. The polar diagrams explaining the significance of reference signal in current only based methods is shown in Fig.8. The directional index (D) is obtained using (10).

$$\text{Direction index } (D) = \frac{\sum_{n=0}^{N-1} i_r[n] * i_\alpha[n]}{N} \tag{10}$$

Fig. 9 shows the flowchart of the proposed method.

$$D = \begin{cases} +ve, & Forward\ fault \\ -ve, & Reverse\ fault \end{cases} \tag{11}$$

The direction of fault is determined using sign of D as in (11).

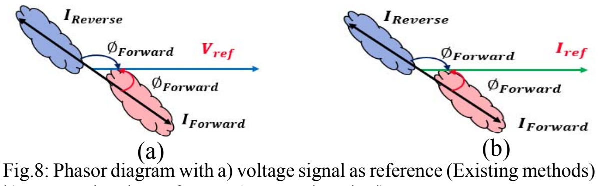

Fig.8: Phasor diagram with a) voltage signal as reference (Existing methods) b) current signal as reference (Proposed method)

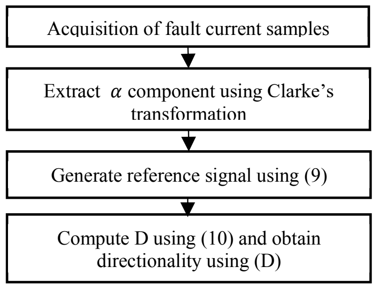

Fig.9. Flow diagram for proposed mitigation approach.

IV. Results and Analysis

A. Illustrative Example

A 2-bus system of 200 km line connected to IBR source is considered. Fig. 10 and Table VII shows the direction of fault for a BC-g fault on Bus M for the system shown in Fig. 2

TABLE VII
FAULT DIRECTION APPROACH FOR BC-G FAULT FOR SCENARIO 2

Relay	Actual Direction	Directional Index (***D***)	Proposed method
R_1	Reverse	$D < 0$	Reverse
R_2	Forward	$D > 0$	Forward

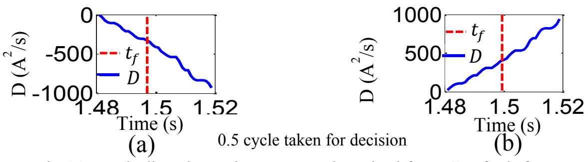

Fig 10. Fault direction using Proposed method for BC-g fault for scenario 2 a) R_1 b) R_2.

B. Comparative Assessment

1) Comparison with Available Methods [3]

The direction of relays R_1 and R_2 for commercial methods and the proposed method are presented in Table VIII. The proposed method identified the fault direction correctly for both relays (R_1 and R_2) whereas commercially available methods failed. A detailed analysis of commercial methods is presented in Section II.

TABLE VIII
COMPARISON OF COMMERCIAL METHODS AND PROPOSED APPROACH FOR BC-G FAULT FOR SCENARIO 2

Relay	Actual Direction	Positive	Negative	Zero	Proposed method
R_1	Reverse	Reverse	Fail	Reverse	Reverse
R_2	Forward	Fail	Fail	Fail	Forward

2) Comparison with Only the Current-based Method [6]

The direction of relays R_1, R_2 for [6] and the proposed method is given in Table IX. Fig. 11 (a) shows the plot of the directional index of phases B and C for a BC-g fault [6]. The direction of both phases B and C are detected as reverse for a forward fault due to high transients, whereas the proposed method detects the direction correctly (Fig. 11(b)).

TABLE IX
COMPARISON OF FAULT DIRECTION FOR SCENARIO 2 FOR BC-G FAULT USING [6] AND THE PROPOSED APPROACH

Relay	Actual Direction	Direction (μ_B)	Direction (μ_C)	Proposed method
R_1	Reverse	Fail	Fail	Reverse
R_2	Forward	Fail	Fail	Forward

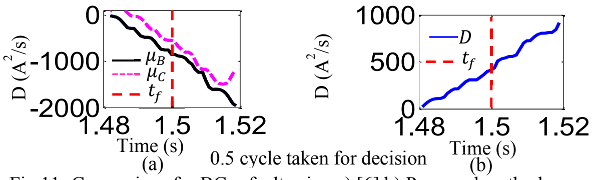

Fig 11. Comparison for BC-g fault using a) [6] b) Proposed method

1) Testing with IEEE 39 Bus System

The proposed method is tested with IEEE 39 bus system as shown in Fig.12. Two fault cases F_1 and F_2 are considered. *Case 1:* A BC-g fault is created on the line connecting Bus 21-22 at 64% of the line from Bus 22. For this fault case, the directionality of the relays R_6, R_5 and R_3 is forward and relay R_4 is reverse. Directionality index is shown in Fig.13 and identified directional information is tabulated in Table X.
Case 2: An A-g fault is created on Bus 16. For this fault case, the directionality of the relays R_1, R_4 are forward and relays R_2,R_3 are reverse. Directionality index is shown in Fig.14 and identified directional information is tabulated in Table XI.
The proposed method determines the direction of the fault as expected for the both cases.

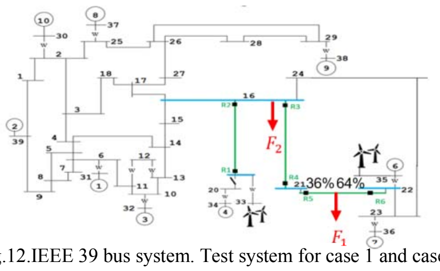

Fig.12.IEEE 39 bus system. Test system for case 1 and case 2

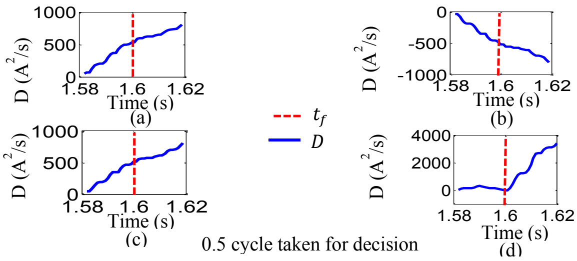

Fig.13.Fault direction computed using proposed method for Relays a) R_3b) R_4 c) R_5 d) R_6 for system shown in Fig 12.

TABLE X
FAULT DIRECTION USING PROPOSED METHOD FOR IEEE SYSTEM FOR CASE 1

Relay	Actual Direction	Directional Index ($\boldsymbol{D}$)	Detected Direction
R_3	Forward	$D > 0$	Forward
R_4	Reverse	$D < 0$	Reverse
R_5	Forward	$D > 0$	Forward
R_6	Forward	$D > 0$	Forward

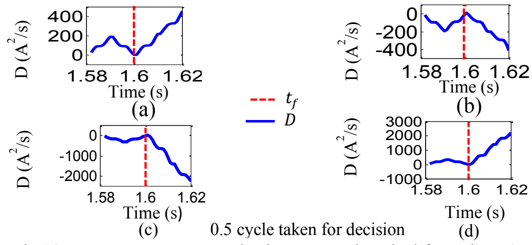

Fig.14.Fault direction computed using proposed method for Relays a) R_1b) R_2 c) R_3 d) R_4 for system shown in Fig 12.

TABLE XI
FAULT DIRECTION USING PROPOSED METHOD FOR IEEE SYSTEM FOR CASE 2

Relay	Actual Direction	Directional Index ($\boldsymbol{D}$)	Detected Direction
R_1	Forward	$D > 0$	Forward
R_2	Reverse	$D < 0$	Reverse
R_3	Reverse	$D < 0$	Reverse
R_4	Forward	$D > 0$	Forward

V. VALIDATION WITH FIELD DATA

The proposed approach is validated with field data. The data consists of three cases of fault on the same system which is acquired from a 300 MW wind farm in India. The length of the transmission line is 22.5km and it is operated at 220 kV. Three cases of B-g fault at ~6% of the line from the windfarm has occurred in October 2021. The voltage and current waveforms for Case 1 seen by the relays for both the grid and IBR end are shown in Fig. 15, Fig.16 and Fig.17 respectively.

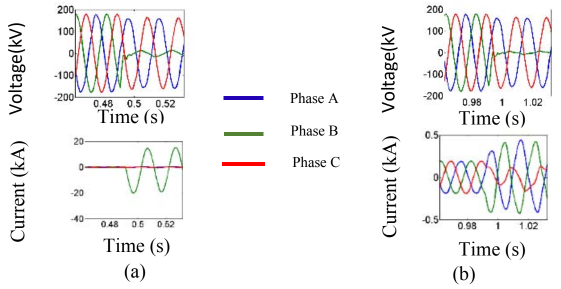

Fig. 15. Voltage and Current waveforms for case 1 BG fault measured from (a) Grid end and (b) IBR end.

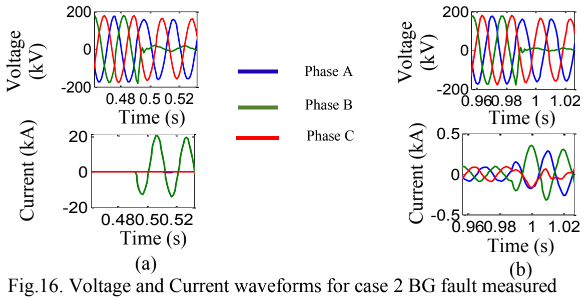

Fig.16. Voltage and Current waveforms for case 2 BG fault measured from (a) Grid end and (b) IBR end.

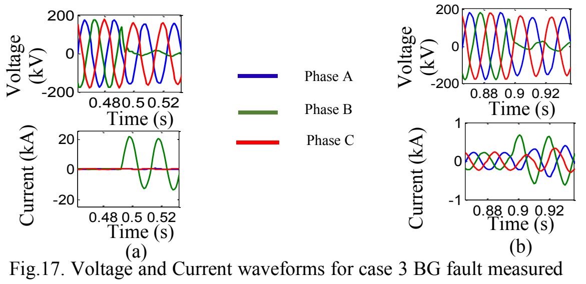

Fig.17. Voltage and Current waveforms for case 3 BG fault measured from (a) Grid end and (b) IBR end.

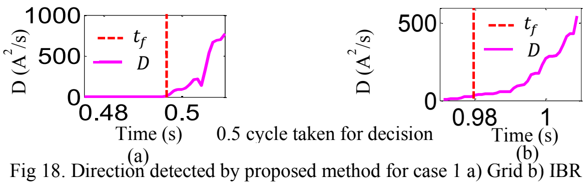

Fig 18. Direction detected by proposed method for case 1 a) Grid b) IBR

Fig. 18 shows the direction of fault obtained for the field Case 1 for both the Grid and IBR end. It can be seen from Table XII that the direction has been correctly identified as forward for IBR end for all the cases compared to other methods. The performance of the proposed method is consistent for both simulated and field data. The existing methods fails to identify the correct direction of fault for the field cases.

TABLE XII
FAULT DIRECTION DETECTED USING THE PROPOSED METHOD FOR FIELD DATA

Case	Actual Direction	Positive	Negative	Zero	[6]	Proposed Method
Case 1	F	F	Fail	F	F	F
Case 2	F	Fail	Fail	Fail	Fail	F
Case 3	F	Fail	Fail	F	Fail	F

VI. CONCLUSION

In this paper, the influence of grid-connected IBRs on the existing commercially available directional methods has been analyzed. A comparative analysis of 64 cases for both conventional and IBR-connected systems shows that traditional methods are unreliable due to varying source strength caused by inverter controls and grid codes in IBR connected systems. The recent current-only-based methods are also unreliable for high transient faults and require fault type information for reliability.

To overcome the fault type dependency and transient problem, a Clarke transformation approach is proposed where the alpha component of the current during fault is used to determine the direction of the fault. The performance of the proposed method is superior as compared with both conventional and recent time domain (only current-based) methods for lines connected with IBRs. The proposed method is validated with field data and found to be accurate. This method can be implemented in all existing relays without changing hardware infrastructure including over current relays as it requires only the current signal at the relay location. Future work could be implementation in IED platform and validation with different renewable connected systems including grid forming inverters.

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