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*Research Article*

# Advanced Optimal Twin-Setting Protection Coordination Scheme for Maximizing Microgrid Resilience

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The increasing penetration of distribution generators (DGs), such as PV systems, has led to a significant power protection concern for optimal overcurrent coordination. However, existing literature indicates that the traditional phase over current relay (OCR) scheme faces challenges such as instability, insensitivity, and lack of selectivity when handling the integration of DGs and ground fault scenarios. To address this issue, this study proposes a new optimal twin-setting OCR coordination scheme for phase and ground events using standard and nonstandard tripping characteristics. The water cycle optimization algorithm (WCOA) is utilized to develop a coordinated optimum strategy that mitigates the effects of DGs on the currents and locations of faults across the power grid. To demonstrate the efficacy of the proposed approach, different case studies of an IEEE power network (9 buses) equipped with two 5 MW PV systems are conducted using industrial software (ETAP). Under various fault conditions (phase and ground faults) and power network operation modes (with and without PVs and islanding modes), the outcomes of the newly developed optimal coordination scheme are compared to the results of conventional schemes. The proposed twin OCR coordinating scheme is found to reduce the total tripping time of OCRs up to 62.3% and increase the selectivity of the relays without miscoordination events.

## 1. Introduction

Overcurrent relays (OCRs) are commonly used to protect subtransmission and distribution systems by finding and separating faulty parts. Coordination of OCRs is important to ensure that only the faulty element is disconnected, and the optimal operation sequence of the primary and backup relays is achieved for each protected area [1]. However, the integration of distribution generators (DGs) has created challenges in OCR coordination, due to changes in fault characteristics and dynamics resulting from two-directional power flow. This has led to misoperational relay conditions and protection blinding, interfering with the selectivity and coordination of protective relays. Protection systems for microgrids are challenging to model because they are required to function both when they are connected to the power grid and when not (islanding mode) [1, 2]. To address this issue, OCR coordination has been framed as an optimization problem with the goal of minimizing relay tripping time through optimal setting determination, regardless of whether the microgrid is connected or in islanded mode. The traditional and modern OCR schemes are focused on using phase OCRs [3] to identify and isolate various faults.

However, the detection of ground faults (GF) in microgrids is challenging for OCR protection due to changes in the current behavior, low fault status, and the existence of arcing faults with high impedance. Approximately 80–70% of the faults are single line to ground (LG) faults, making them the most common. In microgrid systems, it is crucial to coordinate OC relays according to the various forms of ground problems [1–4]. The challenges associated with detecting GF and other fault types in microgrids increase the complexity of designing an effective OCR protection system. This complexity leads to selectivity issues during both phase faults (PF) and GF conditions, making it difficult for OC relays to accurately detect and isolate faulty components.

Moreover, developing a protection OCR coordination scheme for a power grid connected to distribution generations (DGs) has become one of the most challenging tasks in operating microgrid system. This highlights the need for advanced protection techniques that can effectively address the new fault characteristics for both PF and GF of microgrids to ensure their safe and reliable operation.

Several OCR coordination schemes have been developed in the literature to determine the optimal settings of OCR. Typically, phase OCR (POCR) is used to coordinate OCRs by minimizing the operation times of OCRs [5]. Conventional approaches for coordinating OCRs [1–5] are limited in their ability to protect microgrid. This is due to the fact that power networks with DGs have different operation modes and power flow scenarios that require more advanced and flexible protection schemes as described in Table 1. The proposed POCR schemes in [1–5] did not consider the different operational modes of microgrid systems or EF problems. On the other hand, the existing literature, as described in Table 1, lacks detailed research on developing effective OCR protection systems and addressing GF problems in microgrid.

Authors in [19, 38] presented a dynamic POCR scheme to solve the GF challenges by using the stranded time current characteristic without considering the other type of characteristics or investigating the importance of using and coordinating between POCR and Ground OCR (GOCR). In [20], authors proposed an objective function to coordinate both POCR and GOCR in microgrid protection using only single-to-ground fault calculations (LG). However, the study in [19] did not consider different PF and GF events and consider only the stranded time current characteristic.

The single line to ground fault is considered one of the most common types of faults occurring in electrical networks. Therefore, effective coordination between ground and phase protection devices is essential to ensure network stability and protection. Based on previous researches, as highlighted in Table 1, emphasis has been placed on POCR for network protection against all faults, coordinating protection devices and setting them for the fault current of a three-phase fault. In the event of a single line to ground fault, protection devices may delay in isolating the fault and may fail to detect faults with resistance, posing risks to the network, whether with the presence of distributed generation (DG) or in isolated network scenarios. Therefore, developing innovative POCR and GOCR protection coordination strategies is essential to ensure the effective operation and protection of microgrid under different fault scenarios (PF and GF). Hence, this study is aimed at introducing a new scheme for both and together POCR and GOCR by utilizing and investigating standard (IEC curve) and nonstandard time current characteristics for maximizing microgrid resilience. This study uses various types of faults and different grid operation modes to determine the efficacy of the suggested approach. Furthermore, the optimization task for POCR and GOCR has been addressed in this study using the water cycle optimization method (WCOM) to minimize the tripping time. The following is a summary of the primary contributions of this paper:

(i) A new protection approach for both POCR and GOCR with optimal coordination, taking into account the various operation modes of the microgrid system and all fault scenarios. The approach is aimed at achieving the maximum sensitivity and selectivity by coordinating both POCR and GOCR

(ii) An optimal coordination method for POCR and GOCR using standard and nonstandard time current characteristics to minimize the operational time for relays with no record of miscoordination events compared to conventional OCR schemes in published works

(iii) The proposed optimal coordination approach is evaluated under different fault and microgrid operation scenarios. In addition, the proposed scheme does not use communication to reduce the cost and need communications infrastructure, as well as the cost of computing, to make the POCR and GOCR coordination technique more reliable

This article is structured as follows: Sections 2 and 3 present the problem statement and describes the methodology of the new twin optimal POCR and GOCR scheme. In Section 4, the discussion focuses on the simulation results and analysis. Section 5 shows the conclusions and future of this study.

## 2. Problem Statement: Illustration-Based Analysis

Microgrids are considered more complex than traditional networks. In the event of a fault, particularly of the type DG, such as synchronous-based distributed generations (SBDGs), the fault currents contributed up to seven times of rated current. In the case of inverter-based distributed generations (IBDGs), the contribution could be approximately two times the rated current. This causes challenges for conventional protection devices. Therefore, the selection of current protection device characteristics is crucial for safeguarding networks against both large and small fault currents. This ensures minimal response time while maintaining coordination among protection devices, aiming to achieve enhanced stability and reliability [1, 10].

Maintaining the timely operation and reliability of a microgrid with DGs requires a highly sensitive protection scheme. To demonstrate the coordination problem of trinational OCR [1, 7–10] by using only the POCR for both PF and GF events, Figure 1 depicts a single-line diagram of a power distribution network. The grid consists of two sources

Table 1: Summary of optimal POCR and GOCR coordination approaches.

| Ref. no. | Year | POCR | GOCR | Faults | DGS | Selectivity and sensitivity for GF | Optimal POCR/GOCR setting (twin setting) |
|---|---|---|---|---|---|---|---|
| Proposed method | | ✓ | ✓ | LLL, LG | ✓ | ✓ | ✓ |
| [6] | 2023 | ✓ | ✗ | ALL | ✗ | ✗ | ✗ |
| [7] | 2023 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [8] | 2023 | ✓ | ✗ | LLL, LG | ✗ | ✗ | ✗ |
| [9] | 2023 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [10] | 2023 | ✓ | ✗ | ALL | ✗ | ✗ | ✗ |
| [11] | 2023 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [12] | 2022 | ✓ | ✗ | LLL, LG | ✗ | ✗ | ✗ |
| [12] | 2022 | ✓ | ✗ | LLL, LG | ✗ | ✗ | ✗ |
| [13] | 2022 | ✓ | ✗ | ALL | ✓ | ✓ | ✓ |
| [14] | 2022 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [15] | 2022 | ✓ | ✗ | ALL | ✗ | ✗ | ✗ |
| [16] | 2022 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [17] | 2022 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [18] | 2022 | ✓ | ✗ | LLL | ✗ | ✗ | ✗ |
| [19] | 2022 | ✓ | ✓ | ALL | ✓ | ✗ | ✗ |
| [20] | 2021 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [21] | 2021 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [22] | 2021 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [23] | 2020 | ✓ | ✓ | LG | ✓ | ✗ | ✓ |
| [24] | 2020 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [25] | 2022 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [26] | 2021 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [27] | 2019 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [28] | 2019 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [29] | 2020 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [30] | 2018 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [31] | 2018 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [32] | 2017 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [33] | 2017 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [34] | 2017 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [35] | 2017 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [36] | 2016 | ✓ | ✗ | ALL | ✗ | ✗ | ✓ |
| [37] | 2016 | ✓ | ✗ | LLL | ✗ | ✗ | ✓ |
| [38] | 2016 | ✓ | ✓ | ALL | ✓ | ✓ | ✓ |

(the utility grid and DG), two lines protected by two POCRs. The primary POCR (PORCP) and the backup POCR (POCRB) are coordinated from the load to the source sides. In fault events of F1, F2, and F3, the PORCB will operate with a delay (coronational time interval (CTI)) as a backup relay, as shown in Figures 1 and 2.

In traditional POCR protection scheme, as shown in Figure 1, the current transformers (CTs) measure the current and provide it to POCR. The current will be compared to pickup POCR and plug setting multiplier for POCR (PSMP) based on the IEC block, and then, the tripping time will be determined by using traditional (IEC) inverse-time OCR equation. The POCRP trip block provides a tripping signal to the circuit breaker (CB1). In case of POCRP failure, the PORCB operates with a delay (CTI equal to 0.3 seconds between the primary relays and backup relays) as a backup relay. The POCR will face challenges in detecting the GF events, red line in Figure 2, as the pickup current of GF should be lower than the phase pickup currents ($I_{\text{pickup}}$) which usually equal to 1.3 of the full load ($I_{\text{load}}$). In addition, connecting DGs such as solar power sources (PV) to the network, as shown in Figure 1, increased the maximum fault current at POCRP but decreased it at POCRB, compared to the grid without DGs. In the event of a malfunction at

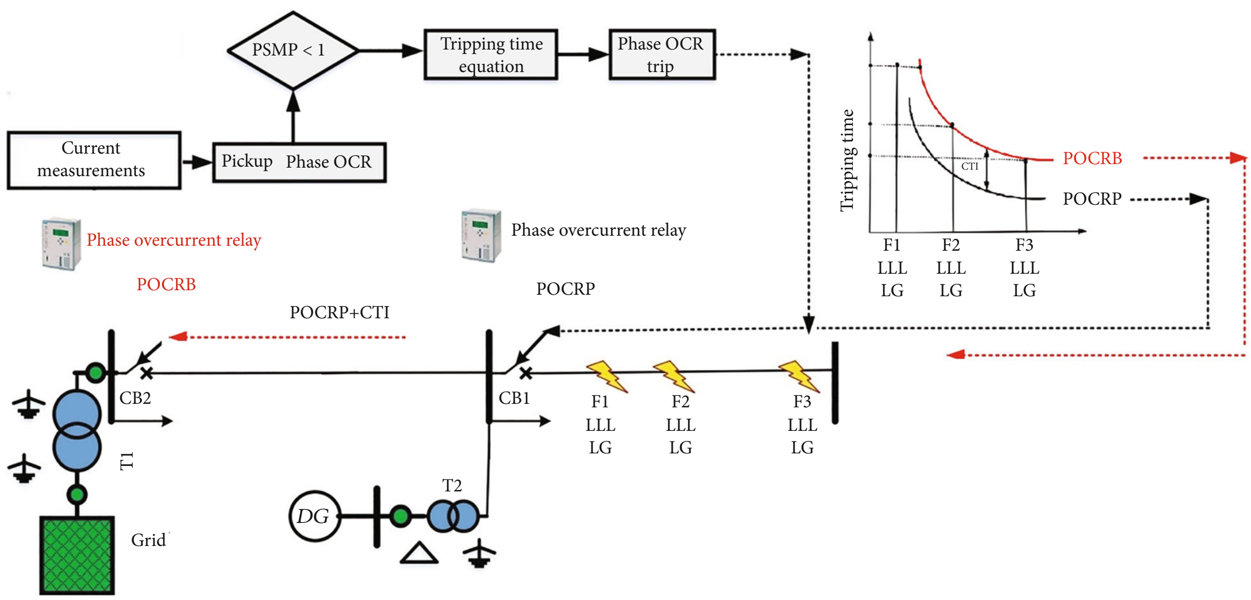


Figure 1: POCR coordination protection producer for a microgrid system.

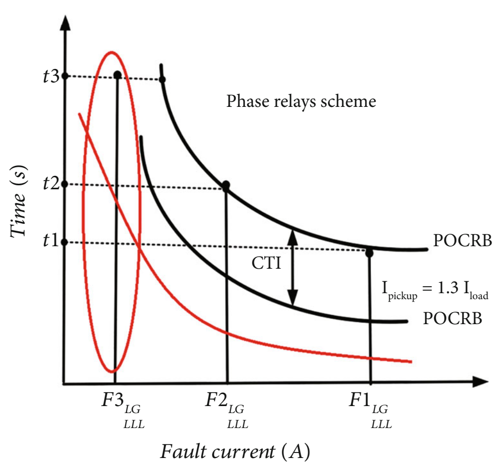


Figure 2: POCR coordination protection scheme and miscoordination events for PF and GF.

F2 in a grid with DGs, the fault current level increases at the primary relay and decreases at the secondary relay, potentially resulting in a coordination failure or delay in disconnecting time. In microgrid system with DGs, the fault current is typically too low, as example F3 zone area in red in Figure 2, when the network is islanded, which makes it challenging to detect the fault current (PF or GF) using traditional protection schemes [19, 23]. Therefore, it is imperative to design and develop an innovative twin OCR protection scheme for both PF and GF events that can address these protection challenges and adapt to various microgrid operation modes. To tackle these challenges, this article presents a new protection approach for both POCR and GOCR with optimal coordination using nonstandard and standard curves.

## 3. The Proposed Twin OCR Protection Scheme

This work introduces a novel optimal OCR coordination scheme for POCR and GOCR using standard and nonstandard tripping characteristic to minimize the total operational time (tripping) with no record of miscoordination, compared to POCR schemes. Section 2 highlights the importance of coordinating both POCR and GOCR functions, as they are available in numerical OCR, for more selective and sensitive protection schemes. The proposed twin protection scheme is aimed at enhancing the efficacy of the OCR system for various categories of faults (PF and GF) by combining both POCR and GOCR in a single OCR coordination problem. The utilization of POCR and GOCR in the primary OCR (OCRP) and backup OCR (OCRB), in the case of PF and GF events, is shown in Figure 3. Additionally, the twin scheme is aimed at significantly reducing clearing time of different faults, which increase the stability of the microgrid. The proposed twin OCR scheme is shown in Figure 3. The current measurements received from the CTs are first fed to abc/012 to determine the current sequence and the type of fault whether PF or GF. The zero-current sequence which is GF will be fed to the block (I0). For both POCR and GOCR, the fault current will be compared to pickup and PSMP based on the IEC block, and then, the tripping time will be determined by using different inverse-time OCR equations, as shown in Figure 4. For both relays, OCRP and OCRB shown in Figure 3, the GOCR function is the primary relay and POCR is the backup relay. In case of GOCR failure, the POCR will be operated. In general, the POCR is set to a pickup current of 1.2 times the load current, while GOCR is set to a pickup value ranging from 0.1 to 0.3 times the load current. In the event of a fault with a high current, the multiples at the GOCR exceed those of POCR, resulting in faster response times. As illustrated in Figures 3 and 4, the

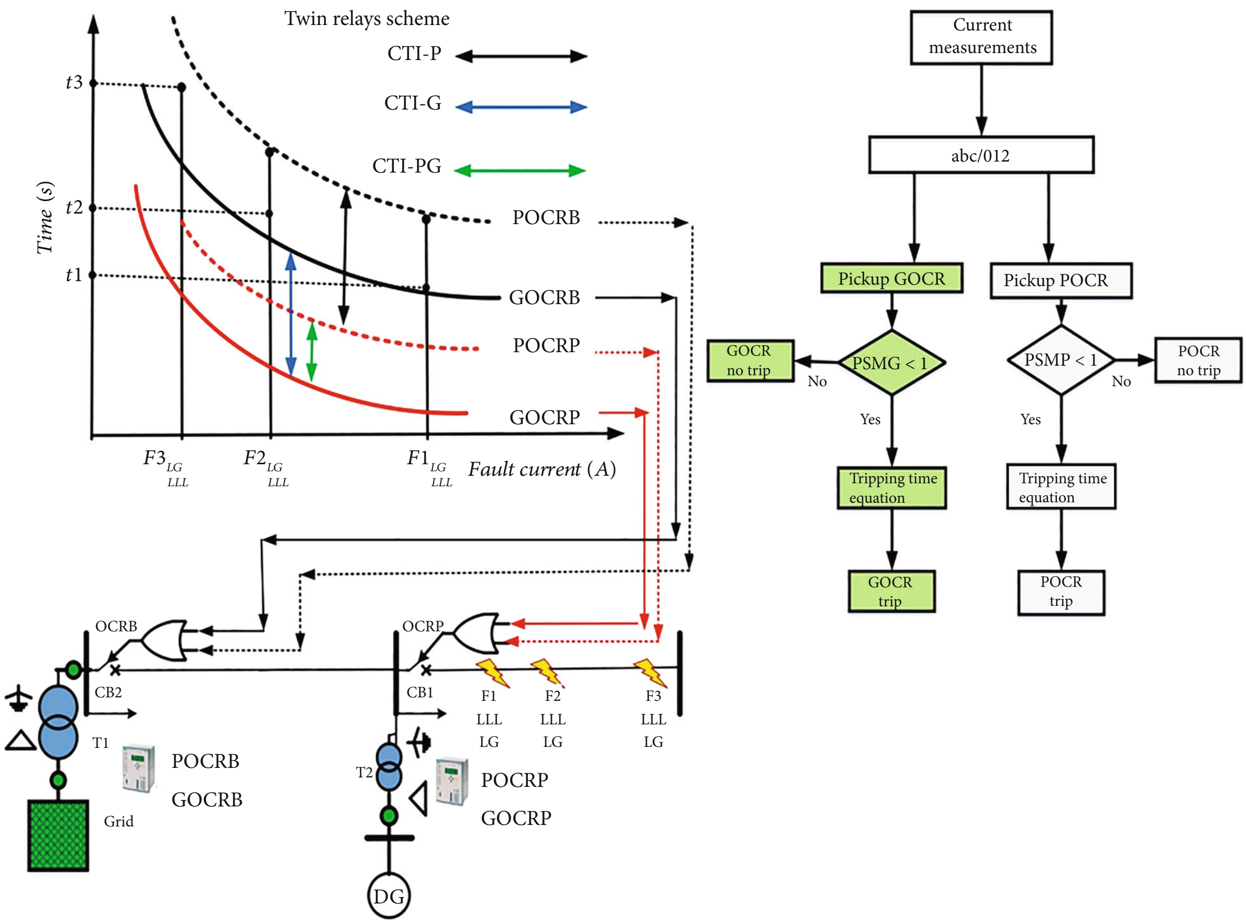


Figure 3: The proposed OCR coordination protection logic for POCR and GOCR.

ground fault protection curve exhibits shorter response times compared to POCR. The proposed scheme logic, as shown in Figures 3 and 4, is aimed at limiting the total tripping time of the OCRs under all fault conditions. The proposed solution works excellently in ground fault scenarios, enabling fault isolation using GOCR, the primary protection for ground faults, while POCR serves as a backup protection for the same line. With this proposed solution, the faulted line can be isolated effectively.

Figure 4 presents a proposed approach for coordinating POCR and GOCR functions in the same numerical overcurrent relay using different time characteristic curves. In this work, in the case of PF event such as LLL, the coordination works properly between POCRP and POCRB taking into account the CTI for POCR (CTI-P). Similarly, in the case of GF, the coordination works between GOCRP and GOCRB, as a primary and backup protection, respectively, by considering the CTI for GOCR (CTI-G). Additionally, the proposed coordination scheme in this work includes the feature local and remote backup; in the case of DF events, the POCRP will work as backup for GOCRP as local backup protection, which allowed CTI to keep both primary and backup protection in the same OCR. Also, if GOCRP and POCRP did not work at the same fault, GOCRB and POCRB will work as remote backup protection system to ensure high sensitivity and selectivity. The proposed twin scheme is aimed at ensuring high selectivity and stability of the power protection system by minimizing the number of misoperation by evaluating different time characteristic curves for both POCR and GOCR, as shown in Figures 4(a), 4(b), 4(c), and 4(d), as the previous literature [10–17] used only the standard time characteristic. However, as described in Section 2, the sundered curve showed a limited performance in protecting microgrid system with DGs during DF events.

In addition, the application of twin OCR protection scheme is feasible on numerical relay technology, benefiting from significant advancements in terms of speed and accuracy in fault detection. Moreover, these modern industrial protection devices allow for the incorporation of new features in overcurrent relays through user-defined functions. This capability is exemplified in Siemens' and other protective relays, where such characteristics can be implemented [3, 10]. In this paper, ETAP (Electrical Transient Analyzer Program) is employed as a tool, which is recognized for being in line with industry standards. This demonstrates the adaptability of TOCR within the framework of advanced numerical relay technology, showcasing the synergy between innovative features and simulation tools for enhanced performance in fault detection and relay protection.

*3.1. Formulation of POCR and GOCR Coordination Schemes.* The objective of this subsection is to develop a mathematical

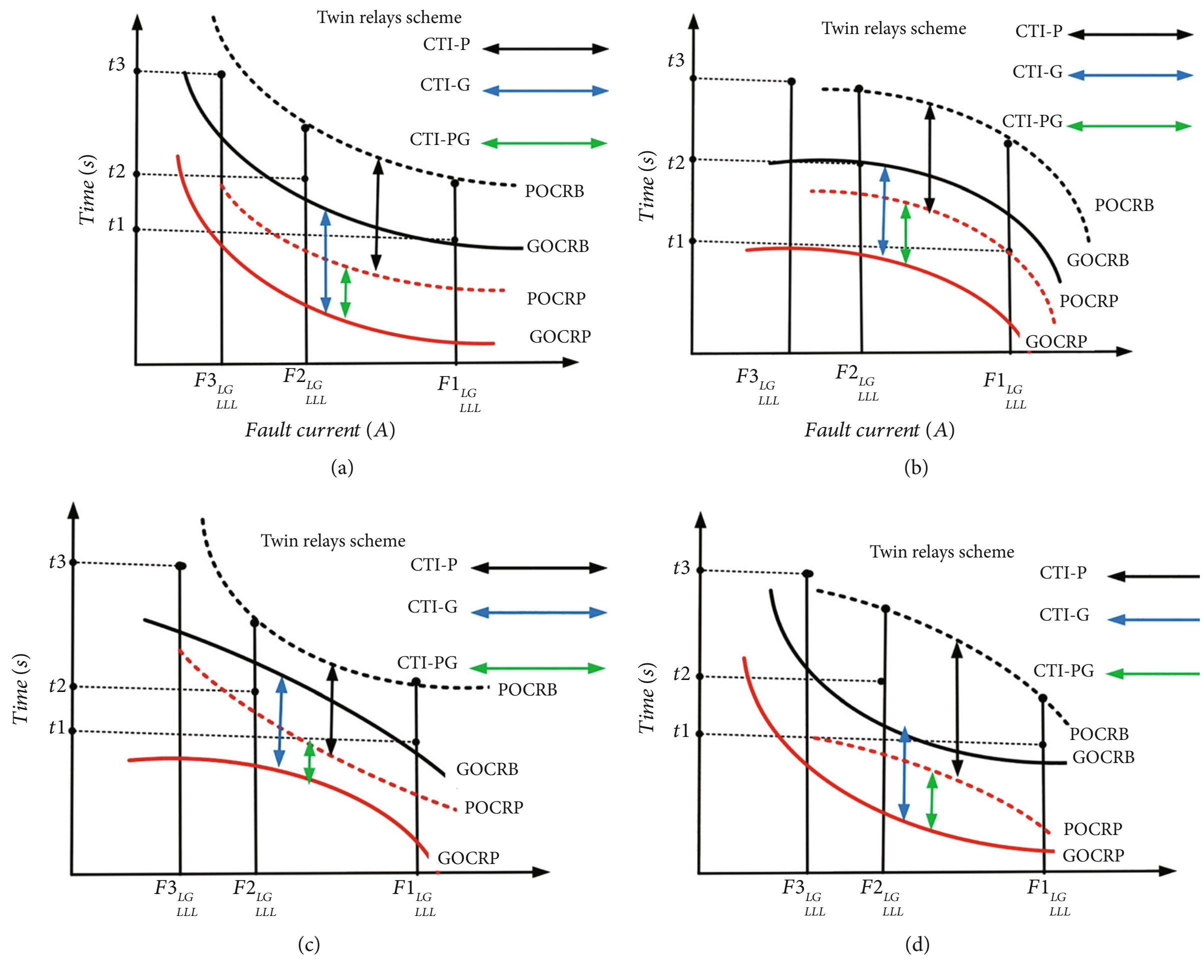


Figure 4: The proposed OCR coordination scheme for both POCR and GOCR: (a) both POCR and GOCR using standard inverse-time characteristics, (b) both POCR and GOCR using nonstandard inverse-time characteristics, (c) POCR using standard and GOCR using nonstandard inverse-time characteristics, and (d) POCR using nonstandard and GOCR using standard inverse-time characteristics.

formulation for the proposed POCR and GOCR coordination approach. In general, studies have formulated the overall operational time of primary and backup POCR as the objective function. However, in this wok, the total tripping time of both POCR and GOCR as primary and backup is considered in developing the objective function. This objective function is formulated while taking into account the selectivity constraints and the CTI-P and CTI-G between primary and backup POCRs and GOCRs, as described in

$$\mathrm{O.T} = \min \sum_{i=1}^{I} \sum_{j=1}^{J} \left( t_{ij}^{\mathrm{GOCR}} + t_{ij}^{\mathrm{POCR}} \right), \tag{1}$$

where O.T is the total tripping time (operational time) for all OCRs (POCRS and GOCRs), $I$ is the number of OCRs, $J$ is the fault location, and $t_{ij}^{\mathrm{GOCR}}$ and $t_{ij}^{\mathrm{POCR}}$ are the tripping time of GOCR and POCR with number $i$ for a fault at $j$, respectively. The $t_{ij}^{\mathrm{GOCR}}$ and $t_{ij}^{\mathrm{POCR}}$ will be calculated based on the type of the time tripping curve.

In case of using the standard time current characteristics (IEC), the $t_{ij}^{\mathrm{GOCR}}$ and $t_{ij}^{\mathrm{POCR}}$ are calculated by using [18, 23]

$$t_{ij}^{\mathrm{GOCR}} = \mathrm{TMS}_i^{\mathrm{G}} \left( \frac{A}{\left( I_{ij}/\mathrm{PS}_i^{\mathrm{G}} \right)^{B} - 1} \right), \tag{2}$$

$$t_{ij}^{\mathrm{POCR}} = \mathrm{TMS}_i^{\mathrm{P}} \left( \frac{A}{\left( I_{ij}/\mathrm{PS}_i^{\mathrm{P}} \right)^{B} - 1} \right), \tag{3}$$

where $A$ and $B$ are parameters related to the type of OCR current-time curve and defined based on the IEC OCR standard presented in [1–3], $I_{ij}$ is the fault current, $\mathrm{PS}_i^{\mathrm{P}}$ and $\mathrm{PS}_i^{\mathrm{G}}$ are the plug setting for the POCR and GOCR, and $\mathrm{TMS}_i^{\mathrm{P}}$ and $\mathrm{TMS}_i^{\mathrm{G}}$ are the time multiplier setting (TMS) for the POCR and GOCR.

On the other hand, the nonstandard current-time characteristic follows logarithmic function [1] and is expressed by (4) and (5) for GOCR and POCR, respectively.

$$t_{ij}^{\mathrm{GOCR}} = \left(5.8 - 1.35 * \log_{\mathrm{e}}\left(\frac{I_{ij}}{\mathrm{Ip}^{\mathrm{G}}}\right)\right) * \mathrm{TMS}_i^{\mathrm{G}}, \quad (4)$$

$$t_{ij}^{\mathrm{POCR}} = \left(5.8 - 1.35 * \log_{\mathrm{e}}\left(\frac{I_{ij}}{\mathrm{Ip}^{\mathrm{P}}}\right)\right) * \mathrm{TMS}_i^{\mathrm{P}}, \quad (5)$$

where $\mathrm{Ip}^{\mathrm{G}}$ and $\mathrm{Ip}^{\mathrm{P}}$ are the pickup current for GOCR and POCR, respectively. By separating the grading time from the fault magnitude and location, the proposed nonstandard characteristic improves the selectivity of the protection system regardless of the fault currents or location [1]. The traditional curves in (2) and (3) face difficulties in detecting minimum faults, as described in Section 2, but the proposed nonstandard characteristic allows for sufficient detection and coordination of POCR and GOCR during all faults, as illustrated in [1, 19, 23]. Furthermore, the objective functions presented in (1) are subjected to selectivity and bound constraints which are described by (6)–(8).

$$t_{\mathrm{backup}} - t_{\mathrm{primary}} \geq \mathrm{CTI}. \quad (6)$$

The operating time for GOCR and POCR which work as primary and backup relays is denoted by $t_{\mathrm{primary}}$ and $t_{\mathrm{backup}}$, respectively. To ensure selectivity, the CTI is chosen to be 0.3 seconds based on IEEE-242 between the local and remote backup OCRs [1, 19].

$$t_{\min} \leq t_{ij} \leq t_{\max}, \quad (7)$$

$$\mathrm{TMS}_{\min} \leq \mathrm{TMS}_i \leq \mathrm{TMS}_{\max}. \quad (8)$$

Equations (7) and (8) are aimed at ensuring that the GOCR and POCR operate within acceptable time limits, within minimum and maximum operational times ($t_{\min}$ and $t_{\max}$) and TMS ($\mathrm{TMS}_{\min}$ and $\mathrm{TMS}_{\max}$). In addition, the determination of the $\mathrm{TMS}_i$ minimizes the total tripping time (O.T) in (1), which is achieved through solving the optimization task.

*3.2. Water Cycle Optimization Algorithm.* The water cycle optimization algorithm (WCOA) is a heuristic optimization method that takes inspiration from the water cycle in seas and rivers [39, 40]. It has been shown by [39] to be a powerful optimization solver in previous power engineering studies and can be implemented using the Optimization Toolbox in MATLAB/SIMULINK [41]. In this article, WCOA is utilized to solve the GOCR and POCR coordination problem, presented in previous subsection and achieve the minimum total operating time. The main process of WCOA consists of iterative steps. Initially, the parameters and primary solution for solving the optimization task in (1) are assigned randomly. The position of the solution is then modified based on the finest results from the preceding phase. In the subsequent step, solutions' locations are swapped, and random new solutions are introduced to prevent local optimal solutions and aim for the optimum solution. Finally, after the iteration process, the WCOA will produce the optimal solution. The main procedures of WCOA are outlined below [39, 40]:

(1) Initial parameters: to determine the optimal value of this parameter, a range of values for each parameter was tested and then issued

(2) Generating a population of solutions randomly for the OCR coordination problem at the start of the algorithm

(3) Calculating each solution's objective function value by solving the OCR coordination task using (1)

(4) Updating the position of solutions and choosing a new location based on the optimal results from the previous point

(5) Swapping the locations of solutions to avoid local solutions

(6) By incorporating a new random solution, the WCOA is able to avoid local and saturation effects when selecting the optimal solution

(7) Since WCOM is an algorithm that is iterative, step 2 is repeated until the utmost number of iterations has been attained

The main characteristics of the WCA were found by careful evaluation across a wide range of values, as described in [39, 40]. The ideal parameter values were determined for achieving the optimal solution of the proposed coordination problem in microgrid protection and recording the minimum tripping time for all OCRs. WCA settings include 1000 iterations, 50 people, $1\mathrm{e}^{-5}$ evaporation constant, and 4 streams/seas.

## 4. Simulation Results and Discussion

This section assesses the proposed twin OCR protection scheme for GF and PF events and its coordination problem, which was discussed in Section 3. The scheme is evaluated using a 9-bus DN (IEEE network) to test its effectiveness under various modes of operation. The performance of the twin scheme, with different possibility of nonstandard curve (LOG) and standard tripping curve (IEC), is evaluated. The results of testing the proposed twin scheme fault conditions are presented, along with a comparison of the scheme to commonly used approaches in terms of total tripping time and CTI error events. Using nonstandard and standard time curves, the WCOA is used to solve the coordination problem, and the results are analyzed and compared. The proposed twin OCR scheme is evaluated using industrial software (ETAP) and compared to standard approaches.

*4.1. Description of the Case Study.* The proposed twin OCR protection is evaluated on a 9-bus feeder IEEE network, as shown in Figure 5, and the optimal twin OCR settings are determined and the minimum tripping time is achieved. The specifics of this network are outlined in [1, 3], and it is generally operated with a high-voltage/medium-voltage utility source and two 5 MVA DGs (PV farms) through a setup transformer rated at 0.4/12.4 kV [1, 38]. This network has 15 twin OCRs protecting it from each fault location from

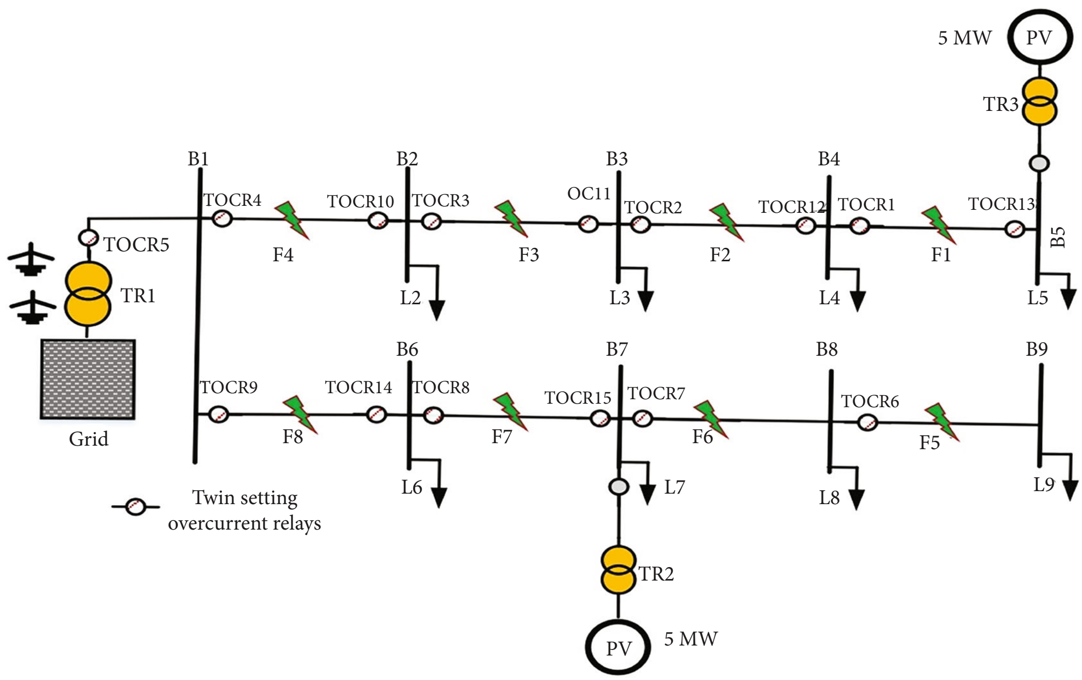


Figure 5: The 9-bus IEEE network.

Table 2: The basic seeing of the twin OCRs (TOCR) at the IEEE network.

| Relay | CTR | POCR | | GOCR | |
|---|---|---|---|---|---|
| | | $PS^P$ (%) | $Ip^P$ (A) | $PS^G$ (%) | $Ip^G$ (A) |
| TOCR1 | 200/1 | 60 | 120 | 20 | 40 |
| TOCR2 | 200/1 | 60 | 120 | 20 | 40 |
| TOCR3 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR4 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR5 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR6 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR7 | 100/1 | 60 | 60 | 20 | 20 |
| TOCR8 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR9 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR10 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR11 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR12 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR13 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR14 | 100/1 | 50 | 50 | 20 | 20 |
| TOCR15 | 100/1 | 50 | 50 | 20 | 20 |

F1 to F8 which represent near- and far-end fault locations from the sources. The three-phase fault (LLL) and line to ground fault (LG) with resistance faults (RF) equal to 0 and 15 ohms are used to evaluate the twin scheme.

Table 2 describes the basic setting of the twin OCRs, where the current transformer ratio (CTR), pickup current ($Ip^P$ and $Ip^G$), and plug setting ($PS^P$ and $PS^G$) for each twin OCR are established based on load flow and fault calculations in accordance with IEC-60909. In addition, the performance of the proposed twin scheme is investigated under DN operation models. The proposed twin scheme is aimed at increasing the selectivity of tripping and maintaining the power continuity on healthy lines to enhance DN stability. This section examines the performance of the twin OCR coordinating scheme for DN using the WCOA in the following cases:

(i) Case 1: the 9-bus IEEE network is powered by a main HV/MV utility feeder, to assess the proposed twin protection scheme on a traditional DN without DGs

(ii) Case 2: the proposed network is powered by a main HV/MV utility feeder and two 5 MVA PV farms to

Table 3: The TMS values for POCR and GOCR in the TOCRs at the IEEE 9-bus network with nonstandard curve (LOG) and standard tripping curve (IEC).

| Relay | Case 1 | | | | Case 2 | | | | Case 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $TMS^P$ IEC | $TMS^P$ LOG | $TMS^G$ IEC | $TMS^G$ LOG | $TMS^P$ IEC | $TMS^P$ LOG | $TMS^G$ IEC | $TMS^G$ LOG | $TMS^P$ IEC | $TMS^P$ LOG | $TMS^G$ IEC | $TMS^G$ LOG |
| TOCR1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.016 |
| TOCR2 | 0.184 | 0.237 | 0.184 | 0.236 | 0.193 | 0.248 | 0.169 | 0.22 | 0.039 | 0.135 | 0.083 | 0.244 |
| TOCR3 | 0.324 | 0.416 | 0.328 | 0.412 | 0.413 | 0.433 | 0.294 | 0.392 | 0.025 | 0.244 | 0.125 | 0.43 |
| TOCR4 | 0.436 | 0.578 | 0.433 | 0.57 | 0.527 | 0.601 | 0.403 | 0.551 | 0.01 | 0.346 | 0.155 | 0.602 |
| TOCR5 | 0.496 | 0.71 | 0.482 | 0.68 | 0.579 | 0.71 | 0.274 | 0.549 | — | — | — | — |
| TOCR6 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| TOCR7 | 0.18 | 0.232 | 0.2 | 0.269 | 0.189 | 0.244 | 0.215 | 0.283 | 0.077 | 0.152 | 0.154 | 0.393 |
| TOCR8 | 0.354 | 0.459 | 0.41 | 0.538 | 0.369 | 0.478 | 0.318 | 0.415 | 0.062 | 0.256 | 0.13 | 0.433 |
| TOCR9 | 0.49 | 0.622 | 0.54 | 0.694 | 0.496 | 0.644 | 0.419 | 0.564 | 0.032 | 0.356 | 0.148 | 0.724 |
| TOCR10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| TOCR11 | 0.054 | 0.138 | 0.123 | 0.179 | 0.08 | 0.129 | 0.13 | 0.184 | 0.063 | 0.129 | 0.078 | 0.229 |
| TOCR12 | 0.15 | 0.288 | 0.288 | 0.389 | 0..257 | 0.26 | 0.308 | 0.348 | 0.196 | 0.266 | 0.206 | 0.543 |
| TOCR13 | 0.353 | 0.497 | 0.562 | 0.72 | 0.628 | 0.455 | 0.595 | 0.722 | 0.491 | 0.454 | 0.438 | 1.22 |
| TOCR14 | — | — | — | — | 1.83 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| TOCR15 | — | — | — | — | 3 | 3 | 0.148 | 0.196 | 0.051 | 0.129 | 0.097 | 0.254 |

evaluate the proposed twin scheme in a modern DN with DGs

(iii) Case 3: the network will operate in islanding mode, where isolated sections of the DN are kept alive by PV systems even in the presence of internal faults

The twin scheme is designed and subjected to the proposed network constraints for CTI and TMS for POCR and GOCR ($TMS^P$ and $TMS^G$), as described in Section 2. The optimal TMS values for the twin OCRs at the 9-bus network are listed in Table 3, which are calculated based on the maximum load currents in the line and different fault scenarios, including LLL and LG faults. To ensure that the primary twin OCRs operate as quickly as possible, the CTIs are assumed to be 0.3 seconds between the local and remote back protection. Moreover, the pickup current for PF and GF is set at 1.2 and 0.2 times the full load, respectively, in this section.

*4.2. Test Results and Discussion.* In this section, the performance of the suggested twin OCR approach (TORC) is compared to the traditional OCR strategy in three different scenarios of power grids (with and without PV and islanding mode). To evaluate the performance, the total tripping times for the traditional phase OCR and TOCR under LLL and LG (RF = 0 ohm) and LG (RF = 15 ohms) faults were computed using the WOCA technique for both approaches. As depicted in Table 4, the proposed TOCR approach outperformed the traditional OCR scheme during LG faults for all three grid operation modes. For example, the total tripping time has been reduced from 40.07, 44.2, and 35.09 seconds at cases 1, 2, and 3 under LG (RF = 0 ohm) for traditional OCR (IEC) to 13.93, 15.1, and 13.4 seconds for twin OCR (IEC), respectively. In the case of minimum fault currents with LG (RF = 15 ohms) fault, the performance of the proposed TOCR was highly sensitive compared to traditional OCR scheme. The total tripping time has been reduced from 22.6, 40.1, and 17.97 seconds at cases 1, 2, and 3 under LG (RF = 15 ohm) for traditional OCR (LOG) to 13.7, 16.2, and 17.1 seconds for twin OCR (LOG), respectively. The nonstandard curve (LOG) for both traditional OCR and TOCR approaches showed highly sensitive performance compared to standard curve (IEC), as presented in Table 4. The total tripping time for traditional OCR using IEC curve and during LLL event was 14.67, 14.59, and 26.64 seconds at cases 1, 2 and 3, while the traditional OCR using LOG curve recorded lower time with 13.5, 12.4, and 14.57 seconds, respectively. Therefore, the best current-time curves for the TOCR were using nonstandard curve (LOG) for both GOCR and POCR.

In order to investigate the selectivity term, the proposed TOCR approach was compared with the traditional OCR scheme. Table 5 shows the recovered results of no trip events at the IEEE network during LG faults (F1 to F8). The proposed TOCR approach did not record any no trip event for the three grid operation modes. On the other hand, the traditional OCR approach was not able many times to trip or take too long to detect the LG faults. For example, the traditional OCR approach recorded 14 and 19 events of no trip during LG faults at case 3 of IEEE network. It has been noticed that the traditional OCR approach is less selective (high number of no trip events) with low LG fault current (RF = 15 ohm) compared to LG with RF = 0 ohm. In addition, the DGs had a negative impact in terms of protection selectivity when using traditional OCR approach, where it had registered higher number of no trip event for the power grid with DGs (case 2 and case 3) compared to power grid without DG (case 1). The highest number of no trip event was recorded for the traditional OCR approach during the islanding mode.

Table 4: The total tripping time in seconds of the traditional OCRs and twin OCRs (TOCR) at the IEEE network.

| Fault scenarios | Traditional OCR scheme | | Twin relay scheme | | | | Grid model |
|---|---|---|---|---|---|---|---|
| | | | GOCR | | POCR | | |
| | IEC | LOG | IEC | LOG | IEC | LOG | |
| LLL | 14.67 | 13.5 | — | — | 14.67 | 13.5 | Case 1 |
| LG (RF = 0 ohm) | 40.07 | 18.96 | 13.93 | 13.6 | 14.67 | 13.5 | |
| LG (RF = 15 ohm) | 49.7 | 22.6 | 15.6 | 13.7 | 49.7 | 22.6 | |
| LLL | 14.59 | 12.4 | — | — | 14.59 | 12.4 | Case 2 |
| LG (RF = 0 ohm) | 44.2 | 38.7 | 15.1 | 14.6 | 44.2 | 38.7 | |
| LG (RF = 15 ohm) | 45.3 | 40.1 | 18.4 | 16.2 | 45.3 | 40.1 | |
| LLL | 26.64 | 14.57 | — | — | 26.64 | 14.57 | Case 3 |
| LG (RF = 0 ohm) | 35.09 | 16.25 | 13.4 | 13 | 35.09 | 16.25 | |
| LG (RF = 15 ohm) | 40.2 | 17.97 | 26.32 | 17.1 | 40.2 | 17.97 | |

Table 5: The no trip events recorded for the traditional OCRs and twin OCRs (TOCR) at the IEEE network for LG faults F1 to F8.

| Fault scenarios | Traditional OCR scheme | Twin relay scheme | Grid model |
|---|---|---|---|
| LG (RF = 0 ohm) | 2 | 0 | Case 1 |
| LG (RF = 15 ohms) | 11 | | |
| LG (RF = 0 ohm) | 2 | | Case 2 |
| LG (RF = 15 ohms) | 15 | | |
| LG (RF = 0 ohm) | 14 | | Case 3 |
| LG (RF = 15 ohms) | 19 | | |

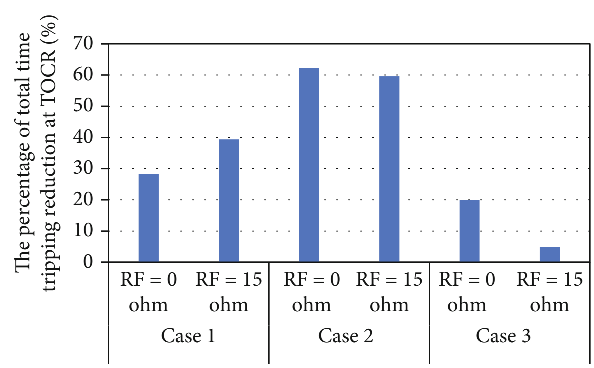


Figure 6: The percentage of total time tripping reduction at TOCR compared to the traditional OCR approach during LG fault events over different grid operation modes and using nonstandard time curves.

Overall, the evaluation of the proposed protection schemes is based on the tripping time under different fault scenarios (LLL and LG) and different fault level (RF = 15 and 0 ohms). Results, as presented in Table 4, from various network scenarios, including cases without photovoltaic (PV), with PV, islanding conditions, and different types of ground faults with resistance, exhibit shorter tripping times while satisfying all constraints. This comparison enhanced reliability and selectivity of the proposed twin OCR protection scheme, making it a more favorable option for ensuring efficient fault detection and system protection, particularly in scenarios involving ground faults. The LG fault is recognized as the most prevalent type of fault, constituting approximately 70-80% of all faults. It causes increased complexity in microgrids, where the coordination of POCR is typically configured for three-phase faults. In the case of a ground fault, POCR may experience delays or fail to detect the fault promptly, leading to extensive isolation of areas and compromising network stability. Therefore, the proposed twin OCR protection scheme offers a solution that can be applied to protection devices. By activating both phase and ground OCR relays and tuning them in conjunction, a more effective and timely response to ground faults was ensured. This not only enhances fault detection but also mitigates the risk of unnecessary isolation and its detrimental effect on network stability, as shown in Table 5.

In this section, the performance of the TOCR scheme using WCOA optimization method was evaluated. The total tripping times under various fault and grid mode scenarios are presented and compared in Table 4. The results show that the TOCR approach outperforms the traditional OCR approach in reducing the total tripping time during LLL and LG fault scenarios for all three grid operation modes. Specifically, during the LG (RF = 0 and 15 ohms) events in case 2, the TOCR approach reduced the total tripping time to 14.6 and 16.2 seconds, respectively, while the traditional OCR resulted in 38.7 and 40.1 seconds, respectively. Furthermore, it should be noted that the optimal TOCR settings obtained from the WCOA led to a more efficient and selective protection system, which can significantly reduce the total tripping time and improve the power system stability, as shown in Figure 6. The percentage of total time tripping reduction at TOCR compared to the traditional OCR approach during LG fault events over the three grid operation modes and using nonstandard time curves (LOG) are presented in Figure 6. For example, the TOCR achieved 28.3% and 39.4% improvement in terms of time tripping reduction compared to traditional OCR approach at case 1 for RF = 0 and 15 ohms, respectively.

## 5. Conclusion

The goal of this work is to propose a fast and sensitive OCR protection scheme for modern and diverse power and fault network architectures. The proposed twin OCR (TOCR) strategy effectively reduces total tripping time and surpasses the traditional OCR scheme in terms of coordination during phase and ground faults. The TOCR approach is developed and optimized using WCOA to determine optimal settings for various fault and grid operation modes. This study is also aimed at providing a straightforward and novel protection strategy for DN with DGs during ground fault scenarios. The TOCR approach successfully completes the coordination task and achieves the minimum tripping time in the three DN operational modes and without any no trip events. For example, the TOCR approach reduces the total tripping time by 62.3% and 59.6% for case 2 with RF equal to 0 and 15 ohms, respectively, indicating that traditional phase OCR is not suitable for primary protection during ground faults. Future research may incorporate machine learning methods to further reduce tripping time and increase the selectivity performance.

## Data Availability

Derived data supporting the findings of this study are available from the corresponding authors on request.

## Conflicts of Interest

The authors declare that they have no conflict of interest.

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