

RESEARCH ARTICLE

Time-Domain Protection Scheme for Microgrids With Aggregated Inverter-Based Distributed Energy Resources

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ABSTRACT This paper proposes a time-domain-based protection scheme for radial and loop microgrid systems with inverter-based resources (IBRs), such as solar photovoltaic (PV) systems and type-4 wind turbines. The protection scheme is designed to function during both grid-interconnected and grid-isolated modes. The proposed scheme provides an ultra-high-speed sub-cycle directional element aided with low bandwidth communication between relays. Like directional comparison schemes, relays identify whether faults are in-zone or out-zone. The directional element is based on time-domain superimposed quantities and Park's transformation algorithms. Specifically, the element calculates the superimposed positive-sequence direct component of transient energy during faults. Superimposed voltage and current quantities are calculated using delta filters and decoupled double synchronous reference frame (DDSRF) filters. The proposed filtering method improves the reliability of the superimposed directional element when IBRs are the main source of fault current. The protection scheme is evaluated on a modified IEEE 34-bus distribution system simulated using an electromagnetic transients program.

INDEX TERMS Fault currents, incremental quantities, inverter-based resources, microgrids, protection, relays, superimposed quantities, symmetrical components, transients, voltage source converters.

I. INTRODUCTION

Each year, more electricity is generated from renewable inverter-based resources (IBRs), such as solar photovoltaic (PV) and type 4 wind turbines. In 2018, PV accounted for 55% of new global renewable capacity, and wind turbines accounted for 28%. Nine countries supplied 20% of their electricity from these resources. This growth is due to the rapid decline in the generation costs of PV and wind resources [1]. Another factor is the impact of integrating IBRs into power systems as distributed energy resources (DERs). Bringing IBRs close to consumers can increase electricity delivery's resilience and reliability by reducing the size and duration of power outages for most end-users [2], [3].

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This idea led to the concept of forming subsystems or "microgrids" to eliminate the need for central dispatch with the ability to operate in grid-isolated mode [4], [5]. Microgrid systems operate, control, and protect predefined subsystems while connecting or disconnecting from the electric power systems (EPS) through the point of common couplings (PCC). The two operation modes available are known as grid-interconnected mode and grid-isolated mode, respectively [6].

Integrating high penetration levels of IBRs into microgrids creates various challenges [7]. Establishing electricity markets, regulation laws, and policies for interconnections are examples of non-technical challenges. Meanwhile, technical challenges arise from controlling and protecting microgrids [8], [9], [10]. Researchers identified microgrid protection issues such as variable fault current levels,

bidirectional power flow, dynamic topology, and IBRs fault current contribution [11].

The dynamic behaviors of fault currents from IBRs are different from synchronous machines. Fault currents are primarily dependent on IBRs controllers and are largely independent of fault locations. Most IBRs provide low fault current magnitudes, around 1.2 pu, with less than a cycle of decaying envelopes. During the initial response, IBRs typically behave as nonlinear sources along with high-frequency transients. Most three-phase IBRs are designed to produce mostly positive-sequence currents, as a result, during symmetrical and unsymmetrical faults. IBRs inject insignificant negative-sequence currents depending upon the switching controller. IBRs only provide detectable zero-sequence currents if wye-grounded transformers are connected on the grid side and delta or wye-ungrounded on the inverter side [12], [13], [14], [15], [16], [17].

A practical philosophy for microgrid protection is to have the same protection strategy for both grid-interconnected and grid-isolated operation modes [18]. The published research on microgrid protection has not led to a commercially available microgrid relay, according to [19]. Nevertheless, several microgrid protection schemes have been proposed, such as differential, central, undervoltage, distance, adaptive overcurrent, and time-domain protection schemes, to name a few [20], [21], [22], [23], [24]. Depending on the microgrid type, topology, and type of the DER, these protection schemes might function competently. For example, [23] provides a review of a few implemented protection schemes in North American microgrid projects.

However, schemes like line current differential and central protection systems are nearly dependent on communication and are probably not economically feasible to implement in residential microgrids. Undervoltage protection is difficult to coordinate and may fail to detect high-impedance faults. Distance and adaptive overcurrent protection have less accuracy during grid-isolated mode [20], [21], [22]. A common disadvantage is the relatively slow fault-clearing time, whereas having a high-speed element is critical for microgrids with high penetration levels of IBRs [15].

This paper proposes a time-domain-based protection scheme for microgrids with IBRs, which functions during grid-interconnected and grid-isolated modes. The scheme provides an ultra-high-speed sub-cycle directional element aided with low bandwidth communication channels. The time-domain directional element is based on superimposed quantities, and a decoupled double synchronous reference frame (DDSRF) transformation algorithms improve the reliability of the directional element when IBRs are present. The proposed scheme is evaluated on a modified IEEE 34-bus distribution system simulated using an electromagnetic transients program.

This paper is organized as follows. First, the background and the proposed scheme are discussed in Section II. Then, a study case is presented in Section III. Finally, section IV concludes the paper.

II. BACKGROUND AND PROPOSED PROTECTION SCHEME

Time-domain protection provides ultra-high-speed fault directional detection [25], [26], [27]. Commercially available time-domain-based relays used for transmission line protection have functioned reliably [28], [29], [30], [31]. Time-domain protection uses traveling-wave or/and superimposed quantities. This paper focuses on the superimposed quantities element, also known as incremental quantities. Academic researchers investigate the possibility of using superimposed quantities in microgrids with different approaches [32], [33], [34], [35], [36].

The authors in [32] review several directional elements and highlight the reliability issues of each method. The authors propose a superimposed impedance-based directional element where the positive-sequence impedance is used for symmetrical faults, and a negative-sequence impedance is used for unsymmetrical faults. The authors in [33] find a system imbalance ratio using instantaneous superimposed positive, negative, and zero-sequence quantities to detect faults. In [34], the authors use a Hilbert transform and superimposed quantities-based directional element. In [35], the authors use communication-assisted energy superimposed-based directional element. The authors in [36] use phasor positive and negative current sequence superimposed quantities to find the direction of the fault and use communication between a microgrid control system and a protection system.

Although [32], [33], [34], [35], [36] propose adequate primary and or backup microgrid protection schemes, investigating time-domain superimposed quantities' schemes in detail with IBRs present as the main source of fault current lies outside these papers' scope.

A. SUPERIMPOSED QUANTITIES

The calculation of superimposed quantity $\Delta x(t)$ measured at a relay terminal is based on subtracting the present $x(t)$ samples from the corresponding stored $x(t - \tau)$ samples, as in (1).

$$\Delta x(t) = x(t) - x(t - \tau) \quad (1)$$

The notation $x(t)$ in (1) is the input of a delta filter and can be measured voltage or current data. The $\Delta x(t)$ is the superimposed quantity for x , which is the output of the delta filter. The τ is a delay in power cycles. Commonly a one-cycle memory buffer is used to temporarily hold one power cycle of sampled data. During steady-state, $\Delta x(t)$ is zero assuming no change in the system from one cycle to the next. However, during faults, $\Delta x(t)$ value is equal to the fault-imposed component. In other words, the superimposed algorithm is based on the fault-generated components and is only influenced by the network impedance parameters. Therefore, power system load flow has minimum impact on the superimposed algorithm [37], [38], [39].

There are three common ways to calculate and utilize superimposed quantities in protection: time-domain, frequency-domain, and phasor-based. All three types use delta filters to calculate superimposed quantities [37]. However, the condition of the input of the delta filters defines

each type, as shown in Fig. 1. Delta filters for the time-domain-based approach are connected to anti-aliasing filters for minimum delay [38].

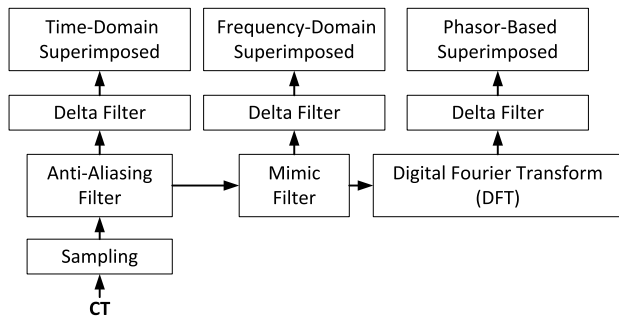


FIGURE 1. The condition of the input of the delta filters defines superimposed quantities type.

In the frequency-domain approach, measured currents pass through a mimic filter to eliminate the exponentially decaying dc component [39]. The mimic filter's design criteria for superimposed quantities may differ from mimic filters used for phasor-based elements and are often referred to as a replica impedance filter. The replica impedance filter is tuned to consider the source impedance value behind a relay [31]. On the other hand, mimic filters for phasor-based elements are designed to suppress dc offset based on the time constant in cycles [40]. However, both replica and mimic filters are high-pass filters and have similar behavior and impacts, such as amplifying the higher-frequency components.

The third type of superimposed quantities is the phasor-based, where the delta filter is applied after a half-cycle or full-cycle discrete Fourier transform (DFT) filter [41]. The phasor quantities are calculated after half-cycle or full-cycle, depending on the DFT filter [42]. Latter, this type may not be considered as an ultra-high-speed scheme.

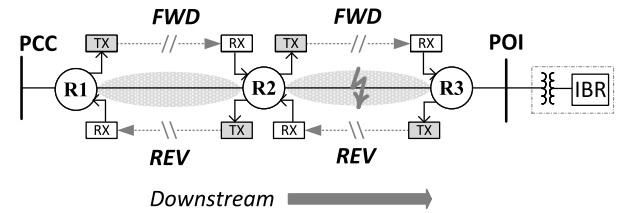
The following section proposes the microgrid protection scheme and an improved time-domain superimposed directional element.

B. PROPOSED MICROGRID PROTECTION SCHEME

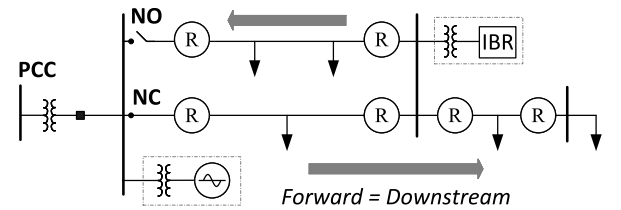
The proposed scheme uses time-domain directional elements and only low bandwidth communication between relays. In directional comparison schemes, relays use communications to exchange information on their directional elements' status and provide fast-tripping for in-zone faults [43]. The proposed scheme is modified to allow relays to communicate within a microgrid. One relay at a border of a zone declares forward (FWD), and one relay declares reverse (REV) for in-zone faults. For out-zone faults, both relays declare FWD or REV.

The microgrid's PCC is chosen as a reference to define upstream and downstream. In radial systems, downstream is looking to the end of the feeder, and upstream is looking back towards the PCC. Relays assume downstream faults as FWD

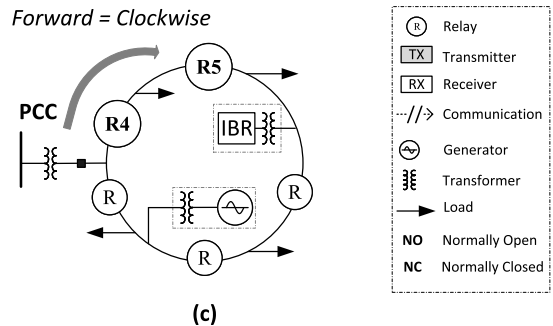
faults and upstream faults as REV faults. In Fig. 2 (a), relay R2 sends FWD signals to downstream relay R3 and sends REV signals to upstream relay R1. Also, relay R2 receives FWD signals from relay R1 and receives REV signals from relay R3. For example, if a fault is applied between relay R2 and relay R3, both relay R2 and relay R3 see an in-zone fault and trip.



(a)



(b)



(c)

FIGURE 2. Upstream relays send forward signals to downstream relays, and downstream relays send reverse signals to upstream relays: (a) Radial system, (b) Parallel feeders with a normally open breaker, and (c) Loop system.

The scheme can be applied to dynamic microgrid topologies. For example, Fig. 2 (b) shows two parallel feeders with normally open (NO) and normally closed (NC) breakers. This setup is just to choose a direction reference for relays, but the breakers' status does not impact the protection scheme. Once the reference is chosen, a relay trips in-zone faults when it declares FWD and receives REV from the other relay.

Similarly, Fig. 2 (c) shows a loop system where relays assume clockwise faults as FWD and anticlockwise faults as REV. For example, for an in-zone fault applied between relay R4 and relay R5, as marked in Fig. 2 (c), relay R4 sees a clockwise fault and declares a forward fault, and relay R5 sees an anticlockwise fault and declares a reverse fault. As a result, relay R4 sends FWD signals to relay R5, receives REV signals from relay R5, and relays trip.

C. PROPOSED RELAY

The proposed relay includes a combination of time-domain and phasor-based protection, as shown in Fig. 3. The time-domain protection has the directional element and the communication capability, whereas the phasor-based protection consists of a voltage-restrained overcurrent element and the backup elements.

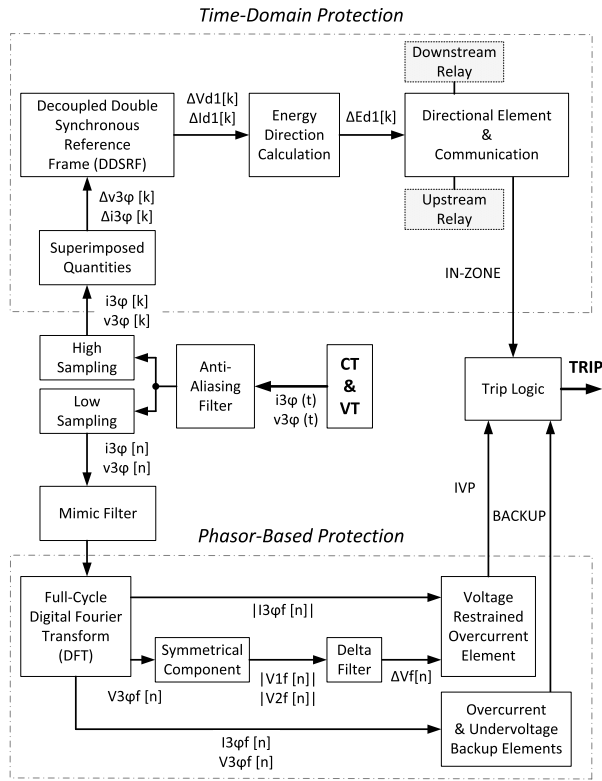


FIGURE 3. Simplified diagram for the proposed relay signal processing, time-domain protection element, phasor-based elements, and communication.

The time-domain protection uses high sampling rates to calculate superimposed voltage and current quantities. First, analog voltage and current measurements are digitized after anti-aliasing filters. The digital quantities are then processed through per-phase delta filters [37], [38], [39], where ϕ is phase-a, b, or c, as shown in Fig. 4 (c). Delta filters use one power cycle memory buffers to hold the samples.

After the delta filters, a DDSRF is connected to improve the time-domain superimposed quantities element's reliability and calculate instantaneous symmetrical components. The DDSRF is based on using two synchronous reference frames rotating with positive and negative synchronous speed, respectively. The purpose is to decouple the effect of the negative-sequence component on the direct axis and quadrature axis (DQ) signals detected by the synchronous reference frame rotating with positive-angular speed and vice versa [44], [45], [46].

The overall DDSRF block diagram is shown in Fig. 4 (a), converting three-phase voltage components to positive and negative sequence DQ components. The positive sequence

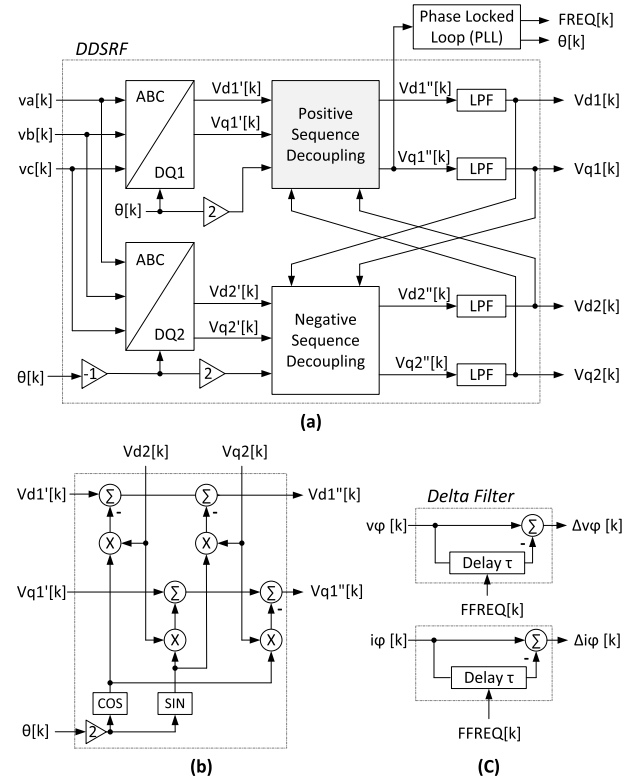


FIGURE 4. Calculating superimposed positive-sequence direct quantities: (a) Decoupled double synchronous reference frame (DDSRF), (b) Positive-sequence decoupling, and (c) Per-phase delta filters.

decoupling algorithm is shown in Fig. 4 (b). The DDSRF algorithm is described below in detail.

The first step converts the three-phase voltage components to DQ components using Park's transformation [47]. The DQ signals are denoted as $Vd1'$ and $Vq1'$ for positive-sequence, where the positive DQ1 transformation is driven by positive synchronous angle θ as in (2).

$$\begin{pmatrix} Vd1' \\ Vq1' \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{pmatrix} \begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} \quad (2)$$

$Vd2'$ and $Vq2'$ are the negative-sequence DQ voltage, respectively. The negative DQ2 transformation is driven by negative synchronous angle $-\theta$, respectively.

The second step decouples the double-frequency negative-sequence component from the positive-sequence component as in (3) and, as shown in Fig. 4 (b). Similarly, the negative-sequence components are decoupled from the double-frequency positive-sequence as in (4).

$$\begin{pmatrix} Vd1'' \\ Vq1'' \end{pmatrix} = \begin{pmatrix} Vd1' \\ Vq1' \end{pmatrix} + \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix} \begin{pmatrix} Vd2' \\ Vq2' \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} Vd2'' \\ Vq2'' \end{pmatrix} = \begin{pmatrix} Vd2' \\ Vq2' \end{pmatrix} + \begin{pmatrix} \cos 2\theta & -\sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \begin{pmatrix} Vd1 \\ Vq1 \end{pmatrix} \quad (4)$$

First-order low-pass filters (LPF) with cut-off frequency $(\omega/\sqrt{2})$ are applied to DQ components [44] and [45]. The output quantities from the DDSRF are DQ positive-sequence components $Vd1$ and $Vq1$, respectively, and DQ negative-sequence components $Vd2$ and $Vq2$, respectively. References [44] and [45] provide more analysis and explanation of the DDSRF algorithm.

The DDSRF algorithm is then used to convert per-phase superimposed voltage and current quantities to DQ positive and negative sequences, as shown in Fig. 5. However, only the superimposed positive-sequence direct voltage $\Delta Vd1$ and current $\Delta Id1$ components are multiplied to calculate the transient superimposed positive-sequence direct "power" or Watt component $\Delta Wd1$.

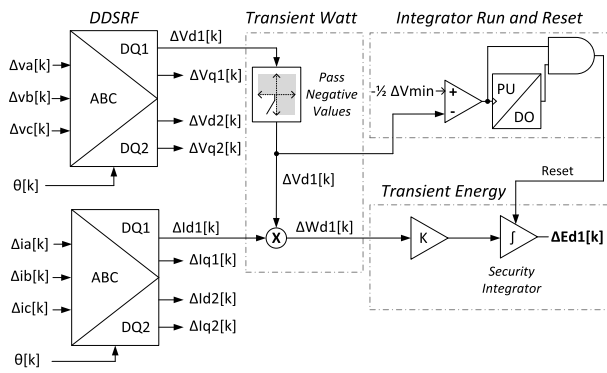


FIGURE 5. Transient superimposed positive-sequence direct Watt and energy.

This Watt component is comparable to the wattmetric ground-fault detection method used in Petersen coil compensated distribution systems. A wattmetric relay can detect the correct fault direction because it depends on the "real" component of the zero-sequence voltage and zero-sequence current, which are independent of the coil and phase-to-earth capacitance currents. The wattmetric relay is designed to be connected to the neutral of three-phase systems and uses zero-sequence quantities [48], [49]. However, the proposed relay is connected to the three phases and uses the DDSRF algorithm to create the "real" component of the product of the positive sequence voltage and current mapped to the direct axis to reduce the impact of the IBRs controller, as will be demonstrated next.

As discussed earlier, IBRs behave as nonlinear sources and produce unreliable negative-sequence currents with high-frequency transients. Using the $\Delta Wd1$ component can be more reliable in microgrids with IBRs because it depends on the direct positive-sequence components. Fig. 6 compares three transient superimposed power methods during a single line to ground (SLG) fault where ΔS is apparent power, ΔSr is replica-apparent power, and $\Delta Wd1$ is the proposed method.

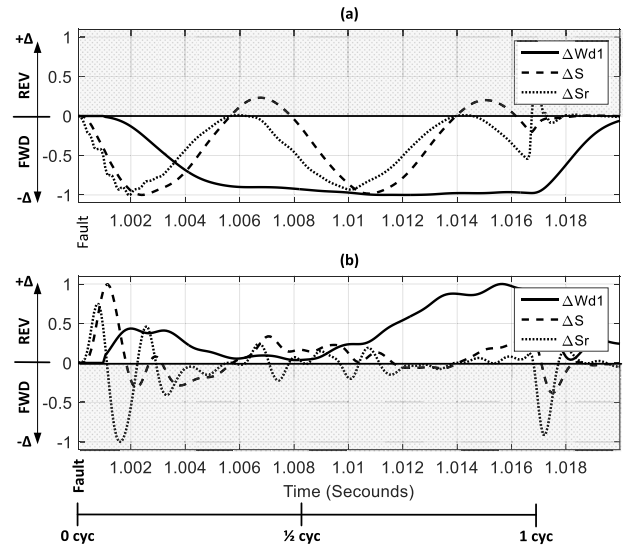


FIGURE 6. Comparison of IBRs impacts on superimposed transient Watt, apparent power, and replica power methods: (a) SLG forward fault at a system with no IBRs and (b) SLG reverse fault at a system with IBRs.

In general, the superimposed-based directional element indicates FWD faults for negative power and REV faults for positive power [38]. In Fig. 6 (a), the SLG fault is applied to be an FWD fault in a system with no IBRs. The ΔS method detected FWD's fault, but the sine wave crossed to the positive plane because of the current angle of dc offset. The ΔSr overcomes this issue using the equivalent source-impedance behind the relay terminal to account for the phase angle mismatch [37], [39]. The proposed $\Delta Wd1$ method provided a more secure result but introduced a one-millisecond delay caused by the DDSRF filter.

The SLG fault is then applied as a REV fault in a system with an IBR, as in Fig. 6 (b). The IBR negatively impacts both ΔS and ΔSr because the IBR current controller responds to the fault and causes the superimposed currents to have a mixture of both inductive and capacitive currents. Thus, both methods fail to provide reliable fault direction indications.

The impact of IBRs on time-domain superimposed quantities elements is presented in [50] and [51]. IBRs' fast control response impacts the current quantities by changing both magnitude and angle. Thus, using time-domain superimposed quantities to detect the fault direction is unreliable, with IBRs present as the main source of fault currents [50] and [51].

In [51], incremental power and replica power quantities are calculated for several cases to simulate IBRs impact on the incremental directional element. A modified IEEE 34-bus distribution system is used for demonstration where different types of DERs are injecting power at a node, and an incremental directional element is part of the protection element on a feeder connected to that node. In one of the study cases, the directional element response is explored by simulating two types of DER where in each case, the resource is the main source of fault currents for SLG fault, as shown in Fig. 7, where the column is (a) an aggregated grid

following IBR and (b) a synchronous generator. The figure shows following incremental quantities (1) delta voltage, (2) delta current (solid trace) and replica delta current (dashed trace), and (3) delta power (solid trace) and replica delta power (dashed trace), reading down the column.

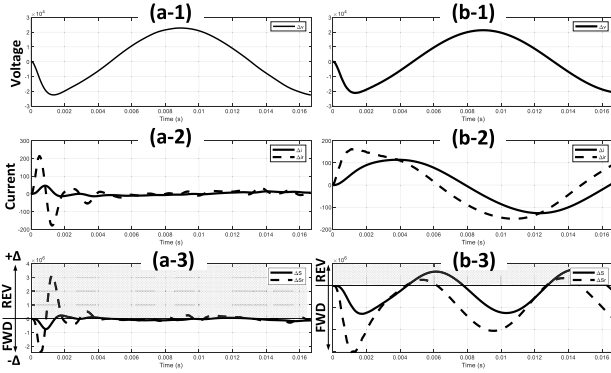


FIGURE 7. Incremental signals during SLG faults: (a) IBR and (b) synchronous generation, where (1) delta voltage, (2) delta current and replica current, and (3) delta power and replica power.

The directional element correctly indicates the fault is in the forward direction when synchronous generation is connected, as shown in Fig. 7 (b). During the SLG fault, the synchronous generation provided fault currents with a decaying DC offset, which caused a delay in the increase in the delta current component (solid line). However, replica power (dashed line in Fig. 7(b-3)) provided a more reliable directional signal because the replica impedance filter suppressed the DC offset in current waveforms, as shown in Fig. 7 (b-2).

On the other hand, the directional element does not indicate the correct SLG fault direction when the IBR is connected, as shown in Fig. 7 (a-3). Neither the delta power nor the replica power provides reliable signals that would allow the directional element to indicate the correct fault direction. In this case, the fault current is mainly supplied by the IBR. As stated earlier, incremental quantities primarily depend on knowing electric network parameters when entering settings, but IBRs' fault currents primarily depend on the control system, and the magnitude and effective angle of the current vary with design choices made by the control designer. Fig. 7 (a-2) shows this issue in the delta current when the IBR mainly supplies the fault current. In contrast, Fig. 7 (b-2) shows the reliable delta current signal when the synchronous generation supplies the fault current.

The proposed method provides a more reliable signal since the direct positive-sequence component reduces the IBRs impact. The $\Delta Wd1$ indicates the correct fault direction with the IBR present as the main source of fault current, as in Fig. 6.

Practically, transient energy is calculated instead of using transient power to increase the superimposed directional element's security [31]. Then, $\Delta Wd1$ is integrated using a run-reset integrator to calculate the superimposed positive-sequence direct energy $\Delta Ed1$, as shown in Fig. 5. The

proposed directional element depends on $\Delta Ed1$ to confirm the fault direction and uses $\Delta Vd1$ to run the security integrator.

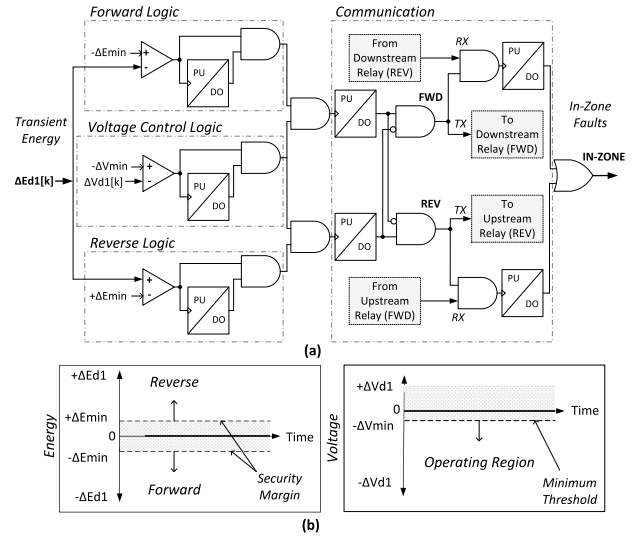


FIGURE 8. Time-domain superimposed-based directional element: (a) Logic and communication scheme and (b) Operating characteristics.

D. SUPERIMPOSED-BASED DIRECTIONAL ELEMENT LOGIC

The superimposed-based directional element logic diagram is shown in Fig. 8 (a). The forward and reverse logic circuits compare $\Delta Ed1$ to negative and positive security thresholds $\pm \Delta Emin$, respectively. The thresholds are small values to create a dead-band zone. Then $\Delta Ed1 < -\Delta Emin$ indicates an FWD fault, and $\Delta Ed1 > \Delta Emin$ indicates a REV fault as in Fig. 8 (b). The voltage control logic compares $\Delta Vd1$ to a threshold $-\Delta Vmin$ as a fault indicator. The voltage threshold could be set as low as 5% of the system's peak line-to-neutral nominal voltage since the phasor-based protection supervises the element.

There are several confirmation timers to ensure the security and reliability of the element. The timers allow the element to indicate direction within the first half-cycle, which is the most reliable period in superimposed schemes. Also, timers are used to freeze the asserted FWD/REV for enough cycles to allow the element to communicate and confirm in-zone faults.

After a fault direction is confirmed, the signal is sent to a downstream relay for FWD faults or an upstream relay for REV faults. The local relay receives a signal: from a downstream relay for REV faults or an upstream relay for FWD faults. The local relay confirms IN-ZONE faults only if it: (1) asserts FWD and receives REV from downstream or (2) asserts REV and receives FWD from upstream.

The element only needs low bandwidth communication to send and receive signals. There are several choices for distribution communications, such as direct pilot wire, multiplexed fiber-optic, and spread-spectrum radio. Communication

systems vary in speed, cost, and reliability [52]. For demonstration purposes, an average communication delay of four milliseconds is assumed.

E. PHASOR-BASED ELEMENT AND TRIP LOGIC

The directional element is supervised by a phasor-based voltage-restrained overcurrent element, as shown in Fig. 8. The three-phase currents are filtered by the mimic filter and the DFT filter, as shown in Fig. 3. The overcurrent element compares three-phase currents I_{af} , I_{bf} , and I_{cf} to a current threshold ϵ_i , which can be set to a sensitive level that is less than load currents, as shown in Fig. 9.

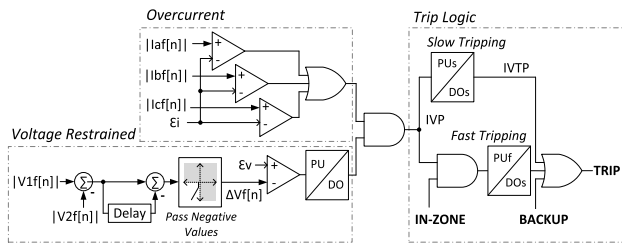


FIGURE 9. Phasor-based superimposed voltage-restrained overcurrent element and trip logic with fast and slow-tripping.

The unsymmetrical voltage phasors from the DFT filter are converted to symmetrical phasors using symmetrical components transformation to calculate the phasor-based positive-sequence and negative-sequence voltages for the voltage-restrained overcurrent element, as shown in Fig. 3. Then, the difference between positive-sequence voltage V_{1f} and negative-sequence voltage V_{2f} is calculated, as shown in Fig. 9.

After that, the phasor-based superimposed voltage quantity ΔV_f is calculated using a delta filter that functions as the time-domain-based delta filter discussed earlier. Finally, the overcurrent is restrained by the delta voltage ΔV_f , where the threshold ϵ_v determines the element sensitivity, as shown in Fig. 9. A typical setting is 20% of the nominal system voltage. Details about using the phasor-based voltage-restrained overcurrent elements in microgrids are presented in [24].

The voltage-restrained overcurrent element asserts IVP if both overcurrent and voltage-restrained comparators are satisfied. The relay then uses fast-tripping logic if both the IVP signal from Fig. 9 and IN-ZONE signal from Fig. 8(a) assert where the timer pickup PUF can be set to zero for maximum speed. In case of communication failures, the relay uses IVP only for slow-tripping logic, where timer pickup PUs should be coordinated with other relays, which is not discussed in this paper. The backup scheme uses traditional overcurrent elements (ANSI/IEEE type 50/51), which is useful during the grid-interconnected mode, and an undervoltage element (27), which is useful during the grid-isolated mode. Investigating the backup scheme are beyond the scope of this paper.

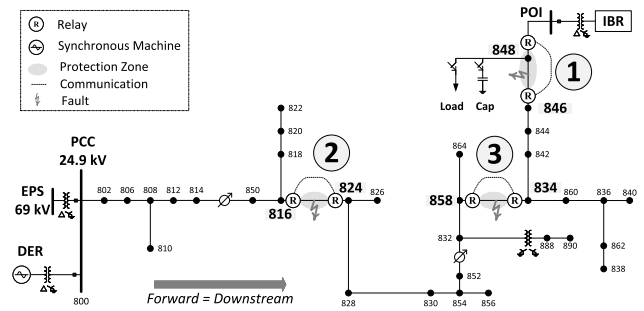


FIGURE 10. Modified IEEE 34-bus distribution system.

III. STUDY CASE: MODIFIED IEEE 34-BUS SYSTEM

A modified version of the IEEE 34-bus distribution system is chosen as a study case [53]. An IBR is connected at node 848, a synchronous DER is connected at Bus 800, and six relays are added to the system, as shown in Fig. 10. The system forms a microgrid by disconnecting from the EPS at Bus 800, which is the PCC. The system is modeled using an electromagnetic transients program, including a 2 MW IBR with a switching voltage source converter (VSC) model, a 2.2 MVA synchronous DER with governor and exciter models, and a digital relay model [54]. The relay model includes filters, time-domain and phasor-based protection elements, and communications between relays.

Three locations on the IEEE 34-bus system are chosen to test the protection scheme, location 1 is close to the IBR, location 2 is in the stiff part of the system, and location 3 is in the weak part of the system. Location 1 includes relays at node 846 and node 848, location 2 includes relays at node 816 and node 824, and location 3 includes relays at node 858 and node 834. Each location is tested during both grid-isolated and grid-interconnected modes with ten possibilities of in-zone fault types. In addition, faults with high (H) and low (L) fault resistances (R_f) are tested for each fault type, where a high R_f is 80 Ω , and a low R_f is 0 Ω for the primary 24.9 kV system.

A. SIMULATION RESULTS

The relay signals and response time is recorded for each scenario in milliseconds, in Table 1. The recorded signals are FWD/REV, IN-ZONE, and TRIP. The system phases are denoted as A, B, and C, and the ground is denoted as G. The relays successfully identify fault direction and zone during both microgrid modes for different fault types and fault resistances.

For example, during the grid-isolated mode, the relay at node 846 correctly indicates an FWD fault with a response time of 2.6 ms, and the relay at node 848 indicates a REV fault with a response time of 2.6 ms for an SLG fault between node 846 and node 848, as shown in the timing diagrams in the lower part of Fig. 11. The relay at node 846 sends an FWD signal to the relay at node 848 and receives a REV signal from the relay at node 848. Then, the relay at node 846 asserts

TABLE 1. Relay element response times in milliseconds for grid-connected and grid-isolated fault cases.

Fault	R_f	Relay at node 846 response time (ms)			Relay at node 848 response time (ms)				Relay at node 846 response time (ms)			Relay at node 848 response time (ms)			
		FWD	IN-ZONE	TRIP	REV	IN-ZONE	TRIP		FWD	IN-ZONE	TRIP	REV	IN-ZONE	TRIP	
Location: 1 Grid-Interconnected Mode	ABC	L	2.24	6.22	6.22	2.24	6.22	6.22	2.24	6.22	6.22	2.24	6.22	6.22	
		H	2.57	6.56	7.30	2.57	6.56	7.30	2.49	6.47	7.30	2.49	6.47	7.30	
	AG	L	2.40	6.39	7.72	2.40	6.39	7.72	2.57	6.56	7.72	2.57	6.56	7.72	
		H	2.90	6.97	14.7	2.90	6.97	14.7	2.82	6.80	10.5	2.82	6.80	10.5	
	BG	L	5.15	9.46	10.9	5.48	9.13	10.9	3.74	7.88	7.88	3.90	7.72	7.72	
		H	5.81	9.79	14.8	5.81	9.79	14.8	2.99	6.97	9.55	2.99	6.97	9.55	
	CG	L	2.90	6.97	7.88	2.90	6.97	7.88	2.74	6.72	6.72	2.74	6.72	6.72	
		H	3.57	7.55	14.9	3.57	7.55	14.9	2.82	6.80	9.63	2.82	6.80	9.63	
	AB	L	2.40	6.39	6.72	2.40	6.39	6.72	2.74	6.72	6.72	2.74	6.72	6.72	
		H	2.74	6.72	7.47	2.74	6.72	7.47	2.90	6.97	6.97	2.90	6.97	6.97	
	AC	L	2.32	6.30	6.30	2.32	6.30	6.30	4.48	8.47	8.47	4.48	8.47	8.47	
		H	2.49	6.47	7.55	2.49	6.47	7.55	3.07	7.06	7.06	3.07	7.06	7.06	
	BC	L	3.65	7.64	7.64	3.65	7.64	7.64	2.57	6.56	6.56	2.57	6.56	6.56	
		H	3.90	7.88	8.88	3.90	7.88	8.88	3.82	7.80	7.80	3.82	7.80	7.80	
	ABG	L	2.32	6.30	6.30	2.32	6.30	6.30	2.74	6.72	6.72	2.66	6.72	6.72	
		H	2.57	6.64	6.89	2.57	6.64	6.89	2.57	6.56	6.89	2.57	6.56	6.89	
	ACG	L	2.32	6.30	6.30	2.32	6.30	6.30	2.24	6.30	6.30	2.24	6.30	6.30	
		H	2.40	6.47	6.89	2.40	6.47	6.89	2.82	6.80	6.80	2.82	6.80	6.80	
	BCG	L	2.74	6.72	6.72	2.74	6.72	6.72	2.24	6.23	6.23	2.24	6.23	6.23	
		H	2.99	7.06	9.05	2.99	7.06	9.05	2.40	6.39	6.39	2.40	6.39	6.39	
Location: 2 Grid-Interconnected Mode	ABC	L	2.24	6.22	6.22	2.24	6.22	6.22	2.40	6.39	6.56	2.40	6.39	6.56	
		H	2.40	6.47	8.38	2.40	6.39	8.38	2.24	6.23	6.23	2.24	6.23	6.23	
	AG	L	2.49	6.47	8.55	2.49	6.47	7.72	2.40	6.39	7.72	2.40	6.39	7.72	
		H	2.90	6.89	15.7	2.90	6.89	15.7	3.40	7.47	12.6	3.40	7.47	12.6	
	BG	L	5.15	9.13	10.9	5.15	9.21	10.9	2.74	6.64	6.64	2.66	6.72	6.72	
		H	5.98	9.96	18.9	5.89	9.96	18.9	2.74	6.81	9.38	2.74	6.81	9.38	
	CG	L	2.90	6.89	7.88	2.90	6.89	7.88	5.06	8.88	8.88	4.89	9.05	9.05	
		H	3.57	7.55	16.9	3.49	7.72	15.9	2.74	6.72	9.46	2.74	6.72	9.46	
	AB	L	2.49	6.47	6.72	2.49	6.47	6.72	2.74	6.72	6.72	2.74	6.72	6.72	
		H	2.74	6.72	7.64	2.74	6.72	7.64	2.57	6.56	7.47	2.57	6.56	7.47	
	AC	L	2.32	6.31	6.31	2.32	6.31	6.31	2.24	6.23	6.23	2.24	6.23	6.23	
		H	2.40	6.47	7.55	2.40	6.39	7.55	3.82	7.89	8.79	3.82	7.89	8.79	
	BC	L	3.49	7.47	7.47	3.49	7.47	7.47	4.48	8.47	8.47	4.48	8.47	8.47	
		H	3.90	7.89	8.88	3.90	7.89	8.88	3.49	7.39	7.39	3.49	7.39	7.39	
	ABG	L	2.41	6.39	6.97	2.41	6.39	6.39	2.16	6.14	6.89	2.16	6.14	6.89	
		H	2.57	6.64	6.89	2.57	6.64	6.89	2.66	6.72	6.72	2.66	6.72	6.72	
	ACG	L	2.24	6.23	6.23	2.24	6.23	6.23	2.82	6.81	6.81	2.82	6.81	6.81	
		H	2.32	6.39	7.72	2.32	6.39	6.89	2.49	6.47	6.97	2.49	6.47	6.97	
	BCG	L	2.82	6.81	6.81	2.82	6.81	6.81	2.24	6.31	6.31	2.24	6.31	6.31	
		H	3.07	7.06	9.05	3.07	7.06	9.05	2.49	6.39	6.81	2.49	6.39	6.81	
Location: 3 Grid-Interconnected Mode	ABC	L	2.24	6.22	6.22	2.24	6.22	6.22	2.74	6.14	6.14	2.16	6.23	6.23	
		H	2.49	6.47	7.30	2.49	6.47	7.30	2.57	6.56	7.22	2.57	6.56	7.22	
	AG	L	2.41	6.39	7.72	2.41	6.39	7.72	2.49	6.47	7.72	2.49	6.47	7.72	
		H	2.74	6.72	13.7	2.82	6.80	13.6	3.07	7.06	7.06	3.07	7.06	7.06	
	BG	L	5.06	9.13	10.9	5.06	9.13	10.9	2.57	6.64	7.55	2.57	6.64	7.55	
		H	5.64	9.63	12.7	5.64	9.63	12.7	2.74	6.81	8.55	2.82	6.81	8.55	
	CG	L	2.82	6.89	7.89	2.82	6.89	7.89	2.66	6.64	7.64	2.66	6.64	7.64	
		H	3.24	7.22	10.7	3.24	7.22	10.7	5.64	9.63	12.5	5.64	9.63	12.5	
	AB	L	2.41	6.39	6.72	2.41	6.39	6.72	2.24	6.23	6.72	2.24	6.23	6.72	
		H	2.66	6.64	6.64	2.66	6.64	6.64	2.40	6.39	7.47	2.40	6.39	7.47	
	AC	L	2.32	6.31	6.31	2.32	6.31	6.31	2.40	6.39	6.39	2.40	6.39	6.36	
		H	2.49	6.47	6.72	2.49	6.47	6.72	2.40	6.39	6.72	2.40	6.39	6.72	
	BC	L	3.57	7.55	7.55	3.49	7.55	7.55	2.49	6.47	6.47	2.41	6.56	6.56	
		H	3.74	7.80	7.80	3.74	7.80	7.80	3.15	7.22	7.22	3.15	7.14	7.14	
	ABG	L	2.32	6.31	6.31	2.32	6.31	6.31	2.49	6.47	6.47	2.49	6.47	6.47	
		H	2.57	6.56	6.89	2.57	6.56	6.89	2.40	6.47	6.89	2.40	6.47	6.89	
	ACG	L	2.24	6.23	6.23	2.24	6.23	6.23	2.82	6.81	6.81	2.82	6.81	6.81	
		H	2.49	6.47	6.97	2.49	6.47	6.97	3.15	7.22	7.22	3.15	7.22	7.22	
	BCG	L	2.74	6.72	6.72	2.74	6.72	6.72	2.16	6.14	6.14	2.16	6.14	6.14	
		H	3.07	7.06	8.05	3.07	7.06	7.06	2.82	6.81	6.81	2.82	6.81	6.81	

IN-ZONE and TRIP with a response time of 6.6 ms and 7.7 ms, respectively, as shown in Fig. 11 (a). Similarly, the

relay at node 848 asserts IN-ZONE and TRIP with a 6.6 ms and 7.7 ms response time, respectively, as in Fig. 11 (b).

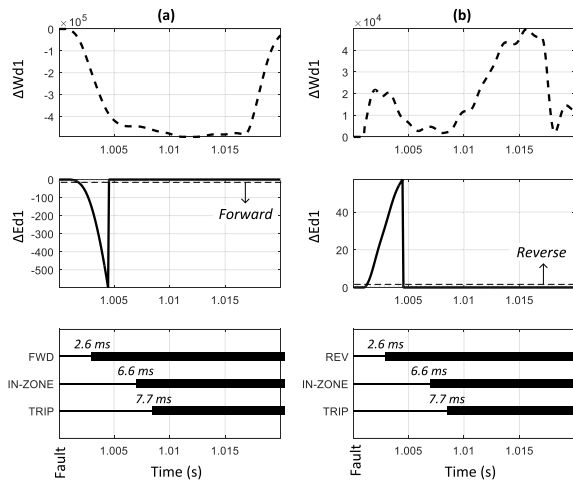


FIGURE 11. In-zone single line to ground fault at location 1 during grid-isolated mode with FWD/REV, IN-ZONE, and TRIP assert times marked in ms: (a) Relay at node 846 response and (b) Relay at node 848 response.

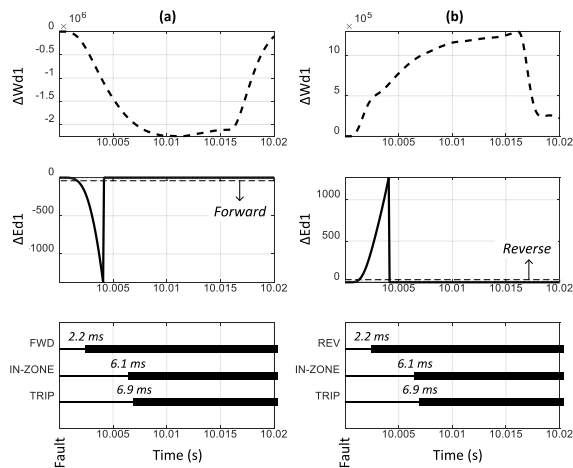


FIGURE 12. In-zone double line to ground fault at location 2 during grid-isolated mode with FWD/REV, IN-ZONE, and TRIP assert times marked in ms: (a) Relay at node 816 response and (b) Relay at node 824 response.

Fig. 12 and Fig. 13 show the responses to a double line to ground fault at location 2 during the grid-isolated mode and a line to line fault at location 3 during the grid-interconnected mode, respectively.

In addition to the logic signals, the figures show two analog signals, the Watt component $\Delta Wd1$ and the superimposed positive-sequence direct energy $\Delta Ed1$. FWD and REV assert if both $\Delta Ed1$ and $\Delta Vd1$ satisfy the thresholds where $\pm \Delta E_{min}$ is a small value and $-\Delta V_{min}$ is 5% of the peak line to neutral voltage of the system, as discussed earlier. Figs. 11, 12, and 13 (b) show reliable analog signals when the IBR is the main source of fault current measured by relays at nodes 848, 824, and 834, respectively. The improved superimposed-based directional elements at each

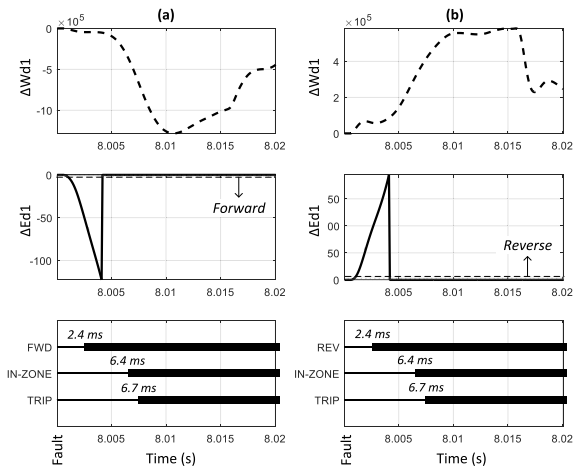


FIGURE 13. In-zone line to line fault at location 3 during grid-interconnected mode with FWD/REV, IN-ZONE, and TRIP assert times marked in ms: (a) Relay at node 858 response and (b) Relay at node 834 response.

relay successfully indicate the direction of faults where fault current is supplied by the IBR.

Table 1 lists the response of FWD/REV, IN-ZONE, and TRIP times in milliseconds for ten possibilities of in-zone fault types with high and low fault resistances at the three locations and during both grid-interconnected and grid-isolated modes. The left section of the table summarizes results for faults in grid-interconnected mode, and the right half of the table summarizes results for the same set of faults with the system operating in grid-isolated operation.

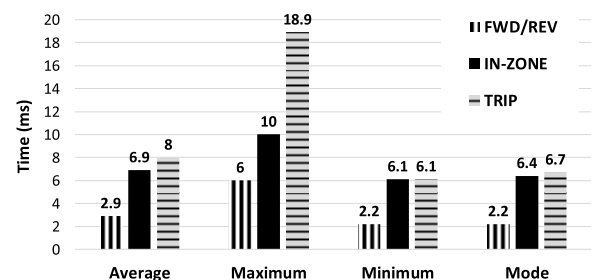


FIGURE 14. FWD/REV, IN-ZONE, and TRIP signals response time statistics for the cases in TABLE 1.

Fig. 14 presents the response statistics of FWD/REV, IN-ZONE, and TRIP times for the data set in Table 1, which includes different fault types and locations with two fault resistance values during both grid-interconnected and grid-isolated modes. The average and mode response times of FWD/REV are less than one-quarter-cycle, and the maximum response time is less than half-cycle. The signal processing delay comes from the response of the anti-aliasing filter, delta filter, and the DDSRF.

The IN-ZONE detection has an additional fixed four milliseconds delay added for communications delay. This delay could be increased or decreased depending on the communication scheme. IN-ZONE average and mode response

time are less than half-cycle, and the maximum is less than one cycle. The average and mode TRIP response times are about half-cycle, and the maximum is slightly above one cycle. The main delay for TRIP comes from the full-cycle DFT filter. Using a half-cycle DFT filter could improve the delay, but it might reduce signal stability.

Furthermore, different response times are observed with different scenarios. For instance, during grid-isolated cases, relays assert FWD/REV 5% faster and assert TRIP 10% faster on average than when grid-interconnected because of the voltage drop rate of change. SLG faults tend to be 15% slower than the average response time of 2.9 ms. Also, for the high fault resistance condition, the relays assert FWD/REV 9% slower and assert TRIP 24% slower than for the low fault resistance case. The high resistance fault case exhibits a small change in voltage and a lower rate of change of voltage, which slows the response of the $\Delta Wd1$ element. In addition, the high fault resistance changes the angle of the fault current, which also impacts the response of the element. However, the trip response is still under 20 ms in the worst case.

The scheme's sensitivity is determined by phasor-based superimposed voltage ΔV_f , where the threshold is set based on the pre-fault analysis. Thus, high fault resistance conditions in stiff systems are challenging because fault resistance coverage depends on the voltage threshold. However, using the proposed superimposed-based voltage-restrained element is an advantage. The proposed element is more reliable than typical voltage-restrained elements because the threshold of the superimposed voltage quantity is based on the voltage change in the system.

Additional cases are also conducted to test the security of the element. A 750 kVAR capacitor bank and a (60+48i) kVA load are switched into the system between relays 846 and 848 in separate cases. The relays did not trip in either case. Several out-zone faults are applied to the system in different locations; the directional element did not assert an IN-ZONE signal in any of the cases. The scheme was also tested in a loop configuration microgrid system and in a system with two parallel feeders with normally open and normally closed breakers. The protection scheme responded correctly in all cases.

IV. CONCLUSION

The proposed microgrid superimposed-based protection scheme provides an ultra-high-speed sub-cycle directional element aided with only low bandwidth communications. The directional element's average response time to indicate fault direction is three milliseconds, and to identify the fault zone is seven milliseconds. The two relays trip for an in-zone fault within a half-cycle during both grid-interconnected and grid-isolated modes. The scheme can be applied to dynamic microgrid topologies and microgrids with radial or loop configurations. Additionally, the improved time-domain superimposed directional element, which uses the DDSRF algorithm, successfully indicates the direction of faults when the IBR is the main source of fault current. The

superimposed positive-sequence direct energy component reduces the negative impact of the IBR control response during faults. The element also was secure against load and capacitor switching as well as out-of-zone faults.

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