On Communication-Assisted Line Protection for Multi-Inverter Microgrid

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Abstract

Protection is critical in maintaining grid stability and reliability. Microgrids, which are small-scale power systems that can operate autonomously or while connected to the main grid, pose unique challenges for protection schemes. Traditional protection methods, such as time-delayed overcurrent relays, reclosers, and fuse-based protection may not be sufficient to detect faults in microgrids. This paper discusses the differences in protection requirements between autonomous and grid-connected microgrids, a comparison of overcurrent and differential protection schemes, and the advancements in microgrid communication, cybersecurity, standards, and test beds. A benchmark 4-bus microgrid system is implemented in distribution voltage ratings, with simulation results demonstrating the effectiveness of synchrophasor-based relays in detecting faults. Showing the feasibility of differential protection over overcurrent protection. Paper is concluding with future work needed to enhance the novel protection concepts.

Index Terms—Microgrid protection, inverters, fault analysis, overcurrent, differential, grid-connected, islanded, 4 bus benchmark and relay.

1. Introduction

In recent years, microgrids have gained popularity due to their ability to improve power quality, reduce energy costs, and increase the reliability of the electrical grid with the integration of PV and Inverter based resources (IBR). Microgrids have unique protection challenges that require specialized solutions. Traditional protection schemes like time-delayed overcurrent relays, reclosers and fuse-based protection may not be effective in microgrids due to bidirectional power flow, limited short circuit capacity, and the potential for unintentional islanding [1]. Synchrophasor-based relays are a promising solution providing fast, accurate fault detection and isolation. These relays use synchronized phasor measurements to detect changes in voltage and current magnitude and phase angle, detecting faults and disturbances in real time [2].

This paper discusses the challenges and importance of microgrid protection schemes, highlighting advancements in synchrophasor-based relays for autonomous and grid- connected microgrids. It compares typical protection schemes to differential protection and emphasizes the significance of microgrid communication, cybersecurity, and standards-based operation. The paper includes a benchmark model and simulation results to demonstrate the effectiveness of synchrophasor-based relays and differential relaying techniques for microgrid protection. The section structure of this paper is divided as follows; Microgrids, Protection schemes, Advancements in microgrid communication, cybersecurity, standards, and test beds, Microgrid Testbed Model, Simulation results, Discussion and Conclusions.

2. Microgrids

A microgrid is a localized energy system that operates autonomously or in conjunction with the main power grid. It consists of distributed energy resources (DERs) such as solar panels, wind turbines, batteries, and other forms of local power generation. Microgrids are designed to provide electricity to a specific area, ensuring a reliable, resilient, and potentially sustainable power supply.

Grid-Connected Microgrids are connected to the main power grid and can both import and export electricity. They can draw power from the main grid during times of high demand or supply excess energy back to the grid when their local generation exceeds demand. When grid-connectable microgrids are being synchronized and connected to the main grid, it represents a significant concern for the utilities, which may encounter frequency, voltage, and load-balance problems during such events. Grid-connected microgrids provide benefits such as grid stability,

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demand response, and the potential for revenue generation through energy trading.

Autonomous (islanded) microgrids normally operate independently from the main grid and do not rely on it for power supply. They have localized energy generation sources, energy storage, and control systems, ensuring continuous electricity supply even during grid outages or emergencies. Islanded microgrids are commonly used in remote areas, islands, or critical facilities where a reliable power supply is crucial. Autonomous microgrids require more advanced protection schemes, as they cannot rely on the larger grid to provide backup power in case of faults or failures. Therefore, the protection system must be able to detect and isolate faults quickly and effectively to maintain stability and reliability.

Hybrid microgrids combine multiple sources of power generation and energy storage technologies to optimize the efficiency and reliability of the system. They typically integrate renewable energy sources like solar and wind with conventional sources such as diesel generators or fuel cells. By utilizing a mix of energy sources, hybrid microgrids can reduce reliance on fossil fuels, lower emissions, and improve overall system performance. Remote microgrids are deployed in areas that are not connected to the main power grid. They are self-sufficient systems that rely on local renewable energy sources and energy storage technologies to provide electricity to isolated communities, mining operations, research facilities, or other remote locations.

One effective solution for microgrid protection is the use of synchrophasor-based relays. Syncrophasors, also known as phasor measurement units (PMUs), are one of the advance- ments in microgrid protection that can improve the performance of protection schemes. Syncrophasors measure voltage and current signals at high speeds and time-stamp them with a common time reference, allowing for accurate and synchro- nized measurements across the grid. By using these measurements, the relays can accurately detect and locate faults in the microgrid, even in the presence of high levels of distributed generation and bidirectional power flow. In addition, relays can provide real- time monitoring and control of the microgrid, allowing for rapid response to changing grid conditions. This is especially important for grid-connected microgrids, where the protection scheme must be able to quickly adapt to changes in the main grid conditions to prevent cascading failures.

Synchrophasors offer real-time and precise measurement of electrical variables throughout the power grid. This technology has many applications, including system model validation, wide-area control, determining stability margins, islanding detection, system-wide disturbance, and dynamic system response; including GPS satellite-synchronized clocks, phasor measurement units (PMUs), phasor data concentrator (PDC), communications systems, and visualization [3]. They are typically obtained through PMUs that are installed in the microgrid. The high accuracy and synchronization of syncrophasors make them ideal for detecting faults in the microgrid. PMUs are capable of capturing samples from a waveform in quick succession and reconstructing the phasor quantity, made up of phase magnitude, and phase angle. Synchrophasor can be used for a variety of protection applications, including fault detec- tion, isolation, and restoration. The IEC/IEEE 60255-118-1 standard defines effective methodologies for the exchange of synchronized phasor measurement data [4].

Existing regulatory frameworks and policies often do not adequately accommodate or incentivize microgrid deployment. Issues such as grid interconnection rules, tariff structures, and permitting processes may create barriers for microgrid development. Updating regulations and establishing supportive policies are crucial for the widespread adoption of microgrids.

Microgrid projects require substantial upfront investments for infrastructure development, including renewable energy sources, energy storage, control systems, and communication networks. Securing financing for microgrid projects and ensuring their long-term financial viability can be challenging, particularly in cases where the cost-benefit analysis or revenue models are not well-defined or when the microgrid serves poor areas.

Microgrids often involve the integration of diverse technologies and systems, including renewable energy sources, energy storage, demand response, and advanced control systems. Ensuring seamless integration, interoperability, and effective coordination among these technologies can be a complex task, requiring standardized communication protocols, compatibility among devices, and proper system design and engineering.

Integrating microgrids with the existing utility infrastructure can pose technical challenges. Coordinating the operation of microgrids with the main grid, managing power flows, and ensuring stability require advanced control algorithms, grid protection schemes, and coordination mechanisms. System integration challenges arise when microgrids need to interface with different utility systems, grid codes, and grid operation practices.

While microgrids aim to enhance resiliency and reliability, ensuring their robustness during extreme events, such as natural disasters or cyber-attacks, can be challenging. Microgrids need to be designed, operated, and protected to withstand disturbances, maintain critical loads, and facilitate quick recovery. Implementing advanced control and protection schemes, as well as addressing cybersecurity concerns, are essential for reliable microgrid operation.

Engaging stakeholders, including utility companies, local communities, regulatory bodies, and end-users, is crucial for successful microgrid deployment. Addressing concerns, ensuring community acceptance, and creating partnerships among stakeholders require effective communication, education, and engagement strategies.

3. Microgrid Protection

Protective relaying solutions for grid-connected and autonomous microgrids share some common principles but also have some notable differences.

In grid-connected microgrids, protective relaying schemes need to coordinate with the main grid's protection system. This coordination ensures that faults or abnormalities in the microgrid do not disrupt the stability and protection of the broader grid. Coordination schemes involve communication and coordination protocols to ensure seamless operation between the microgrid and the main grid. Grid-connected microgrids should be able to detect islanding events, which occur when the microgrid becomes electrically isolated from the main grid. Specialized islanding detection techniques and relaying schemes are employed to detect these events accurately and rapidly. Islanding detection is crucial to prevent safety hazards and ensure a safe reconnection with the main grid after an islanding event. Grid-connected microgrids must incorporate protective relaying schemes to detect and respond to faults on the main grid. These relays are responsible for detecting faults, such as short circuits or abnormal current/voltage conditions, and initiating appropriate protection actions, such as circuit breaker tripping, to isolate the faulted section.

Autonomous microgrids operate in islanded mode, meaning they are not directly connected to the main grid. The protective relaying solutions for autonomous microgrids primarily focus on the internal protection and stability of the microgrid itself. Autonomous microgrids require protective relaying schemes to promptly detect faults within the microgrid. These relays monitor various parameters such as voltage, current, frequency, and power quality to identify abnormal conditions and initiate protective actions like circuit breaker tripping. The goal is to isolate the faulted section and prevent further disruptions within the microgrid. In autonomous microgrids, protective relaying plays a crucial role in maintaining local stability and control. Relays monitor and respond to deviations in frequency, voltage, and power flow to regulate the microgrid's internal operation. They help maintain stability by coordinating the operation of DERs, energy storage systems, and load control mechanisms. Protective relaying in autonomous microgrids should support black start capability, enabling the microgrid to restart and restore power independently after a complete outage. This requires specialized relaying schemes and control strategies to synchronize and coordinate the reconnection of different microgrid components.

Microgrid protection relays have evolved significantly over the years to meet the unique requirements of microgrids. Traditional protection schemes for distribution grids such as time-delayed overcurrent relays, reclosers, and fuse-based pro- tection, have been commonly used by utilities for distribution protection. Their protection ranges from individual feeders to lateral taps. For time delay protection, the closer the relay is to the grid, the longer the time delay for operation is. A typical radial system for distribution is shown in Fig. 1. Reclosers are designed to act in a fraction of the time, a recloser’s rapid trip curve can cause a trip in as little as 1.5 cycles allowing temporary faults to be cleared without intervention. Automatically re-closing breakers after 1 to 5 seconds. Once the recloser has executed a predetermined number of operations, it intentionally slows down the switching time [5]. This allows downstream fuses to clear permanent faults without interrupting the power supply safeguarding fuses.

In the context of microgrids, to ensure effective coordination between upstream and downstream devices, conventional fuse-saving strategies rely on having sufficiently high levels of short circuit current [6]. These schemes have limitations that make them unsuitable for certain situations, particularly in microgrids with complex topologies and bidirectional power flow. An alternative solution for dealing with this issue is implementing adaptive overcurrent protection [7]. This method allows for the automatic adjustment of protection settings based on constantly changing conditions.

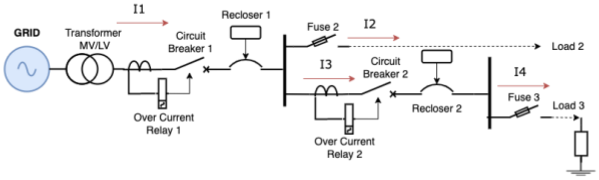


Fig. 1: Traditional protection scheme in distribution

Differential protection is another scheme that has gained popularity in microgrid protection [8]. Unlike typical schemes, differential protection compares the current flowing into a zone with the current flowing out of the zone, providing faster and more selective protection as in Fig. 2. Differential protection is particularly effective for detecting faults in complex microgrid topologies, where traditional schemes may not be reliable.

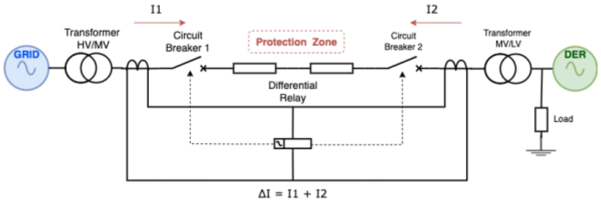


Fig. 2: Differential protection scheme with DER integration

The choice of protection scheme depends on the specific requirements of the microgrid. Fuse-based protection and reclosers are useful in microgrids with lower fault levels, where the cost of implementing more sophisticated protection schemes may not be justified. Time-delayed overcurrent relays suit for simple microgrid topologies with unidirectional power flow, while differential protection is effective for complex topologies with bidirectional power flow due to DER integration.

Modern relays can detect faults quickly and accurately, even in the presence of bidirectional power flow, providing information about the stability of the grid, which is important for maintaining grid reliability. Those relays can be used in both autonomous and grid-connected microgrids. In autonomous microgrids, synchrophasor-based relays can be used to provide islanding detection and protection. In grid-connected microgrids, they can be used for fault detection and protection, and to support grid stability.

4. Microgrid Communications, Cyber-security, Standards, and Testbeds

Microgrid communications are implemented using a combination of technologies and protocols to enable efficient and reliable data exchange between various components within the microgrid. Microgrid communication networks provide the infrastructure for data transmission. Wired or wireless networks may be used, depending on the requirements of the microgrid. Wired networks, such as Ethernet or fiber-optic cables, offer high bandwidth and reliability. Wireless networks, like Wi-Fi or cellular networks, provide flexibility and scalability. The choice of network depends on factors such as distance, data volume, security, and cost.

SCADA systems are commonly used in microgrids for monitoring and control. They enable real-time data acquisition, control, and visualization of the microgrid's components and parameters. SCADA systems collect data from various devices, such as sensors, meters, and controllers, and allow operators to remotely monitor and control the microgrid's operation.

Communication protocols and interfaces are utilized to enable communication between the microgrid's DERs, such as solar panels, wind turbines, and energy storage systems. These protocols facilitate monitoring, control, and coordination of DERs, ensuring optimal power generation, storage, and integration with the microgrid. Microgrid controllers act as the central intelligence for managing the microgrid's operation. They collect data from various sources, make control decisions, and issue commands to different components. Communication protocols like Modbus, DNP3 (Distributed Network Protocol), or IEC 61850 are often used to facilitate communication between the microgrid controller and other devices within the microgrid.

Communication plays a crucial role in demand response and load control in microgrids. Smart meters, energy management systems, and customer engagement platforms enable real-time communication between the microgrid and end-users. This allows for dynamic pricing, load shedding, load shifting, and other demand response strategies to balance energy supply and demand. Microgrid communications should incorporate robust cybersecurity measures to protect against unauthorized access, data breaches, and cyber threats. Encryption, authentication, access control, and intrusion detection systems are employed to ensure the integrity, confidentiality, and availability of data exchanged within the microgrid.

Standardization of communication protocols and interfaces is crucial to ensure interoperability and compatibility among different components and vendors within the microgrid. Standards such as Modbus, OPC (OLE for Process Control), and IEC 61850 provide guidelines for communication in power systems and facilitate seamless integration of diverse devices and systems. It's important to note that the specific implementation of microgrid communications can vary depending on the size, complexity, and goals of the microgrid. Each microgrid requires a tailored communication infrastructure that meets its unique requirements while considering factors such as reliability, scalability, security, and cost-effectiveness.

Compliance with established standards ensures the effectiveness of microgrid protection schemes [1]. Norms and standards enable the integration of protection schemes and devices from different manufacturers, simplify procurement processes, and promote technology innovation. Several standards organizations have published standards related to microgrid protection, including IEEE 1547 standard for interconnection of distributed energy resources with electric power systems [10], IEC 61850 standard for substation automation [11], and UL 1741 standard for Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources; equipment meeting this requirement is known as ”Grid Support Inverters,” ”Smart Inverters,” or ”Advanced Inverters” [12].

Cybersecurity is a critical aspect of microgrid protection. The increasing use of digital communication and the Internet of Things (IoT) in microgrid operations have exposed them to potential cyber threats, communication infrastructure is susceptible to cyberattacks that could compromise security. These threats can lead to data breaches, loss of control, and system outages [1]. Therefore, it is essential to implement robust cybersecurity measures to safeguard microgrid systems from cyber-attacks for reliable operation.

Testing and validation are crucial for ensuring the effectiveness of protection schemes in microgrids. Testbed benchmarks, which are experimental facilities that simulate real-world scenarios, are useful for testing and validating microgrid protection systems, further allowing for the testing of protection schemes under varied operating conditions, including abnormal system conditions [1]. Microgrid test bed bench- mark models, such as the CERTS microgrid, CIGRE European microgrid test system, and GridLAB-D microgrid models, are widely used for evaluating and comparing the performance of different control strategies, protection schemes, and technologies in microgrids [13]. Conducting tests is crucial to spot potential issues and pinpoint opportunities for enhancement, ultimately resulting in heightened dependability and stability.

5. Simulation Testbed

To evaluate the effectiveness of relays in microgrid protection, simulation studies are conducted. Testing and simulation are crucial to validate the reliability of microgrid protection schemes. This section discusses the testing of different protection schemes using typical, and differential relays on a 4 Bus benchmark system for microgrid operation [14]. The tests cover both islanded and grid-connected operations, analyzing various types of fault responses to assess the proposed relaying scheme’s performance.

A slightly modified microgrid version of the IEEE 4-bus system is proposed for testing protection schemes in both grid-connected and islanded modes. This modified microgrid included distributed energy resources such as PV systems in a grid-forming mode of operation to closely emulate a real implementation. The microgrid is then tested for various types of short circuit faults, including single-phase, phase-to-phase, phase-to-phase with ground, three-phase, and three-phase with ground, in both modes of operation. The fault was represented by red lightning in the middle of Line 1, as shown in Fig. 3.

Matlab/Simulink is used to model the 4 Bus microgrid system, shown in Fig.3. It has 4 DGs (Distributive generation) with different types of loads and is connected to the grid through the PCC (Point of common coupling) by a substation feeder. The distribution lines are modeled as short type in MV (Medium Voltage) and the DERs (Distributive energy resources) and Loads in LV (Low Voltage), representing a real-life topology. The DER consists of solar PV with IBR (inverter-based resources) in grid forming based on [15] with droop control, voltage restoration, and frequency restoration based on [16], voltage and current instantaneous limiters for protection of the semiconductors against faults based on [17]. The microgrid was tested for all types of short faults in both islanded and grid-connected modes of operation, and the most important values for microgrid parameters are listed in Tab.I.

TABLE I: Main Microgrid Parameters

Main Components	Parameter Specification
Grid Feeder (MV) & PCC (LV)	$4.1kV/240V$, $50Hz$
Distributed Generation(DG) in LV	$240V/120V$, $50Hz$
Transformers(TR) (Y-Y) (MV/LV)	$30kVA$, $4.1kV/240V$, $50Hz$
Distribution Line (L) Short Lines	$4.1kV$, $500m$

Implemented typical protection schemes like overcurrent relays, reclosers, and fuse-based protection were in some cases [1] insufficient in identifying faults in most cases. Instead, a variety of differential protection scheme was implemented using relays placed at both ends of the protected section. The scheme utilizes phasor magnitude and angle (directional) comparison of the current at two ends of the line segment [20][21], resulting in an effective response for islanded and grid-connected operations. The generalized sinusoid given as $A(t) = A_m \sin(\omega t \pm \Phi)$ represents the sinusoid in the time-domain form, where ω denotes the angular velocity of $\omega = 2\pi f$, and f denotes the frequency. The vector magnitude is the peak of the sinusoid while the phasor complex magnitude is the RMS value [18]. Overall, the input constitutes three-phase current measurements, and the output is synchrophasor measurements for voltage and current magnitudes and phase angles.

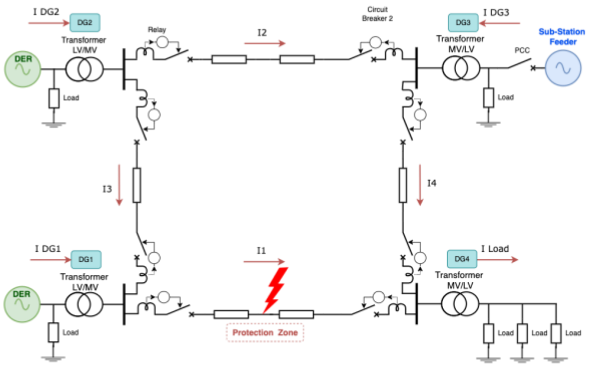


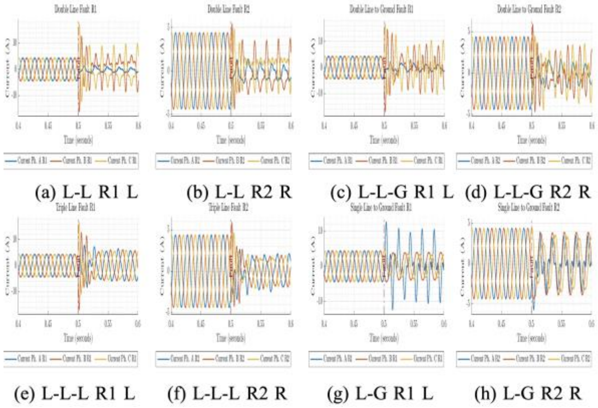
Fig. 3: Microgrid Benchmark 4 Bus System - Network

6. Simulation Results

During a fault, the increased current causes a high peak and imbalance in the line currents, which is detected by the overcurrent relay when the pickup threshold is exceeded. It then isolates the faulty line by opening the circuit breaker. Coordination between overcurrent relays is essential to ensure only the faulted section is disconnected, while the rest of the system remains operational. Simulation results using Matlab/Simulink showed that traditional protection schemes were effective in detecting and isolating faults in grid-connected mode but had limitations in sensitivity and selectivity when IBRs were operating in islanded mode. The synchrophasor- based differential protection scheme demonstrated better se- lectivity and sensitivity and was able to quickly detect and isolate faults in both islanded and grid-connected modes. This was confirmed by comparing the responses at both ends of the compromised line.

The relay was set to not trip the circuit breaker to allow fault current visualization, but in practice, a maximum clearing time of 5 cycles is allowed [5]. The fault occurred in the middle of Line 1 between DG1 and DG4 at 0.5 seconds into the simulation, and all types of faults were tested in both grid- connected and islanded modes. Fig. 5 and Fig. 6 display the fault response in Line 1 for all types of faults in islanded and grid-connected mode respectively, with measurements taken from three-phase wave currents at each end of the line used by relays R1 (Left) and R2 (Right).

Overcurrent relays have a current range setting from 50% to 200%, while earth fault relays have a setting range from 10% to 770% in increments of 10% and 20% respectively [19].

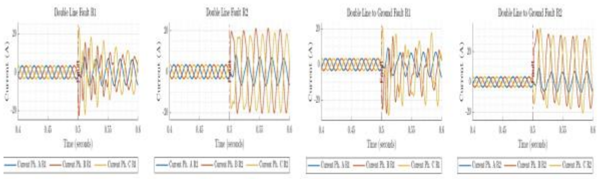


(a) L-L R1 L (b) L-L R2 R (c) L-L-G R1 L (d) L-L-G R2 R

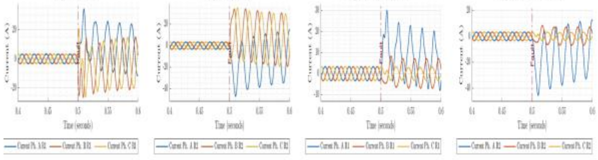
(e) L-L-L R1 L (f) L-L-L R2 R (g) L-G R1 L (h) L-G R2 R

Fig. 5: Waveform Response Islanded R1&R2

In grid-connected mode, OC relays can detect faults due to interaction with the main grid and chain response in adjacent lines. The current settings must be sensitive enough to detect faults quickly and accurately, but high enough to prevent false tripping caused by normal load variations and tap loads. Time delays are coordinated so that the closest OC relay to the faulted section trips first until the faulted section is isolated, followed by the next closest relay. The minimum pick-up current should be twice maximum load, and the time delay should be long enough to avoid nuisance tripping caused by harmless transients, yet fast enough to open the circuit when a hazard exists [19]. The time delay for instantaneous relays is typically less than 3 cycles [20].



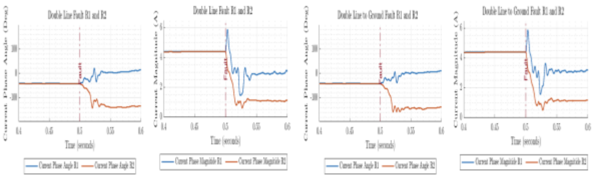
(a) L-L R1 L (b) L-L R2 R (c) L-L-G R1 L (d) L-L-G R2 R



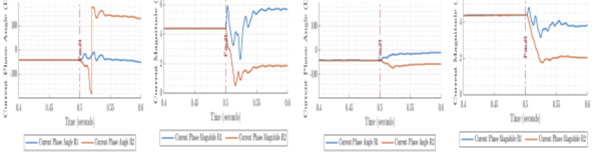
(e) L-L-L R1 L (f) L-L-L R2 R (g) L-G R1 L (h) L-G R2 L

Fig. 6: Waveform Response Grid Connected R1&R2

Tab.IIa and IIIa show the maximum peak current values for different fault scenarios at Line 1 in grid-connected and islanded mode, respectively. Tab.IIb and Tab.IIIb display the corresponding RMS current values, respectively. The peak currents in islanded mode are approximately one-third of those in grid-connected mode, making it difficult for typical overcurrent relays to detect a fault.



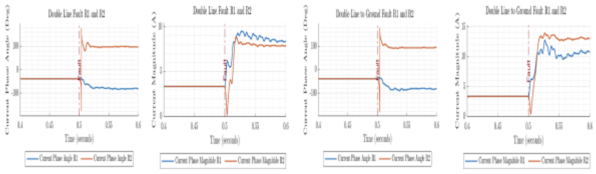
(a) L-L R1&R2 (b) L-L R1&R2 (c) L-L-G R1&R2 (d) L-L-G R1&R2



(e) L-L-L R1&R2 (f) L-L-L R1&R2 (g) L-G R1&R2 (h) L-G R1&R2

Fig. 7: Phase Angle and Magnitude Islanded R1&R2

Tab.IV and Tab.V show synchrophasor results for all fault types at Line 1 in grid-connected and islanded mode, respectively. The first and second rows correspond to sending end relay R1 and receiving end relay R2 responses. Comparing the phasor magnitudes in Tab.IVa and Tab.Va, and phasor angles in Tab.IVb and Tab.Vb for both ends of the line, we can identify variations in current levels for both modes of operation.



(a) L-L R1&R2 (b) L-L R1&R2 (c) L-L-G R1&R2 (d) L-L-G R1&R2

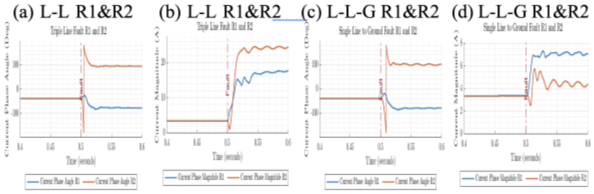


Fig. 8: Phase Angle and Magnitude Grid Connected R1 and R2

TABLE II: Grid Connected Fault Ride Through Currents

Phase Response	Short Circuit Type of Fault (Maximum Current (pu))				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Phase A L.	30.0688	8.1909	9.2117	34.2741	34.4753
Phase B L.	8.4135	15.5256	15.8050	17.1280	17.1280
Phase C L.	3.4645	23.5100	21.1578	20.9745	20.9745
Phase A R.	19.6622	8.1894	9.2101	22.7473	22.7808
Phase B R.	8.4121	21.8249	34.7216	34.0752	34.1479
Phase C R.	3.4633	19.1529	35.3491	35.0800	35.0574

(a) Wave Peak Current

Phase Response	Short Circuit Type of Fault (Current RMS (pu)				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Phase A L.	8.9013	4.7030	4.7161	12.3789	12.4276
Phase B L.	4.3777	6.1642	7.8821	12.3748	12.3932
Phase C L.	2.0846	7.8348	10.4906	12.2844	12.2853
Phase A R.	15.6839	4.7015	4.7145	17.3277	17.3592
Phase B R.	4.3742	14.0597	15.6844	17.2853	17.2985
Phase C R.	2.0846	13.3094	16.3745	17.2267	17.1919

(b) RMS Current

TABLE III: Islanded Fault Ride Through Currents

Phase Response	Short Circuit Type of Fault (Max. Current (pu))				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Phase A L.	12.5701	4.9837	4.9837	7.8433	8.0918
Phase B L.	4.3986	12.6726	14.6803	12.7627	12.5288
Phase C L.	4.4068	17.3966	16.8044	16.8293	16.8602
Phase A R.	4.9755	4.9755	4.9755	4.9755	4.9755
Phase B R.	4.3894	5.3803	5.8929	5.9093	5.8790
Phase C R.	4.3962	4.8274	4.4764	4.6126	4.6915

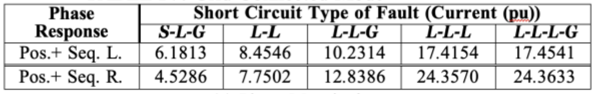
(a) Wave Peak Current

Phase Response	Short Circuit Type of Fault (Current (pu)				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Phase A L.	5.1949	0.7815	0.8177	4.0647	4.0930
Phase B L.	2.8825	3.8457	4.3336	4.1421	4.1122
Phase C L.	2.3882	4.4344	4.7594	3.9797	3.9782
Phase A R.	1.7520	0.7800	0.8164	1.3503	1.3626
Phase B R.	2.8779	1.7700	1.6058	1.3364	1.3554
Phase C R.	2.3830	1.1973	1.6391	1.3405	1.3071

(b) RMS Current

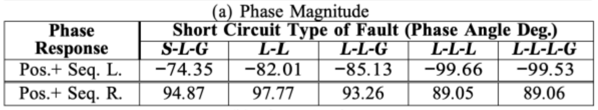
The ends-of-line magnitude comparison can suggest the presence of a fault or tap load, while the angle comparison identifies a sign ± change in degrees, indicating that the current is feeding the fault. These results are consistent with Fig. 7 and Fig. 8. Under islanded mode, the peak currents observed have been about one-third of those in grid-connected mode. This means that typical overcurrent relays would likely not be able to detect the fault. Additionally, current levels return to normal levels within 1−2 cycles, which is below the time delay needed to decide if there is a fault.

TABLE IV: Grid Connected Mode



Phase Response	Short Circuit Type of Fault (Current (pu))				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Pos.+ Seq. L.	6.1813	8.4546	10.2314	17.4154	17.4541
Pos.+ Seq. R.	4.5286	7.7502	12.8386	24.3570	24.3633

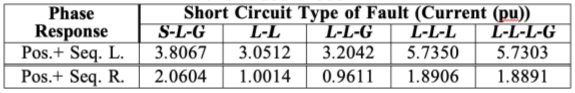
(a) Phase Magnitude



Phase Response	Short Circuit Type of Fault (Phase Angle Deg.)				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Pos.+ Seq. L.	−74.35	−82.01	−85.13	−99.66	−99.53
Pos.+ Seq. R.	94.87	97.77	93.26	89.05	89.06

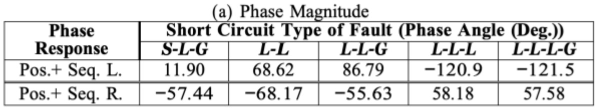
(b) Phase Angle

TABLE V: Islanded Mode



Phase Response	Short Circuit Type of Fault (Current (pu))				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Pos.+ Seq. L.	3.8067	3.0512	3.2042	5.7350	5.7303
Pos.+ Seq. R.	2.0604	1.0014	0.9611	1.8906	1.8891

(a) Phase Magnitude



Phase Response	Short Circuit Type of Fault (Phase Angle (Deg.))				
	S-L-G	***L-L***	***L-L-G***	***L-L-L***	***L-L-L-G***
Pos.+ Seq. L.	11.90	68.62	86.79	−120.9	−121.5
Pos.+ Seq. R.	−57.44	−68.17	−55.63	58.18	57.58

(b) Phase Angle

8. Conclusions

Microgrids have become increasingly popular due to their ability to provide improved power reliability, greater utilization of renewable energy resources, and energy independence. Integrating DERs into microgrids presents new challenges related to protection and control. This paper has discussed the importance of protection schemes in maintaining grid stability and reliability in microgrids. We highlighted the advantages of using synchrophasor-based relays for faster and more accurate fault detection and isolation in both autonomous and grid- connected microgrids. We have investigated protection schemes such as time-delayed overcurrent relays, reclosers, and fuse- based protection with differential protection, further providing an overview of existing standards and testbeds for microgrid implementation and protection studies.

The fault detection scheme essentially based on current directional comparison [21] can be used to detect faults in microgrids. It is a protection scheme that compares the direction of currents at different points in the electrical network to identify the location of faults. It can be employed as a fault detection technique to determine the presence and location of faults within the microgrid. The currents measured at ends of line segments are compared to determine their instantaneous direction. It can be achieved using phase angle comparison or polar comparison techniques. Phase angle comparison involves comparing the phase angles of the currents, while polar comparison compares the polarities of the currents. If a fault occurs within the microgrid, there will be a variation in the current direction or polarity at different points in the network. By comparing the direction or polarity of the currents, the protection system can identify the location of the fault. The faulted section can then be isolated by tripping the corresponding circuit breaker. Current directional comparison is typically used for detecting faults such as short circuits, line-to-line faults, or line-to-ground faults within the microgrid. It offers fast fault detection and helps in isolating the faulted section promptly, minimizing the impact of faults on the microgrid's operation.

It is important to note that current directional comparison may have limitations in certain scenarios, such as when faults occur close to the measurement points or in cases of a large fault resistance. Therefore, it may be beneficial to combine current directional comparison with other protection techniques, such as overcurrent protection, impedance-based protection, or distance protection, to enhance the overall reliability and accuracy of fault detection in microgrids.

Simulation results presented in this paper, using a 4 Bus benchmark model, illustrate that relatively simple directional comparison techniques provide fast and accurate fault detection. Challenges related to communication, cybersecurity, and standardization need to be addressed. Future work needs to be done on secure communication protocols, testing and certifying microgrid protection schemes, and exploring new approaches for integrating, as well as aggregating DERs into microgrids while maintaining grid generation-load balance, stability, reliability, and resilience. This paper highlights the potential for using relatively simple relay techniques to improve the reliability and resilience of microgrids, paving the way for future advancements in microgrid protection.

As microgrid deployment scales up, maintaining consistency, scalability, and standardization become important. Integrating various protection schemes, some requiring communication, evolving interoperability standards and control strategies facilitates easier integration, technology adoption, and replication of successful microgrid models. Addressing these challenges requires collaboration among policymakers, utilities, technology providers, financiers, and local communities. By overcoming these barriers, widespread microgrid deployment can contribute to a more resilient, sustainable, and decentralized energy future.

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