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RESEARCH ARTICLE

Advanced Microgrid Protection Utilizing Zero Sequence Components With Hard-Ware-in-the-Loop Testing

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ABSTRACT Microgrid protection and ground fault management are critical aspects of modern power distribution systems, especially with the increasing integration of Distributed Generators (DGs) such as renewable energy sources. Effective protection schemes are essential to ensure the reliability, safety, and resilience of microgrids under various fault conditions. This study addresses a new advancement in microgrid protection and ground fault management. Firstly, the research integrates zero sequence components into the time-inverse characteristics of phase Overcurrent Relays (OCR) and creates a dynamic scheme between two group settings for phase and ground faults. This enhancement improves ground fault detection and provides robust backup for ground OCR, thereby enhancing the overall reliability of microgrid protection schemes. Secondly, the study demonstrates the use of Configurable Function Blocks (CFCs) in digital relays to dynamically adjust relay settings based on zero sequence current detection. This functionality optimizes relay performance under varying fault conditions, addressing mis-coordination issues in low-value ground fault scenarios at traditional OCR scheme and improving fault detection and clearance times. The proposed strategy is extensively validated through Hardware-in-the-Loop (HIL) testing, ensuring its feasibility and effectiveness in real-world scenarios. HIL testing confirms the practical applicability and robustness of the proposed protection scheme, enhancing its reliability. Finally, the study provides a comprehensive framework for the implementation of the proposed protection strategy in real-case protective relays. It includes a detailed methodology and validation process, offering practical guidance for operators to implement and optimize microgrid protection systems.

INDEX TERMS Distributed generation, ground faults, protection coordination, hardware-in-the-loop.

I. INTRODUCTION

A. BACKGROUND

The emergence of microgrids has transformed modern electricity grids by providing numerous benefits that have fundamentally changed power generation and distribution. Microgrids employ advanced control systems and algorithms to optimize energy distribution, ensuring consistent power availability. This has led to enhanced power quality, efficiency, and reliability, greatly benefiting electricity consumers. Moreover, microgrids facilitated the integration of renewable energy sources (RES) and energy storage

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systems (ESS) at the distribution level, which is pivotal in addressing climate change [1], [2]. The increased utilization of clean energy necessitates an environmentally sustainable energy system. Microgrids enabled the efficient incorporation of solar panels, wind turbines, and other renewable energy sources into the grid. Additionally, energy storage systems enhanced grid efficiency and reliability by ensuring that energy from renewable sources is effectively stored and distributed [3]. However, the integration of RES and ESS introduced new challenges for protection systems due to changes in fault characteristics. The variability and distributed nature of renewable energy sources can modify fault currents and fault detection parameters, complicating traditional protection strategies [4], [5]. Therefore, advanced protection schemes must be developed to manage these complexities and ensure the continued reliability and safety of the electricity grid.

B. LITERATURE REVIEW

The protection of electrical networks, particularly within microgrids and Distributed Generation (DG) environments, has garnered significant research attention. Various studies have focused on relay coordination and protection schemes to enhance ground fault detection and overall system reliability. A study by [1] investigated directional Overcurrent Relays (OCRs) and directional ground-fault protection for Malaysia's 33 kV underground cable system. This research compared the efficacy of directional relays to pilot-wire schemes, identifying optimal relay configurations to ensure efficient protection during fault scenarios. Another study highlighted the importance of efficient relay settings by proposing a novel tripping characteristic for directional OCRs to improve the operation of protective systems in DG-integrated networks [2]. This research significantly reduced relay operating times by optimizing relay settings through a protection coordination optimization (PCO) model. Advancements in relay coordination methods are further demonstrated by a study employing a new Nondominated Sorting Genetic Algorithm-II (NSGA-II) algorithm approach, which aims to minimize discrimination times between primary and backup relays while optimizing their operating times without relying on weighting factors. This approach addressed both near and far-end faults, yielding improved coordination results [3]. Enhanced optimization techniques are also explored using the Interior Point Method (IPM), which introduces a New Objective Function (NOF) designed to improve the coordination of directional overcurrent relays in meshed networks by simultaneously considering the operating times of both primary and backup relays [4]. Furthermore, an adaptive directional overcurrent relaying technique has been proposed, which utilizes superimposed positive-sequence and negative-sequence currents to enhance protection coordination and improve fault identification accuracy. This method adapted to fault current magnitude using an Inverse Definite Minimum Time (IDMT) characteristic, ensuring efficient fault protection in microgrid operations [5]. In general, these studies collectively highlighted the ongoing efforts to enhance protection systems in electrical networks, particularly within the context of microgrids and distributed generation, by developing more efficient and reliable relay coordination and fault detection mechanisms.

A strategy introduces new Time-Current Characteristics (TCCs) for directional OCRs in distribution networks. By incorporating auxiliary variables into the operation time model, this approach facilitated faster fault clearing and demonstrated superior relay performance compared to traditional methods [6]. Furthermore, optimization techniques have been refined using meta-heuristic algorithms to set directional overcurrent relays in microgrids. This method, validated on an IEEE 9-bus 4-DG microgrid in ETAP, enhances reliability and negates the need for additional equipment to manage changing fault currents during mode transitions [7]. Addressing coordination challenges, a multi-objective optimization algorithm has been proposed to adjust key parameters, such as the Plug Setting Multiplier (PSM) and Time Setting Multiplier (TSM). This algorithm aimed to minimize discrimination time between primary and backup overcurrent relays, thereby enhancing adaptability to microgrids with distributed energy resources [8]. Additionally, a new relay setting model for overcurrent relays in N-1 and N-1-1 states has been developed to maximize load restoration while maintaining radial network topology. This model, validated using the GE Multilin model-750/760 in ETAP software, focused on specific fault types but underscored the need for more general scenario coverage [9]. Another study emphasized the integration of DGs in both utility-connected and off-grid modes, prompting the development of a method that adapts negative-sequence overcurrent backup for improved coordination and fault direction determination. This approach has been validated through Real-Time Digital Simulator testing [10]. Additionally, a new algorithm for determining relay hierarchies using phase signals has been proposed, which facilitates easy adaptation to different backup tripping and reconfiguration events, thereby enhancing system resilience [11]. In optimizing protection schemes for microgrids, combining phase and ground overcurrent protection functions with an Evaporation Rate Water Cycle Algorithm (ER-WCA) has been suggested. This approach enhanced fault protection through optimal grounding strategies [12]. Overall, these studies highlighted ongoing advancements in relay coordination and protection techniques, addressing the evolving challenges in microgrid environments while improving the overall reliability and efficiency of electrical networks.

A study introduced a method focusing on the ratio of positive sequence current and voltage for fault detection in distribution systems with PV plants, improving relay operations [13]. The Manta Ray Foraging Optimization algorithm (MRFO) has been applied to enhance protection coordination in distribution networks with wind-powered DG, demonstrating the effectiveness of adaptive protection structures [14].

Another study presented a new algorithm using negative and zero sequence currents to improve overcurrent line protection in medium voltage networks for two-phase faults, validated through DIgSILENT Pow-er-Factory simulations [15]. In smart grids, a hybrid optimization algorithm utilizing a genetic algorithm, particle swarm optimization, and linear programming optimized protection schemes under N-1 contingency, incorporating the probability of different configurations [16]. Innovative relay coordination schemes using two-level characteristics optimize operating time and minimize thermal impacts during short-circuit events, adapting to system contingencies [17]. Metaheuristic optimization strategies continue addressing operational time and reliability in various ground fault scenarios [18], and emphasizing the importance of considering fault type and pre-fault load flow for optimal protection settings [19]. An adaptive protection scheme for isolated microgrids was introduced using third harmonic voltage from inverter-based distributed generators to ensure optimal coordination without communication, considering various network configurations [20]. The impact of inverter-interfaced renewable energy resources (IIRERs) on directional relaying schemes necessitates revisiting relay settings to adapt to dynamic fault responses, highlighting changes required for system operators and manufacturers [21]. Optimizing fault current limiter (FCL) and directional OCR settings in distribution networks with high DG penetration effectively maintained relay coordination and reduced short-circuit currents, as suggested [22]. Additionally, a methodology optimizing Ground-Fault Relays (GFRs) in resonant grounding medium-voltage networks enhanced sensitivity and selectivity during Phase-to-Ground (Ph-G) faults, emphasizing safety standards [23], [24].

However, TABLE 1 identifies several critical research gaps in these studies for modern OCR schemes that need to be addressed. Firstly, there is a notable absence of the lack of developing dynamic phase OCR schemes, which limits the understanding of OCR scheme performance under diverse fault conditions. Additionally, there is insufficient exploration of OCR schemes' effectiveness under different fault resistance modes, which are increasingly common in modern power systems. Furthermore, there is a lack of real hardware tests to validate OCR schemes, which are essential for ensuring their reliability and performance in practical applications. Lastly, there is a need for more studies that consider industrial limitations and practical constraints in implementing OCR schemes and using phase or ground OCRs. Addressing these gaps will advance the development of more robust and adaptable OCR schemes, thereby enhancing the protection and reliability of modern electrical networks.

C. CONTRIBUTIONS

Microgrid protection and ground fault management are critical aspects of modern power distribution systems, especially with the increasing integration of DGs such as renewable energy sources. Effective protection schemes are essential to ensure the reliability, safety, and resilience of microgrids under various operating conditions. However, several research gaps and challenges remain in the current literature. TABLE 1 identifies several critical research gaps in modern OCR (schemes that need to be addressed. This study addresses these gaps and contributes several novel advancements to microgrid protection and ground fault management:

- Integration of Zero Sequence Components: the research integrates zero sequence components into the time-inverse characteristics of phase OCR and creates a dynamic scheme between two group settings for phase and ground faults.
- Dynamic Relay Settings Using CFC Functionality: The study demonstrates how Configurable Function Blocks (CFCs) in digital relays can dynamically adjust re-lay settings based on zero sequence current detection, ensuring optimized performance under varying fault conditions. The proposed method adjusts phase OCR characteristics to address mis-coordination issues with OCR in low-value ground fault scenarios, improving fault detection and clearance times.
- Validation Through HIL Testing: Extensive Hardware-in-the-Loop (HIL) testing validates the feasibility and effectiveness of the proposed strategy, ensuring practical applicability and robustness in real-world scenarios.
- IEC 61131-3 and SFC in Relay Programming: Application of the IEC 61131-3 standard and Sequential Function Chart (SFC) in relay programming enhances the interoperability and reliability of microgrid protection systems.
- Comprehensive Framework for Implementation: The study provides a detailed methodology and validation process for implementing the proposed protection strategy in real-case protective relays, offering practical guidance for operators.

D. OUTLINE OF PAPER

This article is structured as follows: Section II introduces the problem description, focusing on grounding strategies and fault types and the importance of ground fault studies. Sections III detail the methodology behind the proposed dynamic OCR protection scheme. Section IV presents the discussion and analysis of simulation and Hardware-in-the-loop (HIL) results. Finally, Section V summarizes the findings and discusses potential future research directions.

II. PROBLEM DESCRIPTION: DEMONSTRATION OF DGs IMPACT ON OCR SENSITIVITY.

Coordinating protection relays in distribution networks with different RES presents a complex challenge. OCRs are widely employed in distribution networks due to their cost-effectiveness and simplicity. However, this complexity can lead to challenges, particularly in ensuring the effective and efficient operation of OCRs during fault conditions. Poor coordination can result in extended fault-tripping times,

TABLE 1. Modern OCR schemes for microgrids.

Ref.	Year	Optimization Technique	Phase relay	Ground relay	Type of Fault	Fault Resistance	Dynamic Phase relay	Hardware-in-the-loop (HIL) testbed
[1]	2012	×	✓	✓	LLL, LG, LLG	×	×	×
[24]	2014	NLP	✓	×	LLL, LG, LLG	×	×	×
[3]	2015	NSGA-II	✓	×	LLL	×	×	×
[4]	2016	IPM	✓	×	LLL	×	×	×
[5]	2016	×	✓	×	LLL	✓	×	✓
[6]	2017	NLP, PSO	✓	×	LLL	×	×	×
[7]	2017	DEA	✓	×	LLL, LLG	×	×	×
[8]	2018	MOPSO	✓	×	LLL	×	×	×
[9]	2018	DEA	✓	×	LLL	×	×	×
[10]	2019	×	✓	×	LLL, LG, LLG	✓	✓	×
[12]	2020	ER-WCA	✓	✓	LLL, LG, LLG	×	×	×
[11]	2020	SA, PSO, GA	✓	×	LLL	✓	×	×
[13]	2020	GA	✓	×	LLL, LG, LLG	×	×	×
[14]	2021	MRFO	✓	×	LLL	×	×	×
[19]	2022	×	✓	×	LLL, LG, LLG	×	×	×
[25]	2022	CSS, TLBO	✓	✓	LLL, LG, LLG	✓	✓	×
[17]	2022	NLP	✓	×	LLL	×	×	×
[16]	2022	GA, PSO, LP	✓	×	LLL	×	×	×
[15]	2022	×	✓	×	LLL, LG, LLG	×	×	×
[26]	2022	PSO	✓	×	LLL, LG, LLG	✓	✓	×
[23]	2022	DE	×	✓	LG	✓	×	×
[27]	2023	TWO, CSS	✓	✓	LLL, LG, LLG	✓	×	×
[28]	2023	GA	✓	×	LLL	×	×	×
[22]	2023	SO, SSA, LP	✓	×	LLL	✓	×	×
[29]	2023	MINLP	×	✓	LG	✓	×	×
[21]	2024	×	✓	×	LLL, LG, LLG	×	×	×
[20]	2024	IPA	✓	×	LLL	✓	×	×
[30]	2024	PSO	✓	×	LLL	×	×	×
[31]	2024	MHGS	✓	×	LLL	×	×	×
The proposed study		×	✓	✓	LG, LLG	✓	✓	✓

* NLP: Nonlinear Programming; NSGA-II: Nondominated Sorting Genetic Algorithm-II; IPM: Interior Point Method; PSO: Particle Swarm Optimization; DEA: Differential Evolution Algorithm; MOPSO: Multi-Objective Particle Swarm Optimization; ER-WCA: Evaporation Rate- Water Cycle Algorithm; SA: Seeker Algorithm; GA: Genetic Algorithm; MRFO: Manta Ray Foraging Optimization; CSS: Charged System Search; TLBO: Teaching-Learning-Based Optimization; LP: linear Programming; TWO: Tug of War Optimization; MINLP: Mixed-Integer Nonlinear Programming; SSA: Salp Swarm Algorithm; MHGS: Modified Version of the Hanger Games Search.

equipment damage, and unstable power quality. Effective coordination of protection schemes is especially critical in addressing ground fault conditions in interconnected microgrids. Thus, careful consideration is necessary when designing ground fault protection systems for interconnected microgrids to ensure their reliability and cost-effectiveness.

A. IMPORTANCE OF GROUND FAULT STUDY FOR MICROGRID PROTECTION

Grounding is a fundamental aspect of any distribution grid, involving the connection of the neutral point to the ground to minimize voltage rise on non-faulted phases during faults. This connection is essential for detecting faults through ground protection schemes, ensuring grid equipment safety and maintaining acceptable over-voltages. Several grounding strategies exist, with the most common involving the neutral point with non-solid earthing. While these strategies effectively handle single line-to-ground faults, solid earthing can further mitigate this issue and reduce the risk of electrical shock. Detecting ground faults is challenging, emphasizing the need for reliable microgrid protection systems capable of promptly identifying and isolating such faults. Ground faults occur due to insulation breakdown between a conductor and the ground, leading to current flow to the ground, potential equipment damage, and safety hazards. Understanding ground faults is crucial for the protection of microgrids and multi-looped systems. Ground fault studies are instrumental in developing effective protection strategies that ensure microgrid reliability and safety. Ground fault detectors are commonly used for protection, detecting faults and providing alarm signals to alert operators while automatically disconnecting equipment from the grid to prevent further damage. Furthermore, ground fault studies enhance protection system performance by addressing challenges associated with these faults. High-impedance systems pose a significant challenge due to their low fault current, making detection difficult. Technologies such as arc-flash detection systems can detect and isolate ground faults in these systems. In general, earthing is critical for maintaining grid equipment safety and ensuring acceptable over-voltages. Understanding ground faults is essential for microgrid and multi-looped system protection, with ground fault studies playing a pivotal role in developing effective protection strategies. By utilizing advanced technologies and solid earthing, the challenges associated with ground faults and ensuring continued safe operations can be mitigated.

B. PROBLEM STATEMENT: MIS-COORDINATION ISSUE BETWEEN PHASE AND GROUND OCR IN GROUND FAULT SCENARIOS

Connecting the neutral point of a distribution grid to the ground is a crucial practice for protecting the grid from ground fault scenarios. This connection helps reduce the voltage rise on non-faulted phases during faults, ensuring system stability. Common grounding strategies typically involve non-solid earthing of the neutral point, where single-line-to-ground faults are prevalent. These faults are particularly challenging to detect due to the relatively low magnitude of the associated fault currents. Ground faults, among various fault types, are especially difficult to identify because of their weak current nature, exacerbated by the integration of low inertia resources in microgrids. Reliable microgrid protection systems are essential to promptly detect and isolate such faults, preventing them from escalating into more severe fault scenarios. Implementing a robust protection scheme is vital for effective ground fault protection in multi-looped systems. Investigating ground fault scenarios enhances the reliability and efficacy of protection schemes, minimizing potential hazards. TABLE 2 shows the importance of understanding the occurrence percentage of different fault types in distribution networks [18], [19]. Ground faults are heavily influenced by the system's grounding configuration. The zero-sequence component of ground faults plays a critical role in determining their severity and characteristics. Factors such as zero-sequence impedance and the configurations of distribution transformers primarily influence the ground fault level [23], [25]. The presence of DGs introduces additional complexity in managing ground faults within distribution systems. The diverse nature of these sources can create operational challenges during fault events, impacting the reliability of protection systems, such as phase OCR (POCR) and ground OCR (GOCR) protection. Consequently, coordinating different protection devices, becomes essential yet challenging in complex microgrids, especially with the high penetration of multiple DGs. Effective coordination between protection devices ensures the reliable operation of the grid, maintaining safety and stability in the presence of diverse and distributed energy sources.

FIGURE 1 illustrates two critical issues associated with ground faults that lead to mis-coordination between POCR and GOCR. One significant issue arises in scenarios involving low LG faults at location F3 (Issue A). In this case, there can be a selectivity problem in the detection capabilities of the protection devices. Specifically, GOCR may detect these faults while POCRs fail, resulting in mis-coordination. This discrepancy reduces the reliability of the protection system and causes delays in the tripping process. Such selectivity issues between POCR and GOCR schemes can significantly compromise the overall effectiveness of the microgrid protection system. A significant scenario involves ground faults occurring at locations F2 and F1 within a microgrid, as depicted in FIGURE 1 (Issue B). In these specific instances, such as low-LG faults at F2 and F1, the GOCR is designed to detect and isolate the fault promptly. However, if the GOCR fails to operate or responds slowly, the POCR serves as a backup protection mechanism. While this secondary layer of protection enhances safety, it introduces delays in the fault-clearing process. Ideally, the GOCR should trip first in these fault conditions. If the GOCR is delayed or fails, the POCR will eventually detect the fault and act as a backup, but this process is not instantaneous. The POCR's response is intentionally delayed to give the primary protection (GOCR) time to operate first. This delay, although designed for selectivity, can be detrimental in scenarios where rapid fault clearance is crucial to prevent equipment damage or instability in the microgrid. Therefore, the coordination between POCR and GOCR is essential to ensure the GOCR operates first. Improper coordination settings can result in both relays responding incorrectly. For example, the POCR might be set to trip after a delay for LG faults at F2 and F1, assuming the GOCR will quickly clear the fault. If the GOCR is slow or fails, the POCR's delayed response compromises system protection. Proper coordination involves setting the time-current characteristics of both the POCR and GOCR so that the GOCR responds first to ground faults, with the POCR providing backup with an intentional delay. Mis-coordination occurs if these settings are not accurately calibrated, leading to scenarios where the POCR responds too slowly or trips for faults that the GOCR should have isolated. This mis-coordination reduces the effectiveness of the protection scheme, leading to prolonged fault conditions and potential damage to the microgrid infrastructure. To mitigate the risks associated with mis-coordination and reduce delays in POCR operation when it acts as a backup to the GOCR, it is essential to propose, test, and adjust new characteristics and parameters in the time-inverse characteristics of the POCR. Enhancing the operation of OCRs in all relevant zones by introducing new components to the time-inverse characteristics of the

TABLE 2. The percentage of occurrence for different fault scenarios in DN.

Type of Fault		Percentage of Occurrence
Line-ground	LG	70% to 80%
Line-Line-ground	LLG	10% to 17%
Line-Line	LL	8% to 10%
Line-Line-Line	LLL	2% to 3%

POCR can help cover different fault scenarios and effectively mitigate the impact of ground faults on protection schemes within the microgrid. This approach ensures robust protection for the microgrid, minimizing the risk of disconnection events for DGs during ground faults.

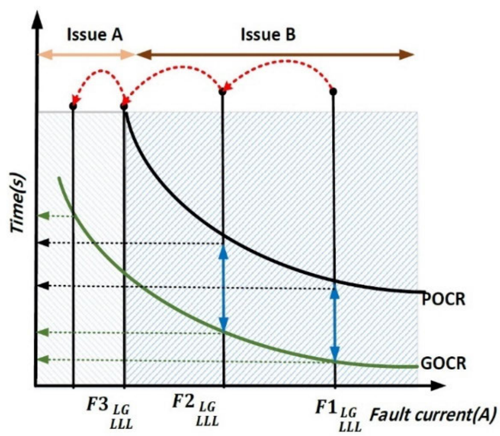

FIGURE 1. Coordination of GOCR and POCR Schemes.

III. PROPOSED STRATEGY: ENHANCED MICROGRID PROTECTION SCHEME WITH IEC 61131-3 AND SEQUENTIAL FUNCTION CHART PROGRAMMING FOR ENHANCED GROUND FAULT DETECTION AND COORDINATION

A. INTEGRATION OF ZERO SEQUENCE COMPONENT IN POCR CHARACTERISTICS

This study aims to resolve the mis-coordination issues between POCR and GOCR in ground fault scenarios by enhancing the detection and coordination characteristics for improved ground fault management. The proposed approach involves incorporating the zero-sequence component of the ground fault current into the POCR detection mechanism. This enhancement is designed to provide more reliable and responsive POCR backup protection for the GOCR, particularly in scenarios involving low-value ground faults where traditional settings may be inadequate, as shown in FIGURE 2. The zero-sequence component in the ground fault current is integral to the proposed strategy in this work. By incorporating this component into the IEC time-inverse characteristics of the POCR, the relay's response based on the magnitude and behaviour of the ground fault can dynamically be adjusted. This integration modifies the POCR's operational characteristics, significantly enhancing its ability to function as an effective backup for the GOCR across various ground fault scenarios, including balanced fault conditions. Therefore, the standard IEC time-inverse characteristic for phase overcurrent relays can be adapted to include the zero-sequence component (I_0). The proposed strategy can be implemented by defining two different group setting configurations. Group A represents the standard characteristic for POCR in balanced fault scenarios without significant zero-sequence influence, as described in (1). Group B encompasses the enhanced settings for POCR, incorporating the zero-sequence component as described in (2). The process of developing the proposed characteristic equation for the POCR involves two group settings. In (1), the t_{GA}^{POCR} is used during phase faults and t_{GB}^{POCR}, Equation (2) is used during ground faults.

$$t_{GA}^{POCR} = TMS_A \left(\frac{A_1}{(\frac{Isc}{I_p^A})^{B_1} - 1} \right) \times \left(\frac{\min(0, I_0 - I_{sc})}{I_0 - I_{sc}} \right) \quad (1)$$

$$t_{GB}^{POCR} = TMS_B \left(\frac{A_2}{(\frac{Isc}{I_p^B})^{B_2} - 1} \right) \times \left(\frac{\min(0, I_{SC} - I_0)}{I_{sc} - I_0} \right) \quad (2)$$

where TMS_A and TMS_B are the time setting multiplayer for group setting A (during phase faults) and group setting B (during ground faults), respectively. I_{Fault} is the fault current, Ip is the pickup current, I_0 is the zero-sequence component and A and B are the standard constants. The modification and integration of zero-sequence components into the IEC characteristics of POCR will significantly enhance the operational strategy for addressing both low and high-value ground fault scenarios, as shown in FIGURE 2. In low-value ground fault scenarios (Issue A), GOCR may detect these faults, but POCR often fails to provide backup due to insufficient sensitivity. By including the zero-sequence component in (2), POCR at group B can more effectively detect these faults, ensuring that even low-value ground faults trigger an appropriate response. This adjustment provides a reliable backup for the GOCR. In high-value ground fault scenarios (Issue B), POCR's delayed backup response can compromise quick fault clearance. The proposed characteristic in (2) reduces the operating time of POCR by incorporating the zero-sequence component, POCR at group B, enabling a faster response. This instant response minimizes damage and maintains system stability during high-value ground faults. Modern digital relays' advanced configuration capabilities, including different group settings (Group A and Group B), facilitate these modifications and adjustments. The Configurable Logic (CFC) feature in digital relays enables the implementation of the proposed characteristics, with the zero-sequence component functioning as a trigger to switch between different relay settings, thereby enhancing the relay's adaptability and responsiveness.

B. PLC REPRESENTATION BASED ON IEC 61131-3 AND HIL PROCESS

The IEC 61131-3 standard defines programming languages for programmable logic controllers (PLCs), including the Sequential Function Chart (SFC), one of the six specified languages, as illustrated in FIGURE 3. SFC is especially pertinent to the integration of IEC 61131-3 with protection relays, as it provides a graphical representation of control logic in a sequential format. This visual approach enhances

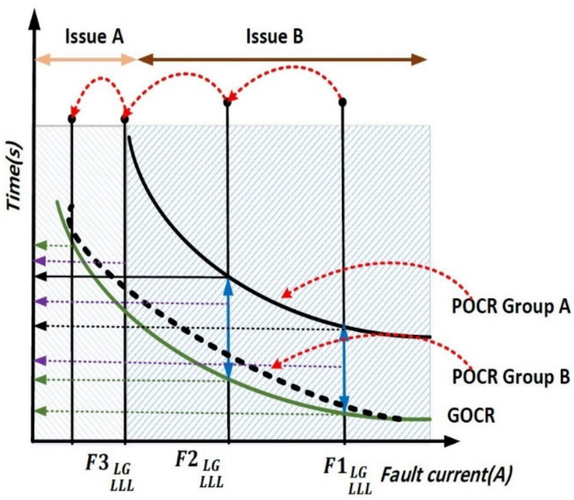

FIGURE 2. Proposed coordination of GOCR and POCR schemes.

the clarity and effectiveness of programming for protection relay applications [32], [33].

The proposed strategy has been validated through Hardware-in-Loop (HIL) testing using a real-time digital simulator and a Real-Time Automation Controller (RTAC). The algorithm was programmed into the RTAC using the IEC 61131-3 industrial automation programming language. Utilizing the Sequential Function Chart (SFC) programming language within the IEC 61131-3 framework, operators can design and implement control logic for protection relays in a structured and sequential manner. The hierarchical structure defined by IEC 61131-3, where a configuration consists of resources supporting tasks, can be utilized to allocate specific tasks for programming protection relay functions. This standardization ensures consistency and interoperability in PLC programming, including protection relays, leading to more reliable and efficient industrial control systems [32], [33]. As illustrated in FIGURE 4, the CFC feature is employed to monitor the presence of the zero-sequence component. Upon detecting a significant zero-sequence current, the relay logic switches from Group A to Group B settings. This switch ensures that the POCR operates with the modified characteristic tailored for ground fault detection and coordination. To validate the feasibility and effectiveness of the proposed strategy, the CFC function in the digital relay was used to implement the modified characteristics in HIL testing environment. HIL testing allows for a realistic and controlled evaluation of the relay's performance under simulated fault conditions, ensuring the practical applicability and robustness of the proposed strategy.

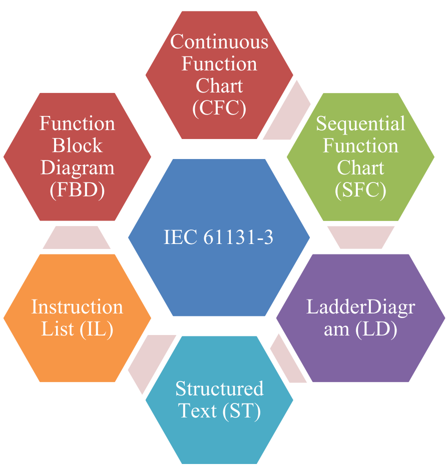

FIGURE 3. Programming languages in the IEC 61131-3 standard.

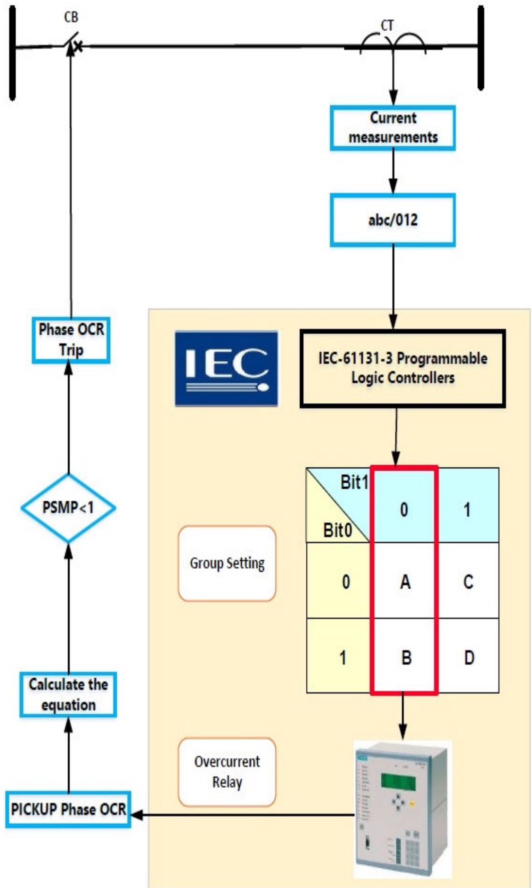

FIGURE 4. The proposed OCR scheme with the IEC 61131-3 standard.

The HIL testing process integrates the implementation of CFC logic and connects it to a real-time simulator capable of generating various fault scenarios, including both low- and high-value ground faults. During the testing phase, different fault scenarios are simulated to observe the relay's response, specifically focusing on the transition between Group A and Group B settings and the subsequent fault clearance times. The relay's performance is then analyzed to ensure that the proposed strategy enhances coordination and detection capabilities for both types of ground fault conditions. This approach ensures robust backup protection by POCR for the

GOCR in both low- and high-value ground fault scenarios. The successful implementation and testing of the proposed strategy using the CFC function and HIL testing will demonstrate its feasibility and potential for real-world applications. The practices outlined in this study, including the testing and fine-tuning of both GOCR and POCR settings, are crucial for optimizing performance and adapting to varying ground fault behaviours within the microgrid.

IV. SIMULATION RESULTS AND DISCUSSION

This section evaluates the performance of the proposed dynamic OCR protection scheme with two group settings (PG-OCR). Firstly, the scheme is assessed using a 9-bus DN based on the IEEE standard to determine its effectiveness under various fault scenarios. The testing results of the proposed scheme under fault conditions are presented, and a comparison is presented with commonly used approaches in terms of total tripping time and Coordination Time Interval (CTI). Secondly, the proposed PG-OCR scheme is evaluated using Hardware-in-the-Loop (HIL) testing to validate its performance and functionality.

A. SIMULATION RESULTS FOR THE 9-BUS DN MODEL

The proposed PG-OCR protection scheme is tested and evaluated on a standard 9-bus IEEE feeder network with photovoltaic (PV) systems, as depicted in FIGURE 5. This network typically operates with a high-voltage/medium-voltage utility source and two 5 MVA PV farms through a setup transformer rated at 0.4/12.4 kV. The network includes 13 OCRs providing protection from fault locations F1 to F8, representing both near- and far-end fault locations from the sources. The basic settings of the OCRs, including TMS for both group settings A and B of the proposed PG-OCR and GOCR for Traditional OCR Scheme, are established based on load flow and fault calculations following IEC-60909 standards, as detailed in TABLE 3. Additionally, the performance of the proposed scheme is investigated under different fault scenarios to enhance selectivity and maintain power continuity on healthy lines, as follows:

- Line to ground fault (LG) with fault resistance equal to 0 and 20 ohms.
- Line to Line to ground fault (LLG).

1) LINE TO GROUND FAULT (LG) WITH FAULT RESISTANCE EQUAL TO 0 AND 20 ohms

In this section, the performance of the proposed PG-OCR scheme is evaluated and compared under LG fault with different fault resistances equal to 0 and 20 ohms. To assess the effectiveness of these approaches, the total tripping times for traditional OCR and PG-OCR under various fault locations are computed based on the TMS, as shown in TABLE 3. The proposed PG-OCR approach significantly outperformed the traditional OCR scheme for the primary relays at all fault locations, as shown in TABLE 4. For example, under fault condition F3, the tripping time of OCR2 was reduced from 0.68 seconds (GOCR) to 0.403 seconds for the PG-OCR approach. The PG-OCR curve exhibited much higher sensitivity compared to the traditional OCR scheme (POCR) with low fault current with fault resistance equal to 20 ohms and the PG-OCR showed a similar performance to GOCR, as evidenced in TABLE 4. Therefore, the most effective current-time curves for the OCR were those using the PG-OCR, as the PG-OCR will remove the need to have GOCR. The traditional GOCR reordered 9 mis-coordination events, where the relay did not detect the faults, as shown in TABLE 5.

TABLE 3. The PG-OCR settings for groups A and B.

OCR	PG-OCR		GOCR
	Group Setting A	Group Setting B	
	TMS		
OCR1	0.01	0.01	0.01
OCR2	0.14	0.15	0.14
OCR3	0.265	0.28	0.3
OCR4	0.37	0.4	0.433
OCR5	0.01	0.01	0.01
OCR6	0.13	0.15	0.13
OCR7	0.264	0.26	0.26
OCR8	0.368	0.37	0.391
OCR9	0.357	0.41	0.56
OCR10	0.01	0.01	0.01
COR11	0.048	0.08	0.14
OCR12	0.15	0.19	0.14
OCR13	0.26	0.35	0.01
OCR14	0.01	0.01	0.01
OCR15	0.05	0.09	0.14

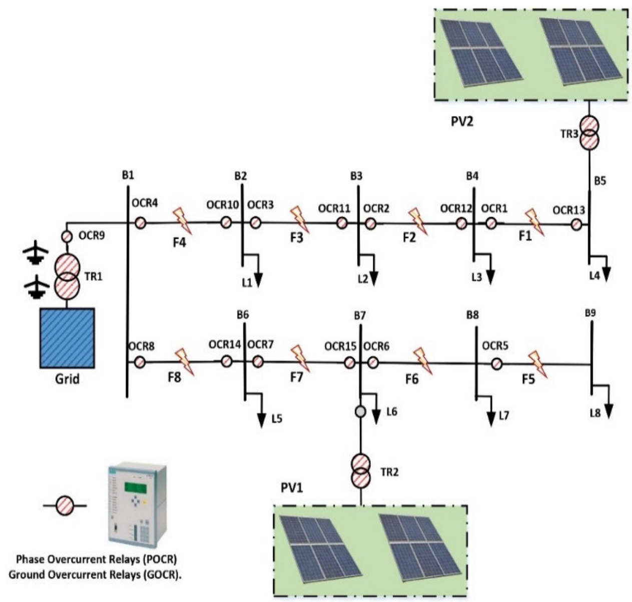

FIGURE 5. IEEE 9 bus system.

TABLE 4. The tripping time for the OCRs schemes (Traditional and PG-OCR) under LG with fault resistance equal to 0 ohms.

Fault location	Fault current	Relay	Traditional OCR Scheme		PG-OCR Scheme (Group B)
			GOCR	POCR	
F1	4726	OCR1	0.0227	0.0227	0
F1	4726	OCR2	0.317	0.317	0.21
F1	1038	OCR13	0.0227	0.76	0.596
F2	5373	OCR2	0.317	0.317	0.204
F2	5373	OCR3	0.68	0.625	0.417
F2	985	0CR12	0.317	0.648	0.402
F2	985	0CR13	0.0227	0.957	0.605
F3	6192	OCR3	0.68	0.601	0.403
F3	6192	OCR4	0.982	0.92	0.616
F3	926	OCR11	0.317	0.295	0.199
F3	926	OCR12	0.317	0.675	0.41
F4	7241	OCR4	0.982	0.869	0.594
F4	6529	OCR9	1.27	1.17	0.745
F4	861	OCR10	0.0227	0.0906	0.0228
F4	861	OCR11	0.317	0.315	0.205
F5	5353	OCR5	0.0227	0.0227	0.0125
F5	5353	OCR6	0.295	0.296	0.204
F6	6141	OCR6	0.295	0.295	0.198
F6	5239	OCR7	0.59	0.628	0.389
F7	6119	OCR7	0.59	0.599	0.376
F7	6119	OCR8	0.887	0.919	0.572
F8	966	OCR14	0.0227	0.0787	0.0275
F8	966	OCR15	0.317	0.296	0.22

TABLE 5. The tripping time for the OCRs schemes (Traditional and PG-OCR) under LG with fault resistance equal to 20 ohms.

Fault location	Fault current	Relay	Traditional OCR Scheme		PG-OCR Scheme (Group B)
			GOCR	POCR	
F1	567	OCR1	0.0227	0.0397	0.0202
F1	567	OCR2	0.328	0.931	0.386
F1	176	OCR13	No trip	3.22	1.1
F2	576	OCR2	0.326	0.916	0.383
F2	576	OCR3	0.814	2.82	0.847
F2	175	0CR12	No trip	No trip	0.888
F2	175	0CR13	No trip	3.24	1.11
F3	600	OCR3	0.812	2.66	0.832
F3	600	OCR4	1.33	6.35	1.36
F3	170	OCR11	No trip	No trip	0.533
F3	170	OCR12	No trip	No trip	0.907
F4	612	OCR4	1.32	6.06	1.35
F4	475	OCR9	2.48	-	2.61
F4	169	OCR10	No trip	No trip	0.0928
F4	169	OCR11	No trip	No trip	0.535
F5	734	OCR5	0.0227	0.0344	0.0187
F5	734	OCR6	0.304	0.691	0.35
F6	746	OCR6	0.302	0.682	0.349
F6	574	OCR7	0.706	2.83	0.788
F7	586	OCR7	0.701	2.74	0.781
F7	586	OCR8	1.19	6.72	1.27
F8	168	OCR14	No trip	No trip	0.0892
F8	168	OCR15	No trip	No trip	0.584

FIGURE 6 showed that the traditional POCR (OCR2 and OCR3) recorded tripping time equal to 0.317 and 0.625 seconds, while the PG-OCR schemes recorded 0.204 and 417 seconds for OCR2 and OCR3, respectively. The proposed PG-OCR showed high performance at low fault current values, as shown in FIGURE 7, where the traditional OCR scheme (POCR) for both primary and backup relays at F3 recorded a mis-coordination event, while the proposed PG-OCR detected the fault and recorded 0.533 and 0.907 seconds tripping time for OCR11 and OCR12, respectively.

2) LINE TO LINE TO GROUND FAULT (LLG)

The performance of the proposed PG-OCR scheme is tested under LLG fault conditions and compared to the traditional OCR scheme, as shown in TABLE 6. The proposed PG-OCR approach significantly improved the sensitivity term (minimizing the tripping time) compared to the traditional OCR scheme for primary and backup relays at all fault locations. For instance, under fault condition F3, the tripping time of OCR3 was reduced from 0.68 seconds (GOCR) and 0.601 seconds (POCR) for the traditional OCR to 0.401 seconds for the PG-OCR approach. The PG-OCR curve demonstrated much higher sensitivity compared to the traditional OCR scheme. Therefore, the most effective current-time curves for the OCR were those utilizing the PG-OCR.

3) HARDWARE-IN-THE-LOOP (HIL) TESTING RESULTS

A real-time simulation platform is employed to execute simulation models in real-time, synchronizing them with hardware components for comprehensive testing. In this work, the HIL testing methodology is integrated to validate the proposed PG-OCR schemes in real-time scenarios, as illustrated in FIGURE 8. This process involves real-time validation using the OMICRON-256 on the SIPROTEC 7SJ631 Multi-function Protection Relay, confirming the efficacy of the proposed PG-OCR scheme. Validation is conducted using computerized test sets and the PG-OCR. As shown in FIGURE 8, The OMICRON Test Universe software is used to control, validate, and record data from the OMICRON-CMC-365 equipment. The HIL testing setup incorporates physical hardware components, including the PG-OCR (SIPROTEC 7SJ631) and power testing equipment OMICRON-CMC-365. Furthermore, a real-time simulation platform is utilized to execute simulation models in real-time, ensuring synchronization with hardware components. Digsi Software and Fault Record Evaluation are employed to program the PG-OCR and to validate and record the data generated

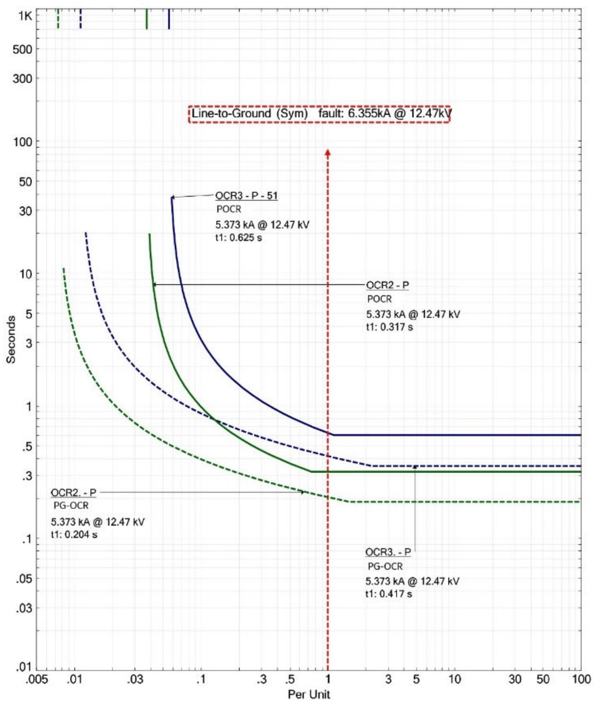

FIGURE 6. Time characteristics curves of traditional OCR and PG-OCR schemes under F2 with fault resistance equal to 0 ohm.

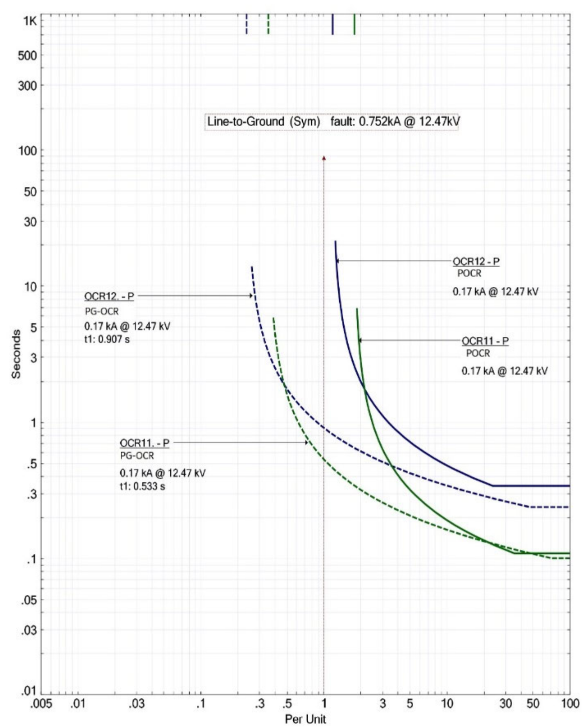

FIGURE 7. Time characteristics curves of traditional OCR and PG-OCR schemes under F8 with fault resistance equal to 20 ohms.

during testing, ensuring accurate and reliable performance assessment.

TABLE 6. The tripping time for the OCRs schemes (Traditional and PG-OCR) under LLG.

Fault location	Fault current	Relay	Traditional OCR Scheme		PG- OCR Scheme (Group B)
			GOCR	POCR	
F1	4931	OCR1	0.01	0.0227	0.0125
F1	4931	OCR2	0.317	0.317	0.208
F1	1722	OCR13	0.0227	0.621	0.526
F2	5383	OCR2	0.317	0.317	0.202
F2	5383	OCR3	0.68	0.616	0.413
F2	1631	0CR12	0.317	0.49	0.346
F2	1631	0CR13	0.0227	0.634	0.533
F3	6390	OCR3	0.68	0.601	0.401
F3	6390	OCR4	0.982	0.909	0.612
F3	1537	OCR11	0.317	0.202	0.167
F3	1537	OCR12	0.317	0.504	0.351
F4	7374	OCR4	0.982	0.863	0.561
F4	7374	OCR9	1.27	1.17	0.746
F4	1438	OCR10	0.0227	0.054	0.023
F4	1438	OCR11	0.317	0.211	0.171
F5	5445	OCR5	0.0227	0.0227	0.012
F5	5445	OCR6	0.295	0.317	0.203
F6	6213	OCR6	0.295	0.295	0.198
F6	5494	OCR7	0.59	0.617	0.385
F7	6350	OCR7	0.59	0.599	0.372
F7	6350	OCR8	0.887	0.906	0.567
F8	1610	OCR14	0.0227	0.0496	0.0226
F8	1610	OCR15	0.317	0.205	0.185

FIGURE 9 presents the HIL testing results for the traditional OCR during a three-phase fault, which behaves similarly to Group A settings at PG-OCR. The testing was conducted using the OMICRON Test Universe software and Digsi software to provide comprehensive insights into the OCR's performance. FIGURE 9(a) shows the injected fault current value of 6 A at three phases using the OMICRON-CMC-365 equipment, crucial for simulating realistic fault conditions and assessing the OCR's response under controlled yet realistic scenarios. FIGURE 9(b) presents the OCR tripping time and detailed settings using Digsi software, including configuration parameters such as the current transformer ratio (CTR), pickup current (IP), and plug setting (PS). The recorded tripping time for the OCR during the three-phase fault was observed, providing a benchmark for evaluating the relay's performance. This performance benchmarking of the traditional OCR's tripping time during the three-phase fault serves as a baseline for comparing the proposed non-standard OCR schemes. The quick and reliable response of the OCR in this scenario is essential for maintaining system stability and preventing equipment damage. The detailed configuration provided by Digsi software allows an analysis of the OCR's performance, and adjustments to the settings can be made to optimize the OCR's response time and coordination with other protection devices.

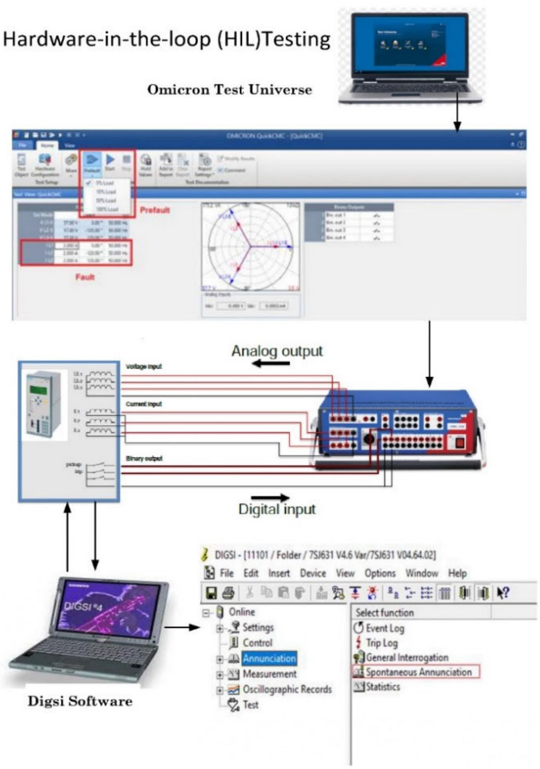

FIGURE 8. Hardware-in-the-Loop (HIL) testing results for PG-OCR.

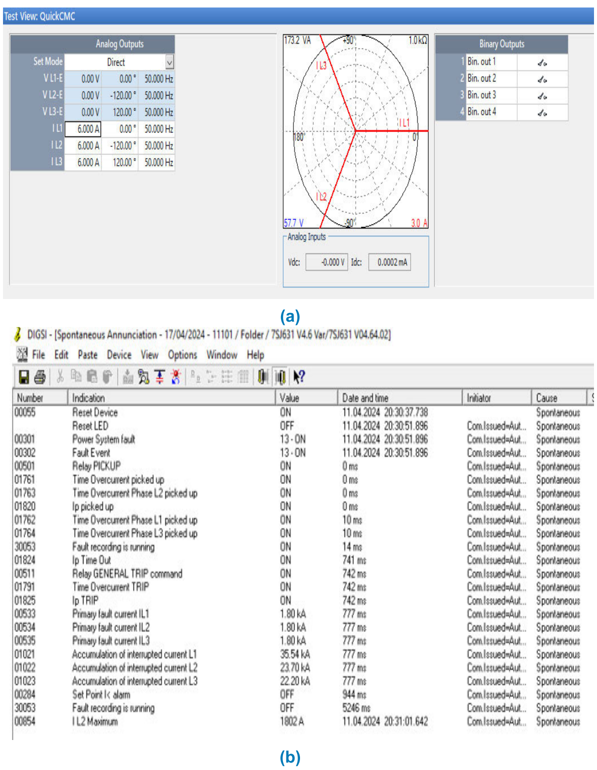

FIGURE 9. Hardware-in-the-Loop (HIL) testing results for OCR, a) OMICRON test. b) Digsi results for OCR.

FIGURE 10 presents the HIL testing results for the proposed PG-OCR scheme during a ground fault scenario, where it transitions from Group A settings (Phase Fault) to Group B settings (Ground Fault). FIGURE 10 (a) illustrates the injection of a 300 mA ground fault at Phase 1 using the OMICRON-CMC-256 equipment, essential for simulating realistic fault conditions and assessing the PG-OCR response under controlled yet realistic scenarios. FIGURE 10 (b) presents the PG-OCR tripping time and detailed settings using Digsi software, including configuration parameters where group B was active. The HIL testing results for the proposed PG-OCR scheme during a ground fault scenario demonstrate the relay's effectiveness and provide a benchmark for further comparison with advanced protection schemes. By using OMICRON and Digsi software, the testing process ensures precise and reliable assessment, reinforcing the importance of accurate configuration and timely response in protection relay performance. This comprehensive evaluation highlights the need for continual improvements in OCR settings and the potential benefits of adopting PG-OCR schemes for enhanced fault detection and coordination in power grids.

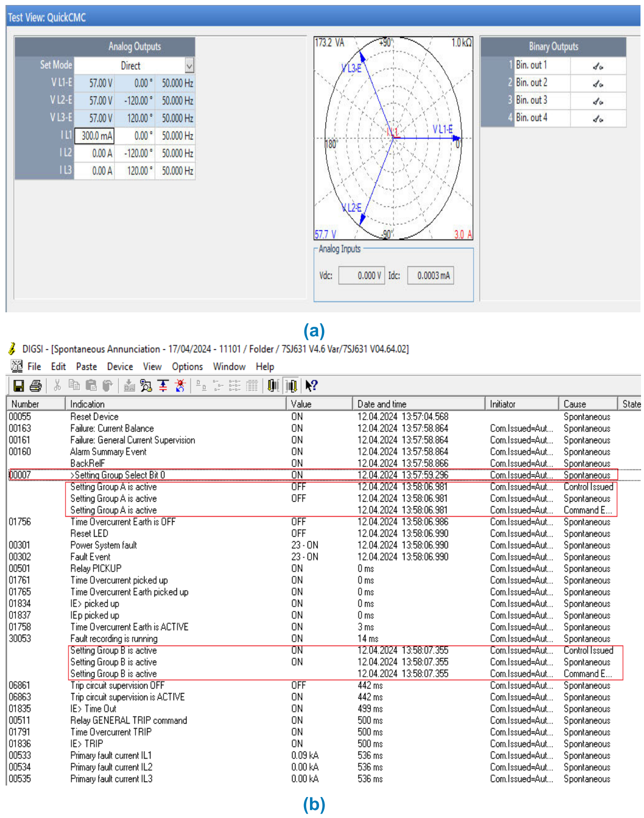

FIGURE 10. Hardware-in-the-Loop (HIL) testing results for PG-OCR, a) OMICRON test. b) Digsi results for OCR.

V. CONCLUSION AND RECOMMENDATIONS

In this study, critical research gaps in microgrid protection and ground fault management have been addressed, focusing on enhancing the performance of Overcurrent Relays (OCRs) under various fault conditions. The integration of zero sequence components into the time-inverse characteristics of phase OCR has been demonstrated to significantly improve ground fault detection and provide robust backup for ground faults. This enhancement ensures that the microgrid remains reliable and resilient even under challenging fault scenarios. For example, the tripping time of OCR3 was reduced from 0.68 seconds (Ground OCR) and 0.601 seconds (phase OCR) for the traditional OCR to 0.405 seconds for the PG-OCR approach. The dynamic adjustment of relay settings using CFCs) in digital relays has shown promising results in optimizing relay performance based on zero sequence current detection. This adaptive approach has effectively addressed mis-coordination issues between POCR and GOCR in low-value ground fault scenarios, leading to improved fault detection and clearance times.

The validation through extensive HIL testing has confirmed the feasibility and effectiveness of the proposed strategy. The real-time validation using OMICRON-256 on SIPROTEC 7SJ62 Multi-function Protection Relay has demonstrated the practical applicability and robustness of the proposed PG-OCR in microgrids protection against three-phase faults. The integration of HIL testing with the development of the protection scheme has ensured a comprehensive assessment of its performance under realistic conditions. Furthermore, the application of the IEC 61131-3 standard and SFC in relay programming has enhanced the interoperability and reliability of microgrid protection systems. This standardized approach ensures consistent and effective relay programming, contributing to improved system performance and reliability. Overall, the comprehensive framework provided in this study offers practical guidance for operators to implement microgrid protection systems. This study highlights the importance of continuous innovation and adaptation in protection relay technology to meet the evolving challenges of modern power distribution systems. Future research could explore further enhancements in relay technology and methodologies to achieve even greater reliability and efficiency in microgrid protection.

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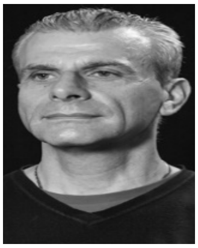

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