

Performance Assessment of An Enhanced Distance Relay In The Presence of Inverter Based Resources

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Performance Assessment of An Enhanced Distance Relay In The Presence of Inverter Based Resources

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Abstract—Fast fault current injection by inverter-based resources (IBR) not only limits the fault current, but also results in different fault current signatures with respect to what is typically observed during a fault with conventional generation. Major research activities across the globe (SANDIA and MI-GRATE projects) have raised concerns that the commercially available distance relays are not reliable and could misoperate in the presence of IBR. This paper evaluates the performance of the protective relay with an enhanced distance algorithm (phase selection, distance characteristics and directional) from multiple dimensions i.e., speed, selectivity, security, stability and dependability. The performance evaluation is done using COMTRADES obtained from electromagnetic transient program (EMTP) which incorporates “Real Controller” IBR Type - III onshore wind turbine and battery energy storage models considering different fault location, fault type, fault resistance, point-on-wave, operating scenarios and IBR penetration levels including 100% renewable generation. Investigation shows that the enhanced distance algorithm provides promising performance in the presence of renewables.

Index Terms—Distance protection, IBR, renewable generation, fault type, weak-infeed, wind turbine generator, battery energy storage.

I. LINE PROTECTION: HIDDEN FACTS

THE two popular and preferred choices for protecting any transmission line across the globe are distance and differential. With over a century of experience with distance and decades of experience with differential protection, they were constantly improved and evolved to meet new challenges. Unlike distance which is a non-unit protection, differential relies on a communication medium to make a decision. One of the obvious and major limitation with any communication assisted unit protection e.g. differential is, when the communication medium is lost. Although, several claims were made regarding very low failure rate or by reducing the probability of failure by using two separate communication channels, still the loss of a channel is practically possible due to,

- natural calamities, or
- communication equipment failure, or
- man-made destruction to communication infrastructure e.g. due to excavation activities

In addition to distance and differential which is typically phasor or sample based, another type of protection which relies on the high frequency information does exist. This unit

based protection compares the high frequency information from both terminals of the line to make a decision. However, this approach has many limitations as listed below,

- communication failure as mentioned earlier,
- as the frequency of interest lies within the electromagnetic interference (EMI) spectrum, the relay has to differentiate whether the high frequency information is actually due to a fault or it is due to EMI, more specifically in the overlapped area as shown in Fig. 1,

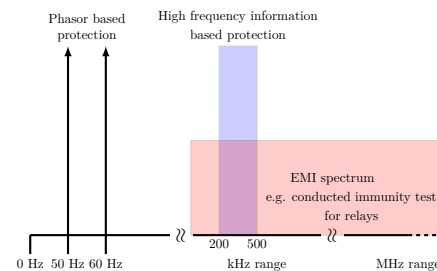


Fig. 1: Protection techniques based on frequencies of interest

- if the decision is made using both high frequency current and voltage e.g. directional element, the performance may be impacted by the type of instrument transformer used for voltage measurement and its response to a fault,
- in the presence of stray coupling, the high frequency information of interest may be highly distorted,
- fault occurs when voltage point on wave is zero or near to zero crossing where high frequency information may not be available to make a decision,
- close-in fault e.g. failure of lightning arrester or line isolator insulation failure may result in failure to capture high frequency information as it demands a very high sampling rate,
- Switch on to fault (SOTF) and trip on reclose (TOR) conditions pose another challenge as it cannot differentiate normal breaker closing scenarios and breaker closing with the fault on the line,
- if the line has in-zone switching e.g. series capacitors or line taps, and
- if the protected section of the line involves a transformer.
- Limitations in protecting short lines and multi-terminal lines

The above limitations raises concern on protection dependability. During such scenarios, any protection technique which cannot guarantee reliable performance has to rely on some other protection function and in this case it is distance which has to make a decision. Fig. 2 stresses the importance of distance even in the presence of new protection techniques.

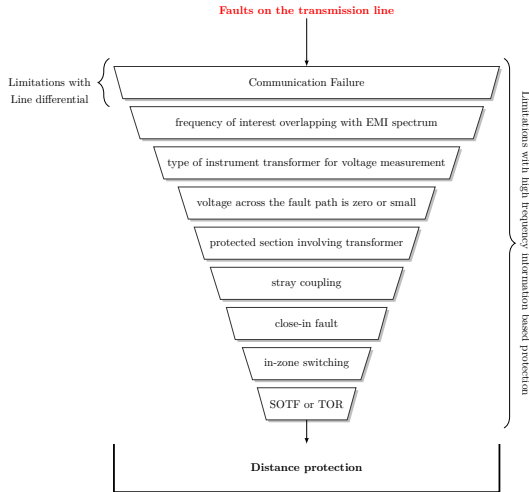


Fig. 2: Significance of distance in the presence of limitations

The paper is organized as follows, where in Section I, we have seen the importance of distance protection. This is followed by the issues and solutions related to distance and its supervisory elements which are discussed in Section II. The performance assessment of these solutions is the focus of this paper. This is assessed using COMTRADES obtained from a test system which is described in Section III. The performance assessment of an enhanced distance relay which incorporates the solutions discussed in Section II are detailed in Section IV. Section V provides insights into the performance and discusses the possible options to secure Zone 1 distance. Section V also discusses the issues and limitations with the available options to secure zone 1 distance using real world events and finally introduces a new approach and its response to real world events.

II. ENHANCED DISTANCE RELAY

The global commitment to move towards ‘Net-Zero’ carbon emissions along with technology advancements and economic factors is resulting in a rapid increase in renewable energy contribution across the globe in recent years. This new technology brings in new fault current signatures not seen by the protective relays for more than a century, which raised concerns regarding the performance of protective relays in the presence of IBR.

In-order to understand the performance of distance protection a joint study by Sandia National Laboratories (SANDIA) and the North American Electric Reliability Council (NERC) [1] investigated the behavior of two different relay manufacturers with COMTRADES obtained from four different original equipment manufacturer models which included, Type III wind, Type IV wind, and PV solar. Another major

study in Europe was undertaken under the project Massive InteGRATion of power Electronic devices (MIGRATE) [2] to evaluate the performance of four commercial relays with Type III wind turbines, Type IV wind turbine and solar.

The above investigations clearly indicated that the commercially available distance relays could fail to provide secure and dependable protection with key issues being the availability or reliability of negative sequence current immediately after and during the fault and phase selector performance. Investigation was carried out to understand the root cause behind the problem and what could be the possible impact on the distance protection due to the presence of IBR. The major impacted elements were,

- **Quadrilateral characteristics:**
 - *Neg. Seq. current:* Top reactance line of the quadrilateral characteristic may be impacted when it is forced to polarize with neg. sequence information, as for certain type of IBRs although negative sequence information may be available, it may not be reliable immediately after the onset of the fault [3].
 - *Zero Seq. current:* Use of Zero-sequence information may be a viable option, however the transformer vector group must support it. The zero sequence information is not impacted by IBR controls in such scenarios. However, still zero sequence information may not be reliable in certain scenarios and one of the real world cases is discussed in [4] (Fig. 16).
 - *Phase current:* Use of phase current to polarize the top reactance line provides fixed tilt and the relay is prone to over-reach for resistive faults in the presence of remote end in-feed. Additionally the fixed tilt achieved using phase current is questionable in the presence of inverter based generation (IBG). The currents can have sudden frequency excursions e.g. crowbar operation or the current frequency can be different from voltage as this is expected to introduce angle errors in phasor estimation. This impact can be visualized with two real world cases as shown in Fig. 3.

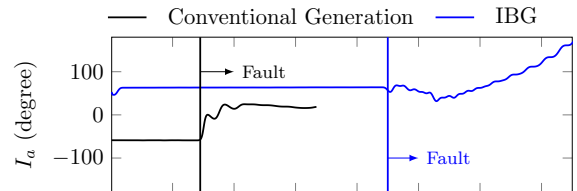


Fig. 3: Real world cases - Phase current angles during fault

- *Adaptive Polarization:* To overcome the above issues, an adaptive polarizing module was introduced in [4], which adapts to the reliable polarization for ground elements without any user intervention. However, there are possibilities where top the reactance line may not be reliable [4] (Fig. 16) and quad cannot be reliable. Under such circumstances the best polarization module switches the characteristic to mho.

TABLE I: Possible solutions for mho swings

Option	Possible Approach	Visualization	Security	Dependability	Remarks
1	Supervising Zone 1 with Offset mho		Yes	No	Resistive reach coverage impacted by Offset mho reverse reach
2	Supervising Zone 1 with Non-directional Quad		Yes	No	
3	Supervising Zone 1 with fixed top reactance line		Marginal	No	<ul style="list-style-type: none"> Relatively less secure than Offset mho or Quad as it opens up the bottom area Top reactance line impacted during frequency excursions in current signals
4	Supervising Zone 1 with dynamic top reactance line		No	No	Zone 1 allowed to tilt only down can improve security but not dependability
5	Zone 1 set to offset mho		No (close-in reverse fault)	Marginal (Resistive faults)	Reduced reach for close-in faults
6	Zone 1 set to Non-directional Quad and using remote infeed to detect reverse fault		No	No (directional may indicate reverse for forward fault)	A real world case proved that relying on remote infeed for directional decision will fail when remote infeed is from renewables
7	Zone 1 with controlled dynamic mho		Yes	Yes	

- *Mho characteristic*: The major issue with mho characteristic is the mho swings as discussed in [4] (Fig. 6 & Fig. 7). This unpredictable dynamic behavior in the presence of renewables has shown security issues. Table I shows how security can be improved using simple

approaches i.e., using supervisory elements like offset mho or Quad or Top reactance line. These approaches have their own limitations and it cannot ensure both security and dependability simultaneously. The concept of controlled dynamic mho was introduced in [4] which uses adaptive dual polarization to constrain the dynamic

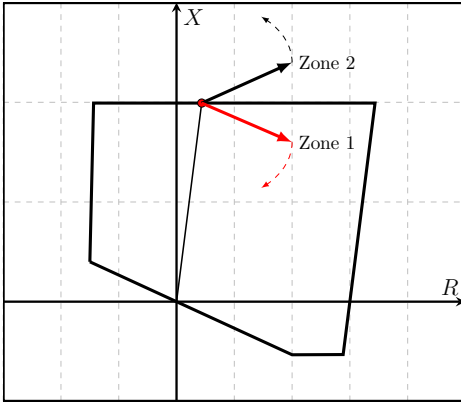


Fig. 4: Quad with best polarizing module

behavior.

- *Fault type supervision*: The fault type identification, where relying on current magnitude or angle was not reliable due to,
 - limited fault currents,
 - due to the availability and reliability of negative sequence information, and
 - variations observed in fault currents based on the adopted controller philosophy or grid codes.
- To overcome the above issues with fault type supervision, a new fault type supervision with sequence voltages and sequence currents was discussed in [4]. In this approach, sequence voltage is given priority, as voltage signals are dictated by the grid in case of grid following type IBRs or the voltage information is less impacted in case of grid forming IBRs.
- *Directional*: The directional decision is impacted in two ways,
 - Operating quantity: sudden frequency excursions or frequency drifts in currents
 - Polarizing quantity: when actual voltage deviates with respect to the memory

Directional security is enhanced by supervising the decision with zero sequence based directional elements and using self only when the actual deviates with respect to the memory.

The details of the above solutions were discussed in [4]. However, this needs to be evaluated from a real world application point of view, not only to understand the performance, but also to understand the limitations, if any. This is the focus of this paper to evaluate the performance of the relay which incorporates the above solutions, i.e.

- Ground Quadrilateral characteristics which dynamically adapts to the reliable polarization for ground distance top reactance line without any user intervention,
- Mho characteristics with fixed dual polarization [5],
- New phase selector using both symmetrical component and delta current information and
- Enhanced security for ground distance directional elements.

as discussed in [4]. This demands for trustworthy voltage and current signals from IBR models. This paper relies on simulation study which incorporates true “Real Controller” (full control system which is used in commercial IBR) models in the simulation environment which is discussed in the next section.

III. SYSTEM UNDER STUDY

As a part of this study, the system shown in Figure 5 is considered which includes the following “Real Controller” models,

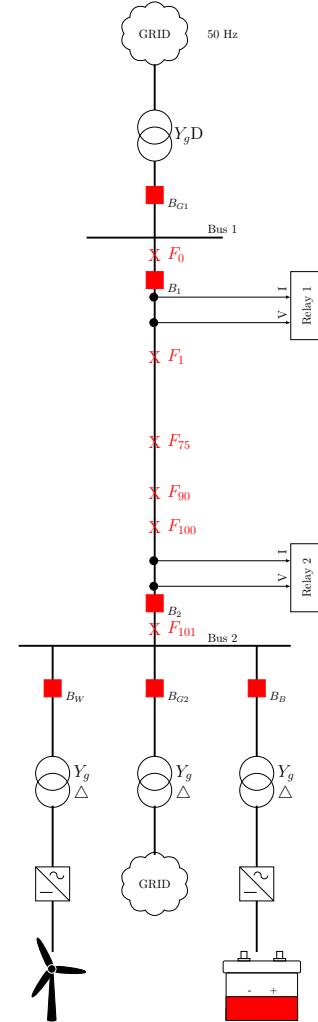


Fig. 5: Power system model used to evaluate the performance of Relay 2

- Type III wind - Double Fed Induction Generator (DFIG)
- Type IV Battery Energy Storage System (BESS)

These renewable energy sources are connected to the grid (Bus 1) via a transmission line which is protected by two relays i.e., Relay 1 and Relay 2. Relay 2 is of main interest as it sees the contribution from renewable energy sources. Different fault scenarios (936 cases) are considered as listed below,

- Type III wind - with generation mix (Breaker B_W , B_{G2} closed and B_B open) and 100% renewable generation (Breaker B_W is closed, B_{G2} and B_B open)

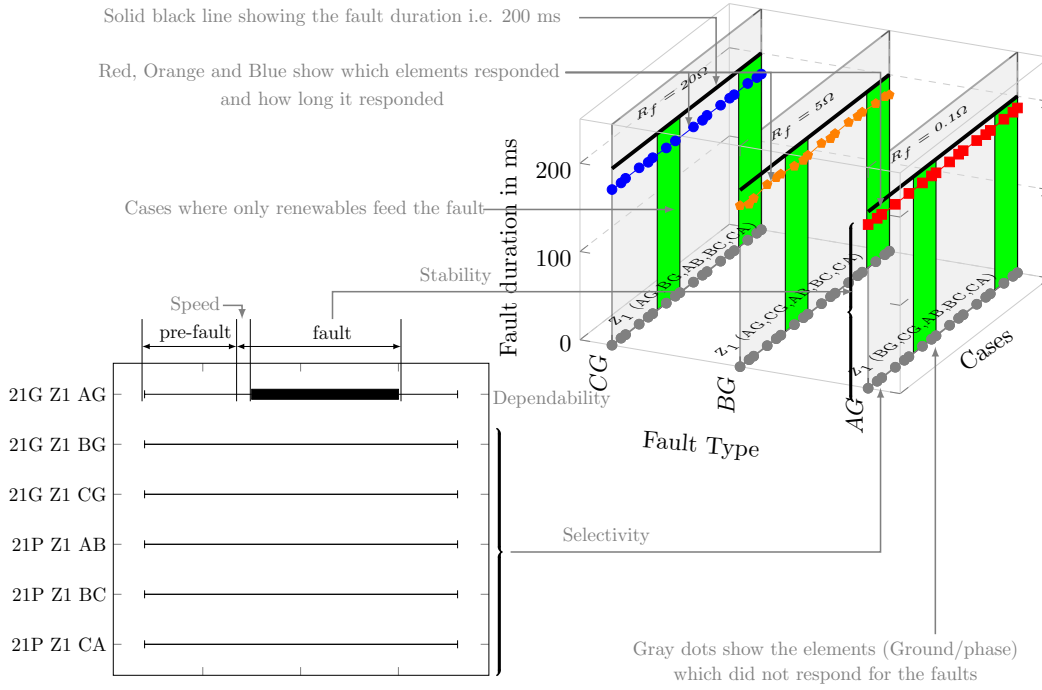


Fig. 6: Distance Zone 1 performance evaluation for AG fault

- fault types - phase to ground (AG, BG, CG), phase to phase (AB, CA), phase to phase to ground (ABG, BCG, CAG), 3 phase fault
- fault location $F_0, F_1, F_{75}, F_{90}, F_{100}, F_{101}$,
- fault resistance (R_f) 0.001Ω (AB, ABC), 0.1Ω (AG, ABG, BCG, CAG, ABC), 5Ω (BG, ABG, BCG, CAG, CA), 20Ω (CG),
- point on wave $0^\circ, 45^\circ, 90^\circ$
- BESS - with generation mix (Breaker B_W is open and B_{G2} and B_B closed) and 100% renewable generation (Breaker B_W, B_{G2} is open and B_B is closed).
 - fault types - phase to ground, phase to phase, phase to phase to ground, 3 phase fault
 - fault location $F_0, F_1, F_{75}, F_{90}, F_{100}, F_{101}$,
 - fault resistance $0.001\Omega, 0.1\Omega, 5\Omega, 20\Omega$,
 - point on wave $0^\circ, 45^\circ, 90^\circ$
- Different SIR combinations at Bus 1

These cases are then played back to the relay 2 which has the new solutions and the performance of distance is evaluated in multiple dimensions as listed below for each case and as shown in Fig. 6 where one AG fault case is shown as an example,

- Speed - Average operating time as different point-on-wave and fault resistance can lead to different operating time.
- Dependability - Dependable operation for in-zone faults
- Stability - Stable relay response throughout the fault duration. As shown in Fig. 6, stable response of individual zone 1 ground and phase elements are monitored throughout the fault duration which in this paper is 200ms.
- Selectivity - Selective element operation for a particular fault type i.e., for phase to ground fault, only the respec-

tive ground distance element should respond, and all other phase distance elements and ground distance elements should not respond. This is shown in the example Fig. 6, where zone 1 AG element responds for AG faults and all other ground and phase elements do not respond are shown as gray dots. Similarly BG and CG faults are shown.

- Security - Secured operation for out-of-zone faults (Zone 1 is set to 80%).

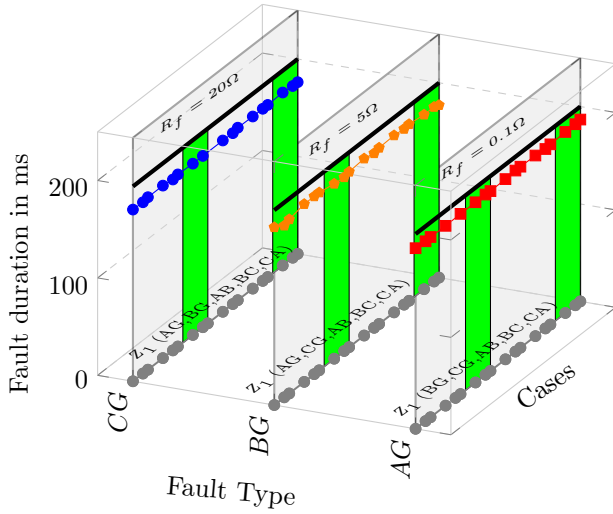
IV. TEST RESULTS AND DISCUSSION

This section discusses the test results and evaluates the performance of the new distance algorithm for the considered 936 cases.

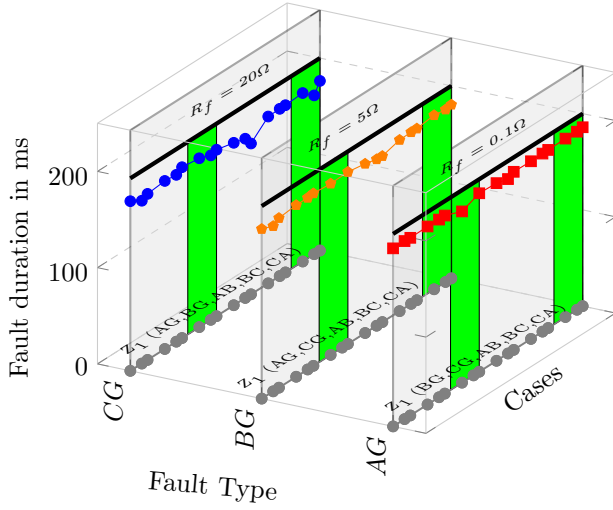
A. Single Phase To Ground Fault

1) *Forward faults in zone 1:* Figure 7 shows the response of relay 2 (Z1 ground resistive reach set to 25Ω) for single phase to ground faults AG, BG and CG at F_{75}, F_{90} and F_{100} considering different fault scenarios as mentioned in the previous section.

Each simulated fault in this study is applied for 200ms and this is indicated by the solid black line in the figure which represents the total fault duration. Let's consider fault type AG and the ideal expectation is ground AG element should respond and BG and CG should not respond. This is observed in Fig. 7(a) and Fig. 7(b) where stable response is seen from AG ground element for the entire duration of the fault without any ground BG and CG element operating. A similar response is observed for BG and CG faults. The figure indicates the total duration for which the zone 1 ground element got asserted and not the operating time, as discussed in the last section.



(a) Type III

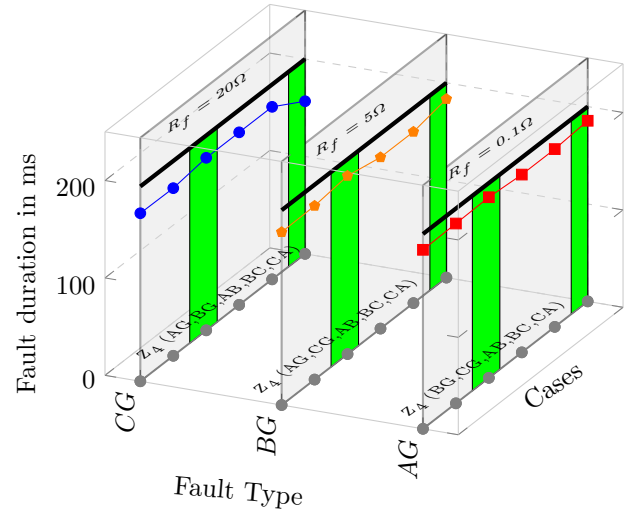


(b) BESS

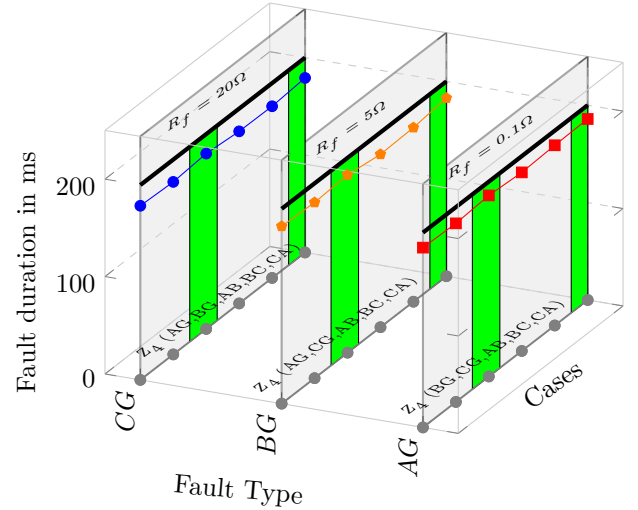
Fig. 7: Zone 1 ground element (Z1G) response for Z1 forward fault (AG - red square, BG - orange pentagon, CG - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

2) *Reverse faults*: Fig. 8(a) and Fig. 8(b) show the zone 4 element response of relay 2 which is set to look in the reverse direction to handle faults at F_{101} . Here again, we observe correct operation in both, zone and the corresponding loop as relay 2 sees the fault current from conventional generation.

3) *Forward faults in zone 2*: In this sub-section remote-end faults i.e., faults at F_0 and F_1 are investigated, and the corresponding relay 2 response is shown in Fig. 9. Although, relay 2 responded reliably for AG and BG faults in zone 2, CG faults shows a dependability issue i.e., zone 2 CG ground element does not respond for the fault, and this is observed in both Type-III wind (Fig. 9(a)) and BESS (Fig. 9(b)) as highlighted in dotted pattern. In Type -III, some of the cases zone 2 CG ground element responded for CG faults, but those are not stable for the entire fault duration.



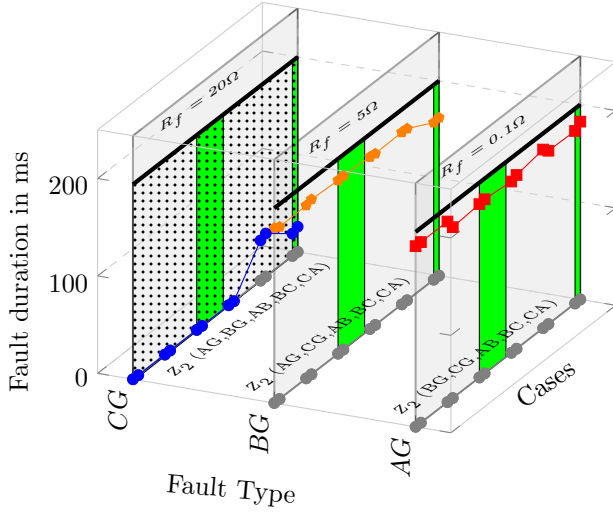
(a) Type III



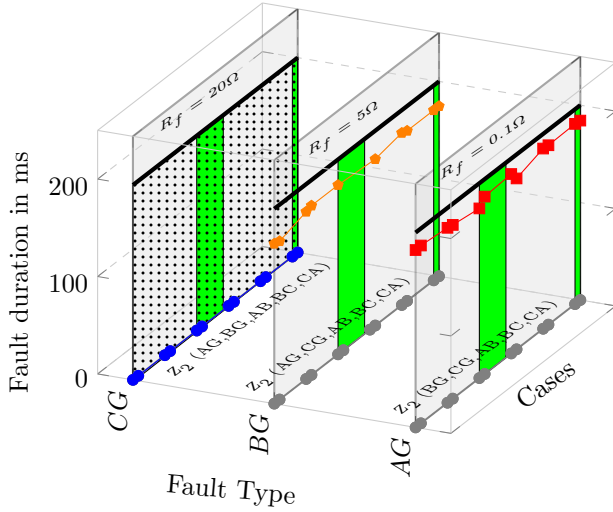
(b) BESS

Fig. 8: Zone 4 ground element (Z4G) response for reverse fault (AG - red square, BG - orange pentagon, CG - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

This is due to the reason that all CG faults are high resistance faults, and these faults are near remote-end with in-feed, which explains the reason why it is not dependable. Since this fault (F_1) lies in the zone 1 area for relay 1, relay 2 provides reliable operation when the relay 1 clears the fault by opening breaker B_1 . This removes the in-feed, thereby providing sequential tripping which is the same behavior as typically observed with conventional generation also. Moreover, it is also observed that the use of aided directional earth fault (DEF) [6], [7] which relies on zero sequence current and voltage is able to handle these faults. Additionally, no zone 1 overreach was observed in both Type-III wind and BESS cases.



(a) Type III

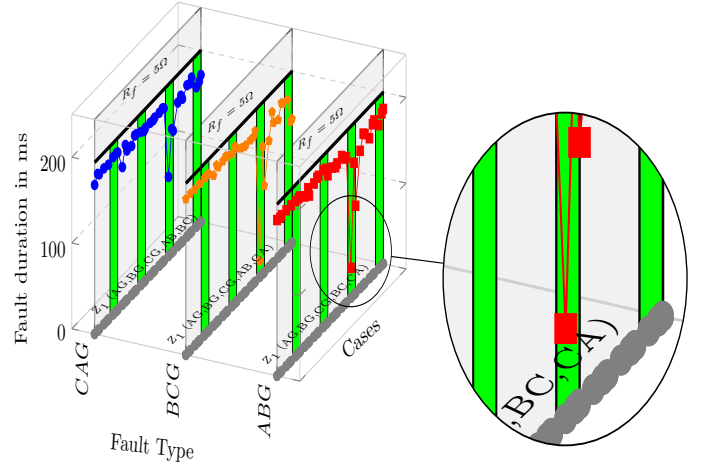


(b) BESS

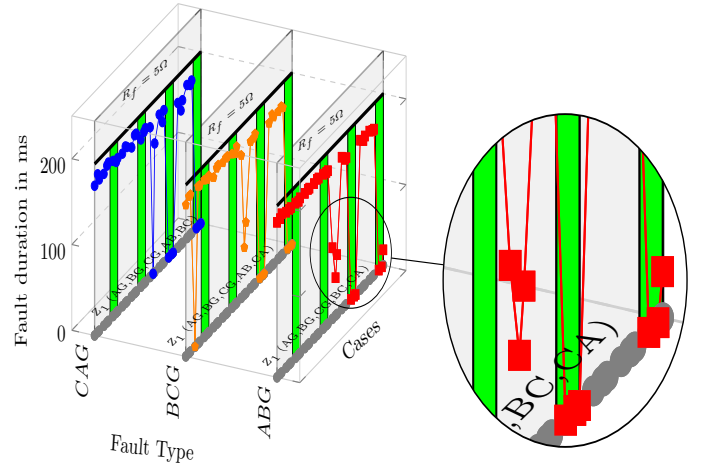
Fig. 9: Zone 2 ground element (Z2G) response for remote-end fault (AG - red square, BG - orange pentagon, CG - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

B. Phase To Phase To Ground Faults

1) *Forward faults in zone 1*: Unlike single phase to ground faults which showed reliable operation for zone 1 faults in the previous subsection, phase to phase to ground fault has shown some issues. Fig. 10(a) shows the response of phase elements for phase to phase to ground faults. Almost all the cases have shown reliable operation except couple of cases where the relay responded correctly but it is observed that it is not solid for the entire duration of the fault. This is even worse for BESS where for some 100% renewable energy scenario, it showed dependability issues (Fig. 10(b)) as the fault current has significant amount of zero sequence quantity making the trajectory to move away from the characteristics. This is because, the estimated apparent impedance (phase element) is inversely proportional to the phase to phase currents.



(a) Type III



(b) BESS

Fig. 10: Zone 1 phase element (Z1P) response for Z1 forward fault (AB - red square, BC - orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

Additionally, the phase over-current supervision which uses phase to phase magnitude information may also prevent the phase zone to release the decision due to significant amount of zero sequence current with respect to negative sequence current (three currents are almost in phase). Thanks to the aided DEF which when used in addition to plain distance, the relay provides reliable operation.

2) *Forward faults in zone 2*: Interestingly, zone 1 phase elements AB, BC and CA overreached for remote-end (ABG, BCG and CAG faults respectively as shown in Fig. 11 for Type III wind. Investigation shows that there is a sudden frequency jump observed in current signal whereas the frequency of the voltage was nominal as it is dictated by the grid, which resulted in zone 1 phase element to overreach. The root cause behind this frequency jump was suspected due to the crowbar operation. However, BESS which is a full converter interface does not show any overreaching problems.

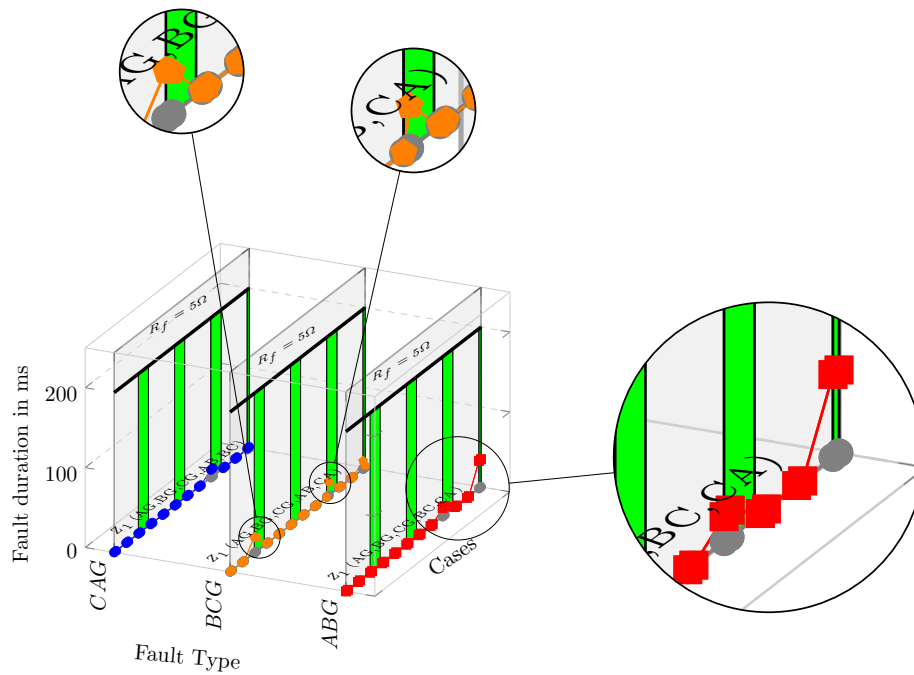
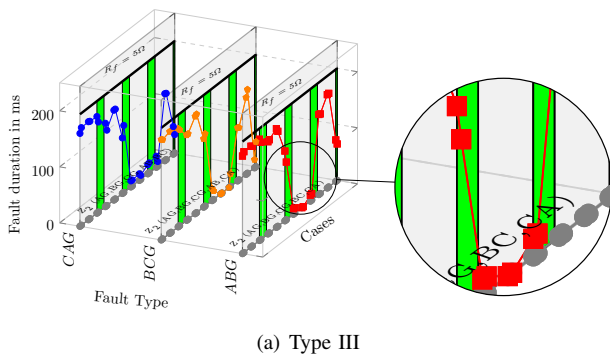
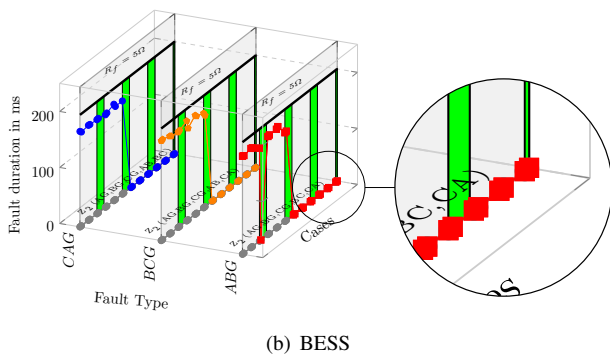


Fig. 11: Zone 1 phase element (Z1P) response for remote-end fault, Type-III wind (AB - red square, BC - orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)



(a) Type III



(b) BESS

Fig. 12: Zone 2 phase element (Z2P) response for remote-end fault (AB - red square, BC- orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

Looking into the other dimension i.e., Fig. 12 zone 2 response. As expected due to remote-end in-feed, we observe a dependability issue in both Type-III and BESS for high

resistance remote-end faults with in-feed. The use of DEF in parallel or relying on sequential tripping i.e. after relay 1 clears the fault as discussed in single phase to earth fault section has ensured reliable operation. The performance of DEF (directional earth/ground fault) for these cases is discussed later in this paper.

C. Phase To Phase Faults

1) *Forward faults in zone 2*: Phase to phase faults have also shown overreaching issues which is shown in Fig. 13. This is similar to what is observed in phase to phase to ground fault and these are again due to sudden frequency jumps observed with Type-III wind generation.

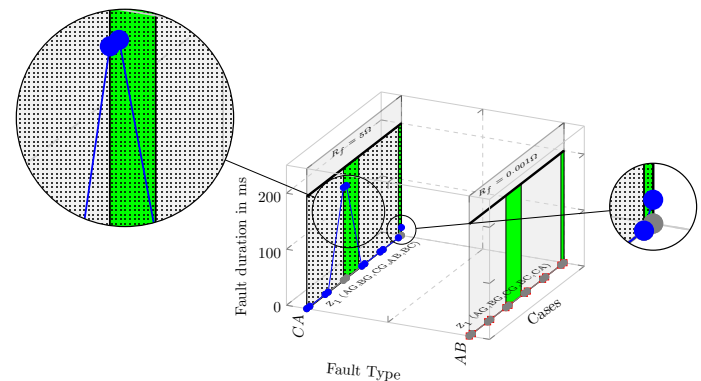
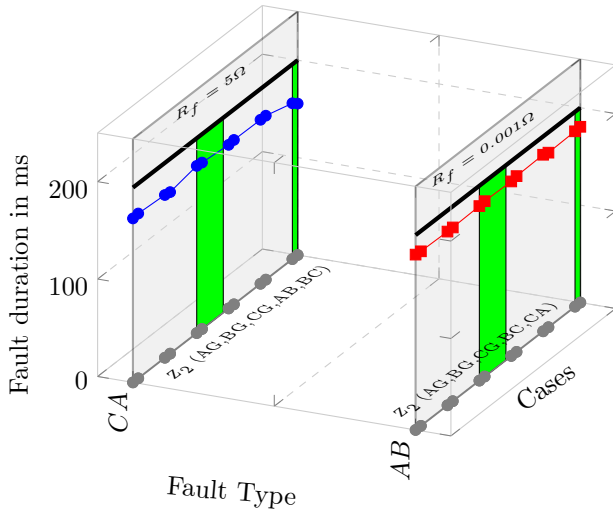
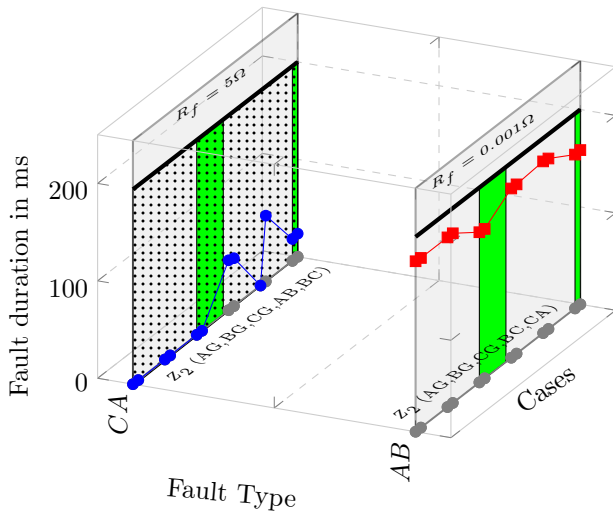


Fig. 13: Zone 1 phase element (Z1P) response for faults in zone 2 (AB - red square, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

Regarding the response of zone 2 phase element BESS has shown dependability issues (Fig. 14(b) - dotted pattern) again due to the reason as mentioned before.



(a) Type III



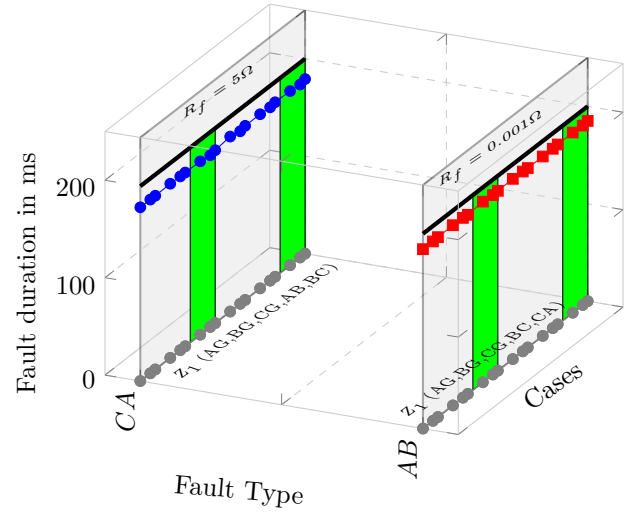
(b) BESS

Fig. 14: Zone 2 phase element (Z2P) response for faults in zone 2 (AB - red square, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

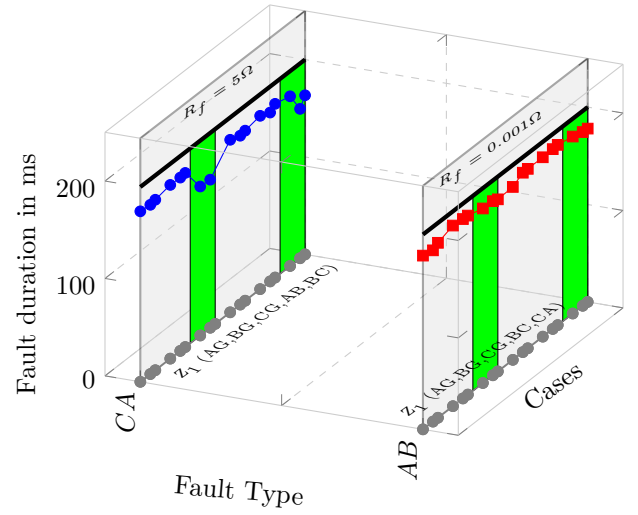
Reliable distance operation for phase-to-phase faults was a major concern reported by earlier studies, mainly due to the lack or unreliable negative sequence information. Although, recent IEEE standard [3] as well as various grid codes across the globe have specified the need for a certain amount of negative sequence injection, still the use of negative sequence may not be reliable either due to the challenges with rotor-side converters or the angle between negative sequence voltage and current could be high during the transient period immediately after the fault.

2) *Forward faults in zone 1:* Fig. 15 shows the response of zone 1 phase elements for phase-to-phase faults and it is

observed that the performance of distance enhancements was reliable.



(a) Type III



(b) BESS

Fig. 15: Zone 1 phase element (Z1P) response for faults in zone 1 (AB - red square, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

D. Three Phase Fault

1) *Forward faults in zone 2:* As expected, overreaching problems is observed due to frequency issues, and this is shown in Fig. 16 for Type III wind where the zone 1 phase elements momentarily overreached for zone 2 faults.

Looking into the zone 2 elements response for the same faults, it was observed to be reliable as shown in Fig. 17 for Type - III wind. However, for BESS, IBR tripping was observed for zone 2 faults. Reliable operation was observed for Type III wind (Fig. 17(a)) whereas for BESS, even though the 3 phase elements responded correctly, it looks like the elements did not respond for the entire duration of the fault.

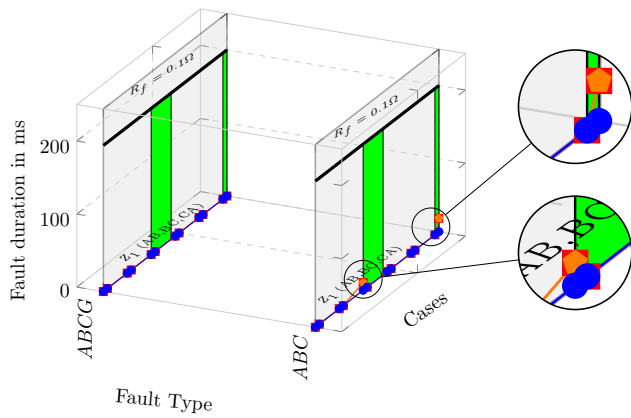
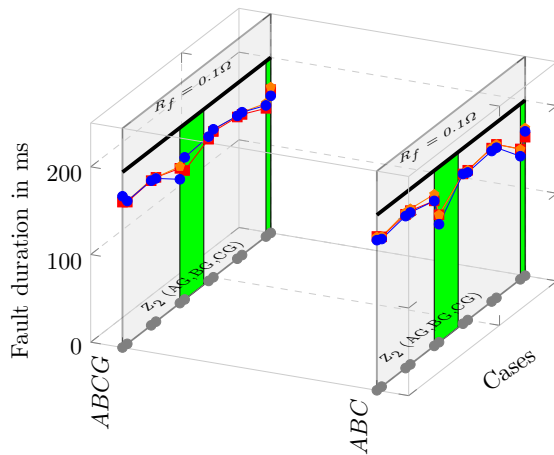
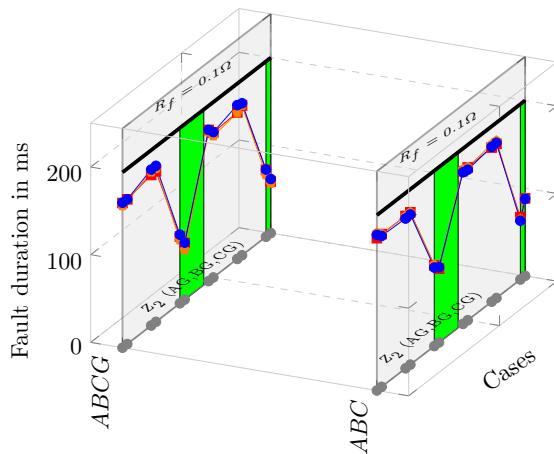


Fig. 16: Zone 1 phase element(Z1P) response for faults in zone 2 (AB - red square, BC- orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)



(a) Type III

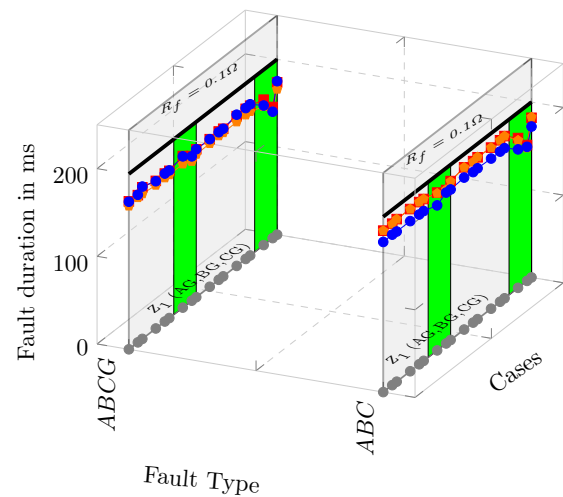


(b) BESS

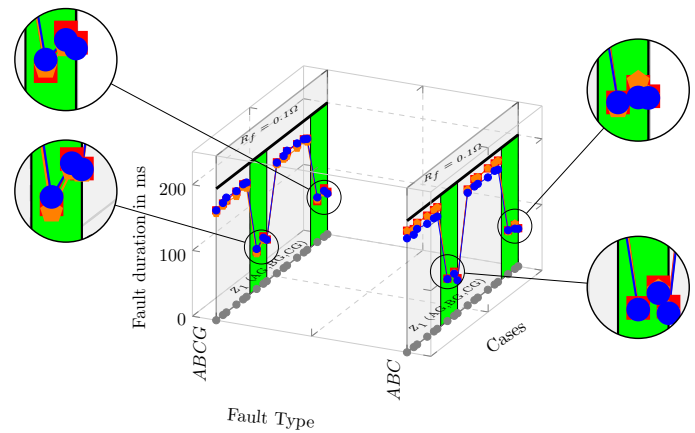
Fig. 17: Zone 2 phase element (Z2P) response for faults in zone 2 (AB - red square, BC- orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

Particularly, this happened for 100% renewable generation case. Investigation shows that this is not a problem from relay response i.e., stable decision, as the inverter ceased operation with a certain trip code for all these highlighted cases in Fig. 18(b) after a certain duration during fault. This explains the reason why the elements dropped out and responded correctly.

2) *Forward faults in zone 1:* Three phase faults are rare, but these faults pose a peculiar problem to IBR, as the tracking reference is lost, which may result in IBRs injecting current signals with arbitrary frequency. However, the recent standard [3] mandates that only small deviations in frequencies are permissible. Fig.18 shows the response of phase elements for 3 phase faults.



(a) Type III



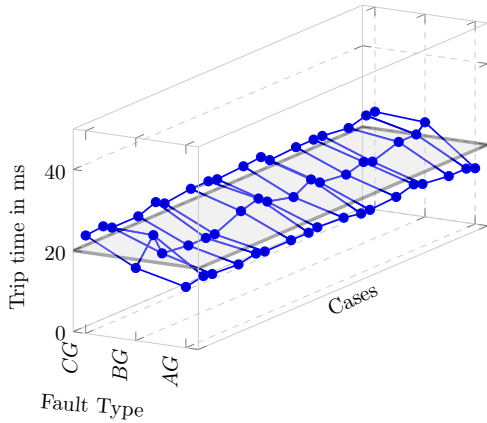
(b) BESS

Fig. 18: Zone 1 phase element (Z1P) response for faults in zone 1 (AB - red square, BC- orange pentagon, CA - blue dot, total fault duration - black solid line, green - fault scenarios with 100% renewable generation)

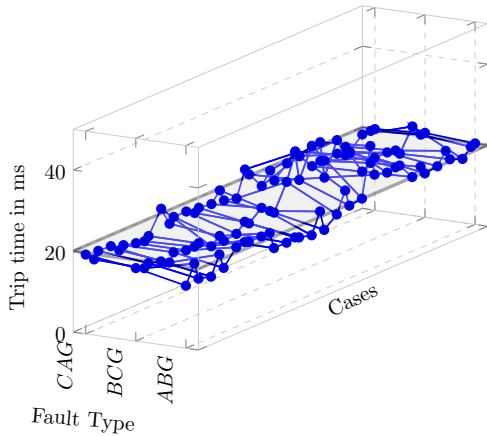
Reliable operation was observed in both Type-III wind and BESS. In the case of BESS with 100% renewable generation Fig. 18(b) element operation was dropped as IBR ceased operation with a certain trip code as discussed before.

E. Speed

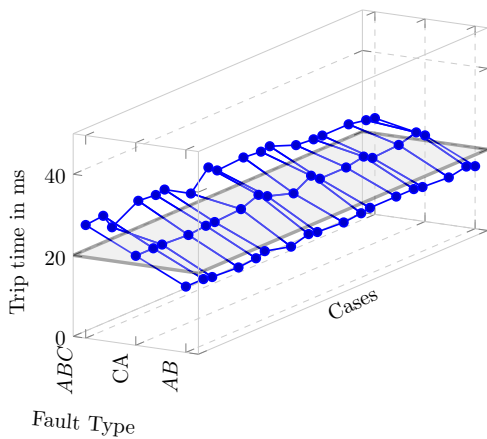
In the above sections the performance of the enhanced distance algorithm was discussed extensively, but this will be of real value, only if the relay is able to clear the fault as fast as possible.



(a) Single phase to ground faults



(b) Phase to phase to ground faults



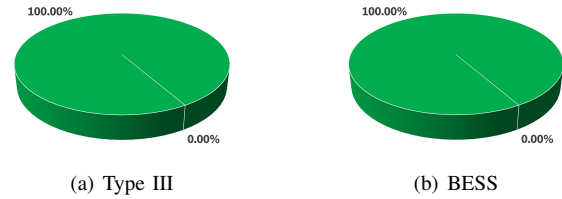
(c) Phase to phase and three phase faults

Fig. 19: Relay response time (includes contact operating time)

Fig. 19 shows the speed of operation for all the considered zone 1 faults. The relay was still able to maintain sub-cycle speed on an average which also includes high-resistance faults.

F. Summary

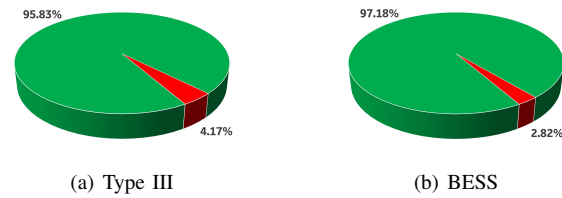
This section summarizes the performance of instantaneous zone 1, considering the 5 criteria as discussed before. Fig. 20 to Fig.23 shows the performance for both Type III and BESS for each fault type. The green portion represents the zone 1 responding correctly and the red portion where the cases are of concern.



(a) Type III

(b) BESS

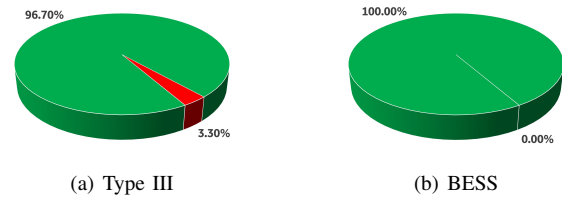
Fig. 20: Single phase to ground faults



(a) Type III

(b) BESS

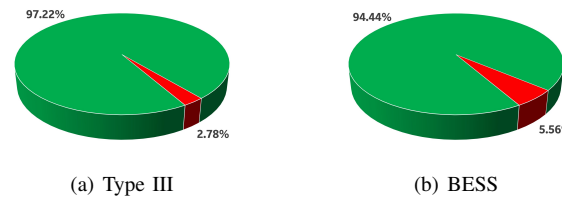
Fig. 21: Phase to Phase faults



(a) Type III

(b) BESS

Fig. 22: Phase to Phase to ground faults



(a) Type III

(b) BESS

Fig. 23: Three phase faults

These concerned cases are mainly due to one criteria i.e., security issues where zone 1 overreached for zone 2 faults, whenever frequency jumps are encountered in current signals with voltage signals being at rated frequency during the fault. Although Zone 2 has shown dependability issues for high resistance ground fault and phase fault, no dependability concerns were observed in Zone 1. In the case of ground faults, the dependability can be improved and this is discussed in the next section.

V. DISCUSSIONS

- The performance evaluation carried out in this work is limited to grid following IBRs. Although, the performance of this enhanced distance has shown good performance with “Real-Controller” grid forming type IBRs, this may need further evaluation as the technology is evolving.
 - Testing was done with quadrilateral characteristics, but the relay uses the best polarization technique [4] which dynamically switches between I_0 or I_2 or it switches to dual polarized mho as and when required.
 - Mho characteristics which rely on single polarization (except self polarization) will be impacted more [4], but this is outside the scope of this paper.
 - Some cases have shown dependability issues where the relay was not able to trip for high-resistance faults in zone 2.
 - Single phase to ground faults or phase to phase to ground faults - When the distance fails to handle this either due to high resistance faults or due to change in apparent impedance by the controller strategy, these faults will be handled by Aided DEF trip when it is enabled. This Aided DEF [6] can be established using,
 - * Zero sequence polarization, or
 - * Negative sequence polarization
- As the use of a negative sequence current quantity has limitations (refer Section II), zero sequence based Aided DEF can be used in conjunction with distance to provide protection against these faults. This zero sequence based Aided DEF uses, zero sequence current and voltage to make a directional decision as shown in Fig. 24.

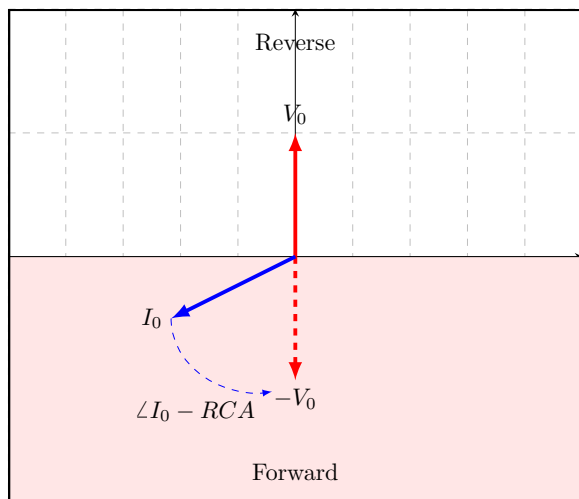


Fig. 24: Directional Earth Fault - Operating principle with zero sequence information

In order to make a reliable decision, V_0 should be above a certain value, if not, Aided DEF has the option to use virtual current polarization, which will allow the Aided DEF to still make reliable decisions

by removing the faulted phase voltage using phase selector information as shown in Table II.

TABLE II: Virtual Current Polarizing

Phase Selector Pickup	V_{pol}
A phase	$V_b + V_c$
B phase	$V_a + V_c$
C phase	$V_a + V_b$

- * Fig. 25(a) shows the response of aided DEF trip for the failed zone 2 Type III wind cases (Fig.9(a), Fig.12(a))
- * Fig. 25(b) shows the response of aided DEF trip for the failed zone 2 BESS cases (Fig.9(b), Fig.12(b)),

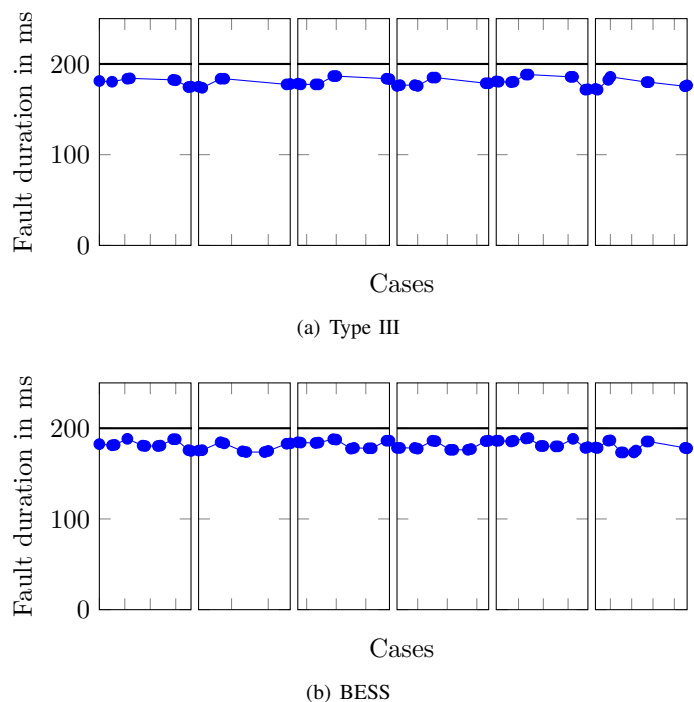


Fig. 25: Aided DEF Trip responding when distance is not able to make a decision, blue circle - Aided DEF response

The above figure clearly shows the DEF was able to provide reliable response for those faults involving ground, where distance was not able to respond. However, the DEF reliability also comes with another limitation, i.e., if the zero-sequence current is too low due to the zero sequence current distribution factor, aided DEF may fail to respond as the angle may not be reliable and the fault will be cleared by scheme based tripping e.g. weak in-feed echo and trip or by sequential tripping like we typically see in a conventional system.

- Phase to Phase faults - zone 2 high resistance faults which showed dependability issues are either cleared by scheme based tripping e.g. weak infeed echo and trip or by sequential tripping, as the relay 2 responds after the relay 1 trips and isolates the fault.

- Another major issue is that overreaching of zone 1 elements for out-of-zone faults was observed due to a sudden jump in frequency more specifically for Type III. One such case is shown in Fig. 26 (refer BCG fault in Fig. 11) where we observe sudden frequency jumps in current signals alone whereas the frequency information in voltage signals do not change abruptly.

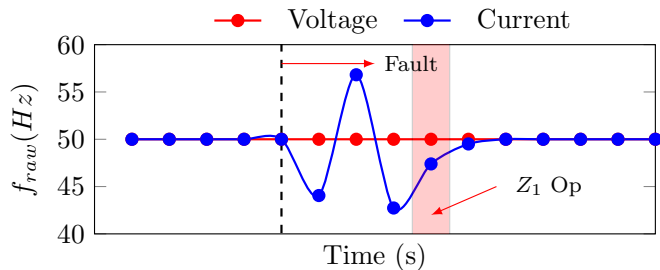


Fig. 26: Frequency jumps in current signal

This results in phasor estimation errors in current as the frequency estimation in the voltage channel is different from current channel, thereby impacting the apparent impedance seen by the relay which causes zone 1 to overreach as shown in Fig. 27.

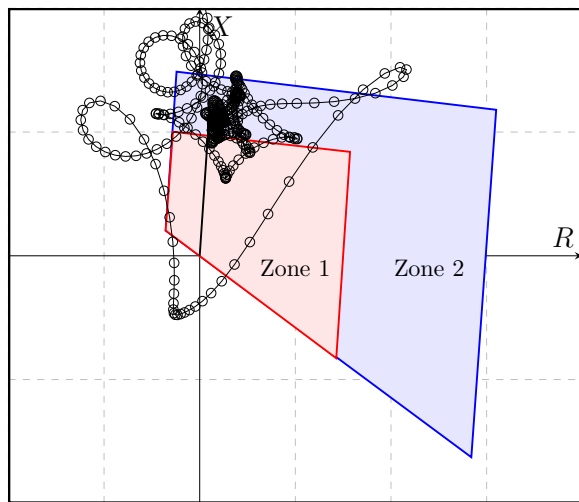


Fig. 27: Frequency jump causing Zone 1 to overreach

The relay sampling system in general does not respond to these sudden frequency excursions as the frequency estimation itself will be slower. Moreover, the frequency estimation will be channel based i.e either voltage or current channel and can be based on per phase or a mixture e.g. Clarke transformation. Even if fast frequency estimation is done, the above issue cannot be addressed. This is because the estimated frequency in one signal is going to dictate the sampling for all analog signals i.e. ($V_a, V_b, V_c, I_a, I_b, I_c$). As the sampling system is common to all phases and not individually controlled this leaves us with options as listed below,

- 1) reduce zone 1 reach
 - An obvious and simple option, but identifying the safe zone 1 reach is a difficult task, as it

needs system studies to be performed considering various factors,

- The availability of reliable and accurate models along with the actual field setting related to IBR controllers adds another complexity to the problem to perform the above studies,
- When zone 1 reach is reduced, this decreases the protected line section where instantaneous response can be achieved and increases the protected line section where time delayed operation is achieved as shown in Fig. 28.

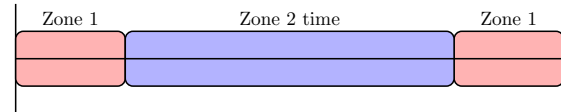


Fig. 28: Impacts on fault clearance when zone 1 reach is reduced

2) Fixed time delay

- Similar to the earlier option, it is difficult to quantify the required time delay to prevent overreaching,
- If longer time delays are needed this may violate the fault clearing times as mandated by the grid codes. Fig. 29 is a real world example which highlights the issue with a fixed time delay, where zone 1 operated late into the fault.
- Unnecessarily delays the tripping for faults without frequency excursion.

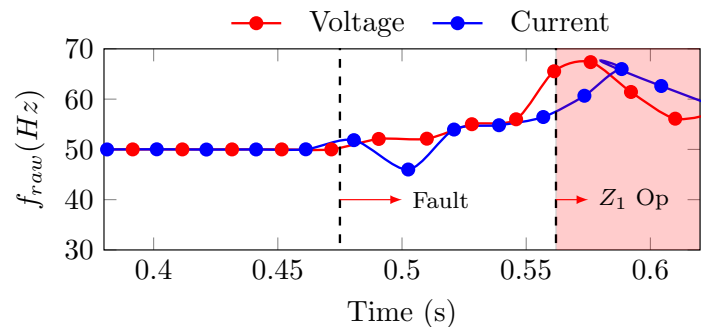


Fig. 29: Raw frequency after pre-processing for a real-world case

3) Disabling Zone 1

- This may be a viable option when the line is protected by redundant unit based protection e.g. differential protection with redundant communication channels,
- This approach increases the project and maintenance cost significantly as redundant channels have to be commissioned and maintained. As discussed in the introduction, although the probability of failure is extremely low, this may not be the case during man-made destruction.

4) Enabling Zone 1 for a certain duration immediately after the fault

- In this option, Zone 1 is disengaged after a certain duration after disturbance is detected as shown in Fig. 30,

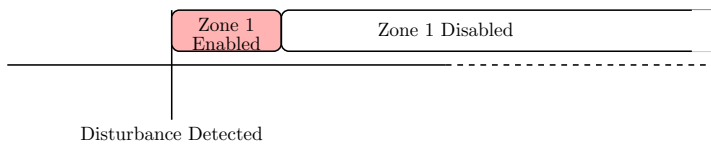


Fig. 30: Enabling Zone 1 for a short duration immediately after the fault

- This may help cases similar to the one as shown in Fig. 29, but fails to provide security for cases where abrupt frequency jumps are experienced immediately after the fault e.g. Fig. 26, making Zone 1 prone to mal-operate,
 - Another scenario would be a close-in reverse fault with this frequency excursion where the fault is fed from the remote end by renewables.
- 5) Engaging Zone 1 after a certain duration with respect to the fault
 - This is in contrast to the earlier option where Zone 1 is enabled after a certain duration immediately after the disturbance is detected as shown in Fig. 31. This is on the assumption that the controller transients die out and Zone 1 is safe to be enabled.

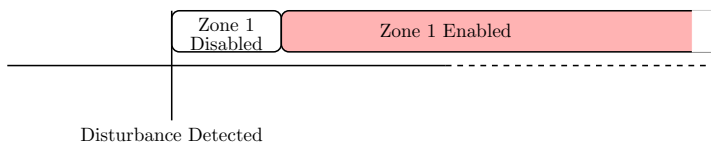


Fig. 31: Enabling Zone 1 after a short duration immediately after the fault

- This may help case shown in Fig. 26, but fails to secure case shown in Fig. 29
- 6) Using frequency information to secure Zone 1
 - Frequency difference between pre-fault and fault or between voltage and current can be used to secure Zone 1 operation,
 - However, this demands fast frequency estimation, also
 - Estimation needs to be done on individual phases, which brings in more complications from a hardware perspective.
 - 7) Use of external information to secure Zone 1
 - Activation of crowbar information may be a useful information to the relay, this can be used by the relay to process it internally and secure the relay operation, but this signal is currently not available from IBR manufacturers,
 - Moreover, this may need to be exchanged between relays e.g. frequency difference between local and remote source, as a result Zone 1 may

need to rely on communication channel to make a decision.

8) Pre-filtering

- Although pre-filtering can reduce the noise in the current channel, still it cannot overcome frequency jump issues
- Filter delay introduces permanent delay to relay response and this will add unnecessary delay when it is not required.

9) Quad with fixed down tilt

- The obvious issue with this approach is that the relay is prone to over-reach for resistive faults in the presence of remote end in-feed,
- Moreover, the relay under investigation uses a Zone 1 which can only tilt down (Fig. 4), still it can be observed that Zone 1 overreached and mal-operated. (Fig.26).

10) Transient detection with adaptive threshold [8]

- Zone 1 is secured by checking the smoothness with threshold which varies with respect to the fault location where the threshold is low/ stringent near to the zone reach and increases/is relaxed as it moves towards the relay,
- This again may fail considering the case as shown in Fig. 26, Fig. 27 where the estimated value will be compared with a relaxed threshold for a certain duration of time and Zone 1 would have been released.

11) Adaptive security count

- This approach is not new, where security counts are increased or decreased as and when required to increase the zone 1 security or to achieve speed respectively,
- Although it looks promising, this may not be sufficient for fault waveforms seen by renewables and Fig. 29 is one such real world example which demands for increased extra security counts, which again brings us back to the same discussion regarding quantifying the security counts.
- Moreover, the conditions to trigger the extra security counts may not be sufficient in the case of renewables as we are facing altogether new issues.

12) Using high frequency information

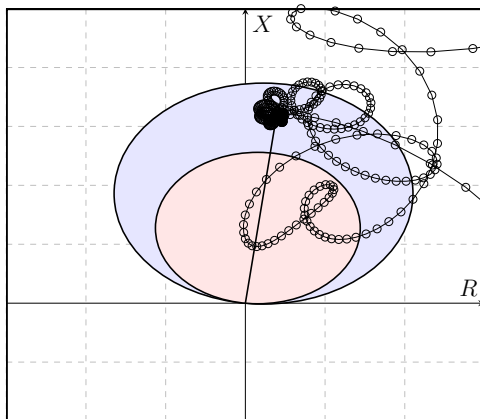
- The use of high frequency information may not be able to cover all practical scenarios,
- The limitations of this or related approaches are discussed in detail in Section I.

13) Time domain distance

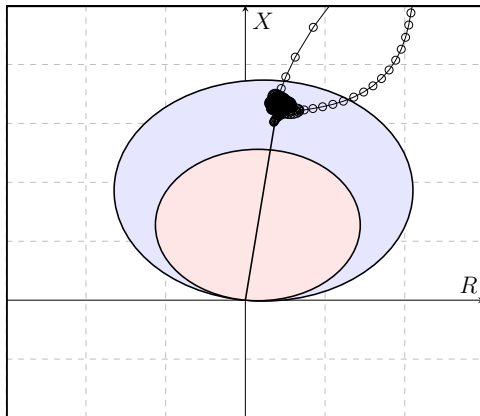
- Super-imposed quantity based time domain distance has its own limitations i.e. dependability for faults near to reach and reliability for faults associated with switching events.
- "True" time domain distance overcomes some of the limitations and with very high speed response however, it is more reliable for strong systems.

The above options with limitation demands for a more robust and generic solution satisfying the following requirements,

- The solution should be independent of any IBR original equipment manufacturer design, e.g. Fig.32 shows the response of different Type IV wind IBR original equipment manufacturer (OEM) designs to same fault and system scenarios.



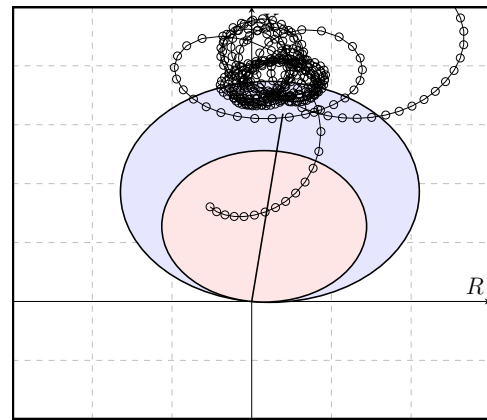
(a) Type IV - OEM 1



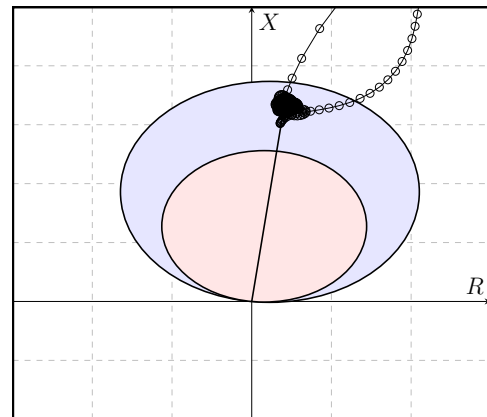
(b) Type IV - OEM 2

Fig. 32: Apparent impedance seen by the relay element for different IBR designs

- The solution should be independent of renewable technology, e.g. Fig.33 shows the response for different renewable technologies for same fault and system scenarios.
- Zone decision should not be blocked or unnecessarily delayed when it is not required e.g. when there is no abrupt frequency excursions or abnormality detected,
- Zone decision should be blocked at the instant when abnormal behavior is detected,
- The solution should be independent of IBR control strategy and
- The solution should be able to differentiate abnormal signals and power swings
- The solution should be independent of grid code requirements e.g. k factor can vary across grid codes (Table 2 in [4])



(a) Type III - OEM 3



(b) Type IV - OEM 2

Fig. 33: Apparent impedance seen by the relay element for different IBR designs

1) *Zone 1 with adaptive bias*: The new zone 1 adaptive bias feature tries to meet the above requirements and is designed to overcome the limitations as mentioned earlier. This is achieved by detecting abnormal information using multiple approaches in voltage and current and deciding whether to,

- allow or block the zone 1 permission to make a decision
- to decide the polarizing information
- to decide which directional approach to rely upon.

Fig. 34 shows how this adaptive bias works. If there is no abnormality detected, the adaptive bias logic is biased towards speed with standard security measures to avoid zone 1 overreaching, however, at any instance of time, during the fault, if abnormality is detected, it is biased towards additional safety measures to decide the best options or combination of options as listed above. The performance of this new logic for the case discussed above in Fig. 26, Fig. 27 is shown in Fig. 35, where it can be observed that permission is released immediately after the fault, but as signal abnormality is detected, it immediately drops to block the zone 1 distance and then releases after certain checks are met, but now additional security measures are brought in to ensure security and it can be observed that zone 1 is effectively secured for zone 2 fault and zone 2 is released.

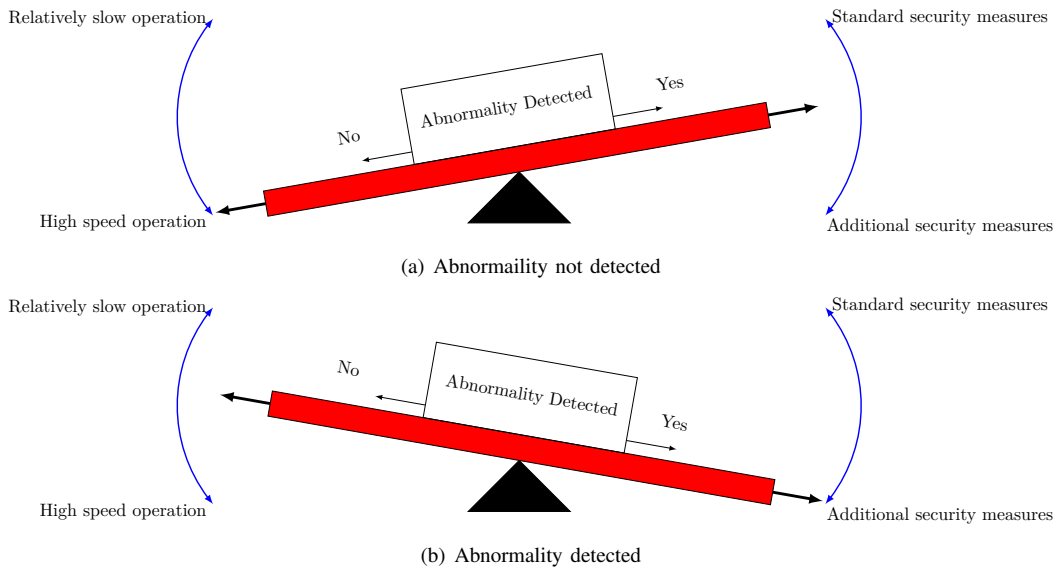


Fig. 34: Enhanced Zone 1 security

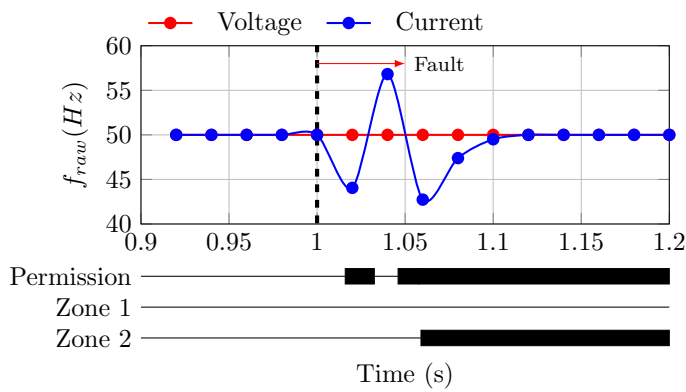


Fig. 35: Performance of new Zone 1 adaptive bias feature when signal quality is bad

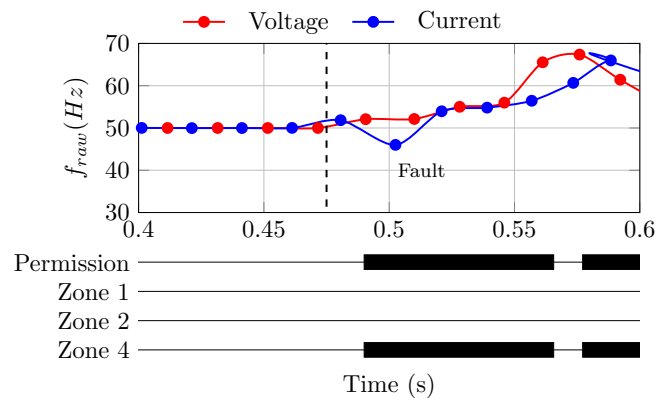


Fig. 36: Performance of new Zone 1 adaptive bias feature for a real-world case

Similarly, the performance of this new feature is also evaluated using real-world case as discussed in Fig. 29. Fig. 36 shows how correct directional decision was still retained with frequency excursion and zone 1 is secured when both voltage and current frequencies drift apart.

It can be observed that the response of the relay is delayed relatively by additional security measures, however, when there is no abnormality in the signal, the decision is made fast and this can be inferred in Fig. 37, where the Zone 1 decision is made within a cycle, i.e. sub-cycle.

- Distance Schemes: Although significance of distance is really felt when the communication medium is lost, the distance also benefits from the availability of a communication medium with the help of schemes as listed below,
 - Weak in-feed echo and trip
 - Blocking scheme
 - Aided DEF scheme

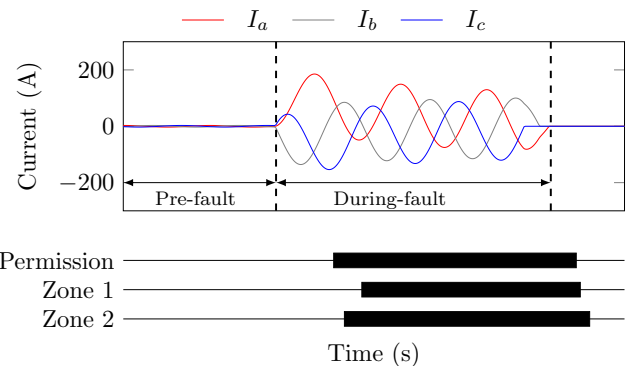


Fig. 37: Performance of new Zone 1 adaptive bias feature when signal quality is good

VI. CONCLUSION

The distance relay mal-operation in the presence of renewables have raised a myth that the life of distance

protection may come to an end. This paper tries to break this barrier by evaluating the performance of an enhanced distance relay from the real-world application point of view. Performance evaluation carried out in this work gives us enough confidence regarding the use of ground distance elements to protect the lines fed by renewable energy sources. Although phase elements have shown issues during frequency excursion, particularly for Type III wind, the use of an enhanced security feature provides promising performance.

ACKNOWLEDGMENTS

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VII. BIOGRAPHY SECTION

Venkatesh Chakrapani received the Bachelor of Engineering degree in Electrical and Electronics Engineering from the Madras University, India, in 2004, Post Graduation in thermal power plant engineering from National Power Training Institute, Neyveli, Ministry of Power, India, in 2005 and the Master of Technology degree from the Indian Institute of Technology Delhi, New Delhi, India in 2010 and holds PhD degree from Indian Institute of Technology Madras. He worked in Delhi Discom for five years where he handled protection, SCADA, commissioning. He holds a trade secret for his invention, filed two patents and authored several technical papers in the area of line protection and he is a senior member of IEEE. Since 2015, he has been with General Electric, and currently holds the position of Senior Lead Design Engineer in Research and Development at GE Grid Solutions, Stafford, United Kingdom.

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Simon Swain received his 1st Class BENG (Hons) Electrical/Electronic Engineering (2004) from Staffordshire University, UK. He joined GEC Alstom T&D in 1995 where he has undertaken many roles such as Technician Apprentice, Component Engineer, Product Support Engineer. In more recent years he took on the Lead role of the Transmission Distance and Differential Team as a Senior Application Software Engineer developing Algorithms for existing product lines. Most recently he is now the Senior Product Manager for the MiCOM P40 Platform & Toolsuite developments within GE Grid Solutions United Kingdom, developing the next generation of Transmission class Products.