Research Article

Implementation of Optimal Protection Coordination for Microgrids with Distributed Generations Using Quaternary Protection Scheme

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The flexible operation of microgrids, along with the availability of distributed generation (DG) units, causes a variety of changes in short-circuit current levels, magnitudes, and directions, which has undesirable effects on the operation of protection systems. Conventional protection schemes use typical directional overcurrent relays (DOCRs) with limited operating capability, unable to respond to microgrid operations in the manner of short-circuit current changes. In this paper, a quaternary protection scheme implemented with dual-directional overcurrent relays (dual-DOCR) and a protection control strategy is developed for protecting against faults in microgrids, taking into account the existence of DGs and connection and disconnection of DG units. The optimal dual-DOCRs setting and coordination are formulated as an optimization problem solved by evolutionary programming to minimize the relay operating times. The proposed protection scheme is implemented with a centralized protection control system based on the smart grid concept to increase the adaptability of the dual-DOCRs, which have multiple relay setting groups in accordance with system state changes. The simulation case studies are performed using the IEEE 14-bus test system, which is modified as a meshed microgrid operation. Test scenarios, including possible operations of microgrids, DGs availabilities, and different fault events, are analyzed and discussed. The comparative studies and simulation results show that the proposed scheme provides efficient coordination between the primary and backup relays and increases the responsibility of the protection system, which can be observed from the significant reduction in the relay operating times, resulting in the enhancement of selectivity, sensitivity, and speed of microgrid protection systems.

1. Introduction

A microgrid is a form of active small-scale distribution system operated in a modern smart grid structure, which has gained more importance, especially in the manner of flexible operation in grid-connected and islanded modes to enhance reliability and security of electricity grids. The integration of distributed generators (DGs) to the microgrid is an essential part of supplying electricity to the loads when operating in the islanded mode. Distributed generations provide higher system efficiency and power quality with fewer environmental impacts than those of the traditional centralized power generation system.

The transitioning from traditional distribution systems to microgrids causes changes in the power flow and short-circuit currents that can adversely affect the operation of the protection system [1]. The electrical power will change from one direction flow to bidirectional one. Meanwhile, short-circuit current magnitude and direction will also change accordingly depending on the operating status of the microgrid, including the type, size, and location of the DGs installed in the system. The conventional protection system designed based on high short-circuit current in a radial system structure under a specific system state uses overcurrent relay equipped with nondirectional elements unable to respond to the dynamic system state changes and will fail

to operate. Failure of the protection system causes various protection issues, including miscoordination, fault tripping, and blinding of protection, which results in the benefits from the microgrid with the integration of DG, which are significantly reduced [2]. The design and implementation of appropriate protection systems for the microgrid with DGs are, therefore, essential for increasing system reliability, security, efficiency, and resiliency.

The development of effective protection systems for the microgrid with DGs is important in determining the two main points: protective devices and protection schemes. The use of nondirectional overcurrent relays that operate regardless of the fault current direction leads to false tripping decisions due to the microgrid operations and the backfeed fault current from DGs [2]. Electromechanical and digital overcurrent relays equipped with directional components and a single relay setting have been developed to overcome the deficiency of faulty current detection [3]. Dual setting directional overcurrent relays (DOCRs) have been proposed in [4, 5] to improve the capabilities of conventional DOCRs for protecting meshed distribution systems with DGs. The proposed relays are equipped with two inverse time-current characteristics whose relay settings will depend on the forward and reverse fault directions. This feature contributes to improving performance in reducing relay operating times. However, the improvement of these relays to provide additional functionality for protecting against faults in microgrids is still a challenge in modern protection systems.

Protection schemes are a crucial part of the planning of the protective device operation according to the specified relay setting and coordination to ensure that the fault events are detected and cleared correctly as quickly as possible. Conservative protection schemes suggest automatically disconnecting the DG from the system in the event of any abnormalities due to safety and security concerns [6]. These methods limit the operation of electrical systems in the form of microgrids. Conventional protection schemes designed in accordance with the recommended practices provided by the IEEE and the IEC standards are used extensively by many electrical utilities to prevent faults in traditional distribution systems [7, 8]. The typical time-current characteristic for conventional overcurrent relays can be determined using the standard relay equations in [8, 9]. Various protection schemes for distribution systems and microgrids that do not require communication capability have been presented in literature where several protection coordination methods have been proposed [10–12]. However, these methods do not take into account the availability of DGs and connection and disconnection of DGs, which cause the variation of fault currents. In addition, the optimal protection coordination using computational intelligence-based techniques such as particle swarm optimization (PSO) [13] and genetic algorithm (GA) [14] has been proposed for determining the optimal relay setting to minimize the total relay operating times. These protection schemes are determined according to specific system state and network configuration in which if any system changes occur, the relay settings must be reevaluated.

In recent years, the protection schemes designed for protecting against faults in microgrids with DGs have been developed in the literature, which can be categorized by the microgrid operations. The protection schemes for grid-connected mode only have been proposed in [15, 16]. In [15], a protection scheme that relies on time-dependent characteristics of fault current is proposed to maximize DG connection. A protection scheme that uses conventional overcurrent relays with definite time grading has been presented in [16]. These methods are unclear about their implementation with the islanded microgrid. The protection scheme for islanded mode must be more sensitive because fault currents in islanding will be of much lower magnitudes than those of the grid-connected system. In this regard, protection schemes for particular islanded mode have been proposed in some literature. These methods are designed based on monitoring different system conditions, such as harmonic content of converter-based DGs (C-DGs) [17], output voltages of C-DGs [18], and symmetrical component combined with residual current [19].

The protection schemes developed for both grid-connected and islanded microgrids have been proposed in [20–22]. An implementation of undervoltage relay for islanded mode together with overcurrent relay for grid-connected mode, which does not require adaptive protection capability, is proposed in [20]. In [21], digital overcurrent relays that can update their setting based on microgrid functions are used for protecting microgrid with a radial system structure. A similar approach that uses an adaptive protection scheme along with communication using IEC 61850 is proposed in [22].

The previous works related to the development and implementation of protection schemes for microgrids with DGs have shown that these methods can be used sufficiently for the protection of faults occurring in grid-connected microgrids with uninterrupted DG connection in radial system structures. However, there is no mention in the literature for the optimal protection coordination of modern DOCRs that are used for microgrids in the mesh structures that take into account the connection and disconnection of the DG units. Therefore, an effective protection scheme, which can adjust the relay settings optimally according to the status of both the microgrid operations and the availability of the DGs, is still a challenge for engineers to improve the efficiency of the protection system.

In this paper, a novel quaternary protection scheme utilizing smart grid technologies and computational intelligence optimization has been developed for protecting microgrids taking into account the availability of DGs. The proposed protection scheme implemented with a centralized protection control strategy is capable of automatically adjusting the optimal relay setting and coordination in accordance with the operations of both microgrids and DGs. The intelligent electronic device- (IED-) based dual-directional overcurrent relay (dual-DOCR) with adaptive relay setting groups is implemented for protecting against short-circuit faults considering both the forward and reverse fault current directions. The relay setting and coordination are optimally determined using the evolutionary programming

(EP) technique to minimize the total relay operating times. The proposed approach aims to mitigate the protection problems arising from the operation of microgrids with the integration of DG units as well as enhance the selectivity, sensitivity, speed, and reliability of the protection system.

2. Conventional Protection Scheme

The conventional relay setting for DOCRs based on the IEC 60255 relay standard is to determine the two main parameters: relay setting current (I_s) and time multiplier setting (TMS) [23]. The operating time of the DOCR expressed in (1) is an inverse-time characteristic function of the relay setting values and the short-circuit current (I) passing through it.

$$t = \frac{A \times \text{TMS}}{\left(I/I_s\right)^B - 1}, \tag{1}$$

where t is the operating time of protective relay. I and I_s are the measured short-circuit current passing through the relay and the relay setting current, respectively. The parameters A and B are the constant values that change according to the time-current characteristics of DOCR.

The protection coordination for conventional DOCRs is a process of determining the operating sequence of the primary and backup relays in accordance with the relay settings and a specific fault current direction under the coordination time interval (CTI) criteria. A typical relay time-current characteristic curve showing the coordination between primary and backup relays is illustrated in Figure 1. Conventional protection schemes assign which relays will be either primary or backup in the system. Figure 2 shows an example of a three-bus meshed microgrid equipped with six DOCRs. If a fault occurs at the middle point of the line section between Bus 1 and Bus 2, relay $R1$ will operate as the primary relay to protect the fault current flowing in the forward direction, and the next relay $R5$, which has the same fault direction setting, will be its backup. Similarly, $R2$ will operate as the primary relay and $R4$ will be its backup, which is responsible for clearing the reverse fault current.

3. Quaternary Protection Scheme

In this paper, a new quaternary protection scheme equipped with intelligent electronic devices- (IEDs-) based dual-directional overcurrent relays (dual-DOCRs) is proposed for protecting against fault in meshed microgrids taking into account the operating status of both microgrids and DGs including the fault current directions. In addition, the proposed relay settings and coordination are optimized using an evolutionary programming (EP) approach. The centralized control strategy with monitoring and communication systems from smart grid technology is utilized for the implementation of the proposed scheme.

3.1. Quaternary Relay Setting and Coordination. The proposed dual-DOCR is capable of bidirectional fault current detection from the use of phase correlation between voltage
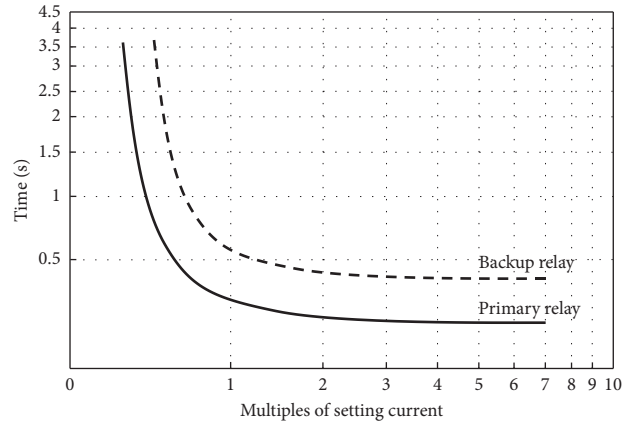

FIGURE 1: The conventional time-current curve and coordination of DOCRs.

Fault direction	Primary relay	Backup relay
Forward	$R1$	$R5$
Reverse	$R2$	$R4$

→ DOCR operation in forward direction
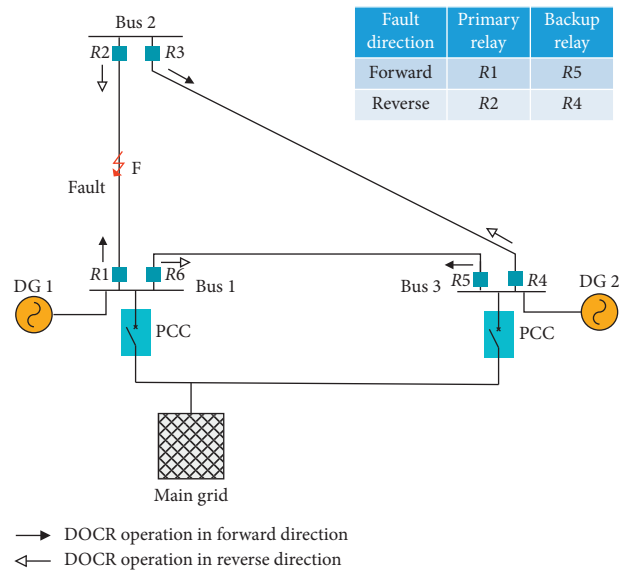←— DOCR operation in reverse direction

FIGURE 2: Operation of DOCRs with the conventional protection scheme.

and current with decision-making logic to discriminate the forward and reverse fault current directions. Each dual-DOCR is equipped with a relay setting group consisting of four pairs of relay setting values according to the microgrid operations and fault current directions, as shown in Table 1. The quaternary inverse time-current curve of each dual-DOCR is depicted in Figure 3. Regarding the dual-DOCR coordination, the relay that is closest to the fault location will operate as the primary relay. Then, the next relay that is closest to the primary relay, which has the same fault direction, is determined to be the backup relay. For the example depicted in Figure 4, if a fault occurs at point F, relay $R1$ will operate as the primary relay for the fault current in the forward direction, and the next relay $R6$ will be its backup. Similarly, relay $R2$ will be the primary relay for the fault current in reverse direction, and the next relay $R3$ is its backup.

TABLE 1: A relay setting group for each system state.

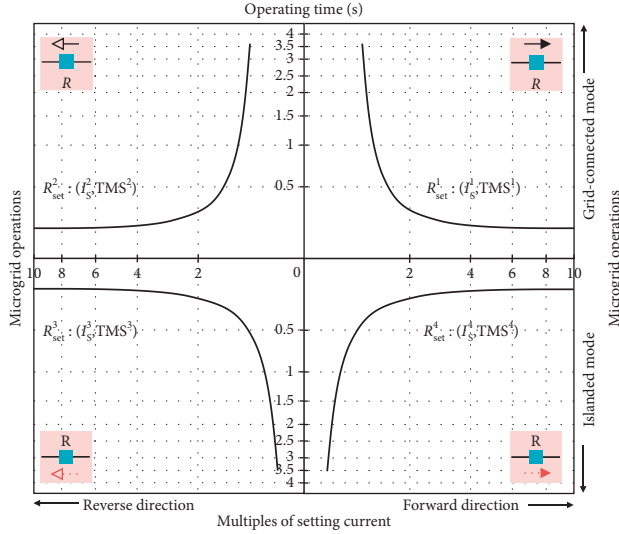| Relay setting group	Microgrid state	Fault current direction
R_{set}^1	Grid-connected mode	Forward
R_{set}^2	Grid-connected mode	Reverse
R_{set}^3	Islanded mode	Reverse
R_{set}^4	Islanded mode	Forward

FIGURE 3: The proposed quaternary time-current curve for each dual-DOCR.

3.2. Optimal Protection Coordination.

The dual-DOCR setting and coordination will be predefined into four relay settings for each system state. The relay operating time (t) of each relay setting is determined from the inverse time-current characteristic function in (2).

$$t_i^n = \frac{A \times \text{TMS}_i^n}{\left(I_i/I_{s,i}^n\right)^B - 1},\tag{2}$$

where i is the relay identifier and n is the relay setting group identifier. The variables t_i^n, TMS_i^n, and $I_{s,i}^n$ are the operating time, the time multiplier setting, and the current setting of the ith relay in the relay setting group n, respectively. I_i is the fault current flowing through the ith relay. The constant relay characteristics A and B are set to be 0.14 and 0.02, respectively.

The optimal dual-DOCR coordination is formulated as an optimization problem. The total relay operating times in (3) is defined as the objective function for the optimal relay setting and coordination to minimize the total relay tripping times in each relay setting group.

$$\text{Minimize } t = \sum_{i=1}^{m} \left(t_i^n\right),\tag{3}$$

where m is the total number of dual-DOCRs in the relay setting group n.

Regarding the coordination condition, the operating time of the primary relay and backup relay needs to be
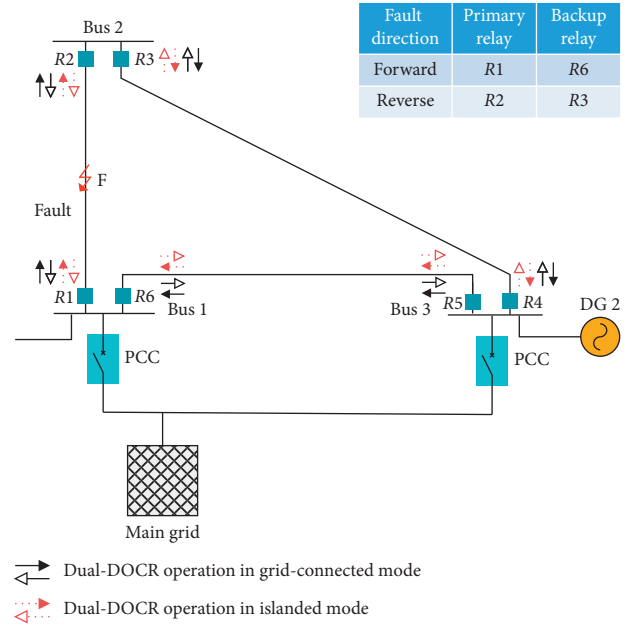

FIGURE 4: Operation of dual-DOCRs with the quaternary protection scheme.

controlled within the coordination time interval (CTI) constraint, which is a minimum time interval, 0.2–0.5 sec, allowed between the primary/backup relays operation. It is set to be 0.20 sec for this study. Therefore, the coordination time constraint is defined in

$$t_{i,\text{bk}}^n - t_{i,\text{pi}}^n \geq \text{CTI},\tag{4}$$

where $t_{i,\text{pi}}^n$ and $t_{i,\text{bk}}^n$ are the primary and backup relays operating times of the ith relay in the relay setting group n, respectively. In addition, the upper and lower relay setting limits can be defined in

$$I_{s,i,\text{min}}^n \leq I_{s,i}^n \leq I_{s,i,\text{max}}^n,$$
$$\text{TMS}_{i,\text{min}}^n \leq \text{TMS}_i^n \leq \text{TMS}_{i,\text{max}}^n,\tag{5}$$

where $I_{s,i,\text{min}}^n$ and $I_{s,i,\text{max}}^n$ are the minimum and maximum limits of the current setting for the ith relay in each relay setting group n, which are determined from the load current calculation. $\text{TMS}_{i,\text{min}}^n$ and $\text{TMS}_{i,\text{max}}^n$ are the minimum and maximum boundaries of the time multiplier setting for the ith relay in each relay setting group n.

Evolutionary programming (EP) is an efficient optimization technique in which populations of individual solutions are evolved through mutation, random changes, competition, and selection. The EP approach in [24] is proposed to solve the optimal coordination problem. The optimization process shown in Figure 5 is performed using MATLAB and DIgSILENT PowerFactory software. The EP algorithm is created as an m-file script in MATLAB for evaluating the optimal solution. The load flow analysis and short-circuit calculation are carried out by a DPL script in DIgSILENT. The data exchange process and interactive communication between these analysis tools are automatically interchanged using the sw.csv file.
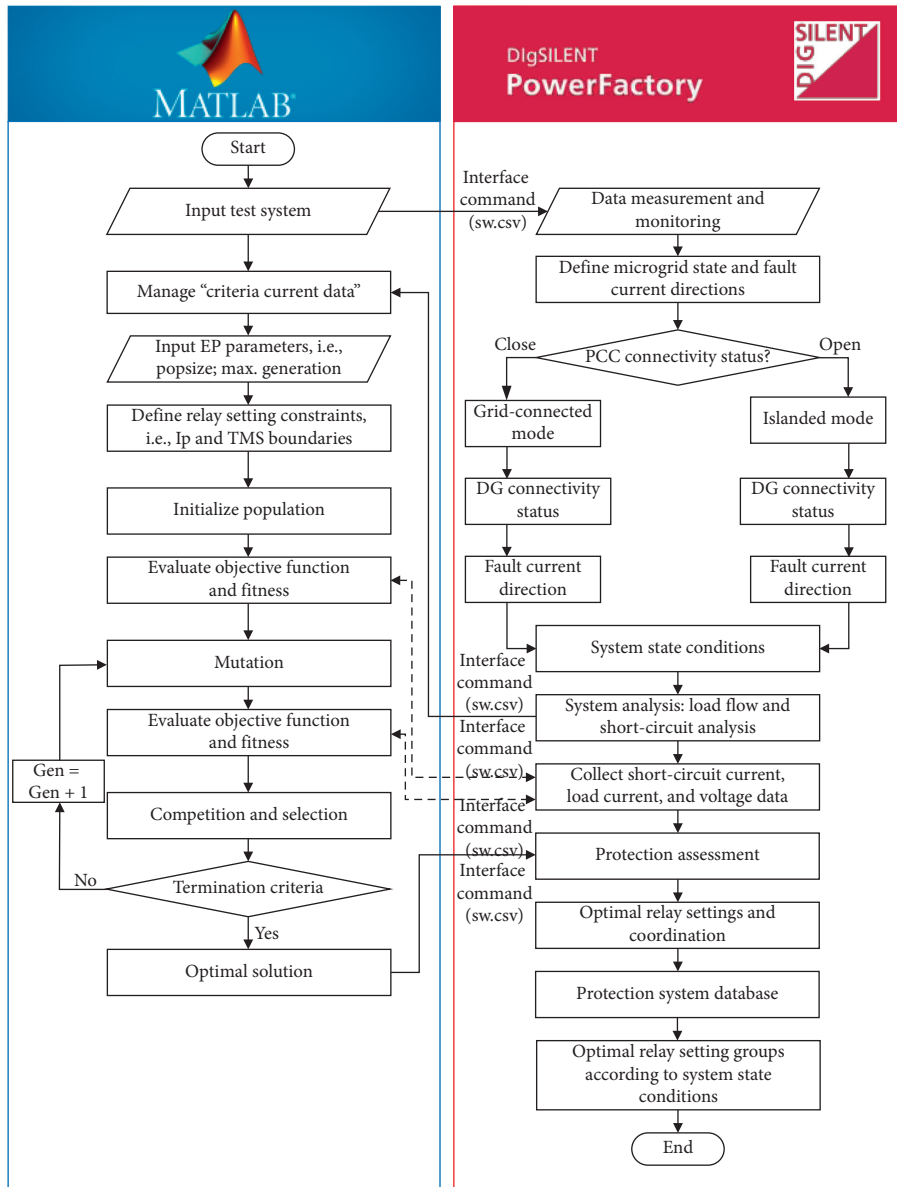
FIGURE 5: Flowchart of the optimal dual-DOCR setting and coordination.

3.3. Protection System Control Strategy. The implementation of the dual-DOCR configuration with the proposed protection system control strategy can be presented in Figures 6 and 7. The protection control algorithm illustrated in Figure 7 consists of the system state monitoring of the microgrid operations and the availability of DGs, from which input data are the status of the point of common coupling (PCC) at the microgrid interconnection and the status of circuit breakers at the DGs. These data will be sent through the communication system conformed with the IEC 61850 standard [21] to the microgrid controller. The centralized protection control system (CPCS) is a function within the microgrid controller that is responsible for the operation and control of the protective relays. The CPCS will determine the present state of the system from the information received and compare it with the predefined system state and the matching of the optimal relay settings stored in

the protection system database, as depicted in Figure 8. If the system state matches, CPCS will send the optimal relay setting group that is predefined for that state to each dual-DOCR. On the contrary, if the system state does not match, CPCS will reassess the optimal relay settings in accordance with that new system state and update the protection system database.

The decision-making process for the operation of dual-DOCR depends on the system state and the status of the fault current directions. The dual-DOCR will receive the operation setting corresponding to the present system state from the CPCS, which makes the relay ready to work regardless of the fault current directions. When the dual-DOCR detects a fault current, the relay will be able to distinguish the short-circuit current direction from the phase correlation of voltage and current with the decision-making logic depicted in Figure 9. Any current flowing into the prespecified
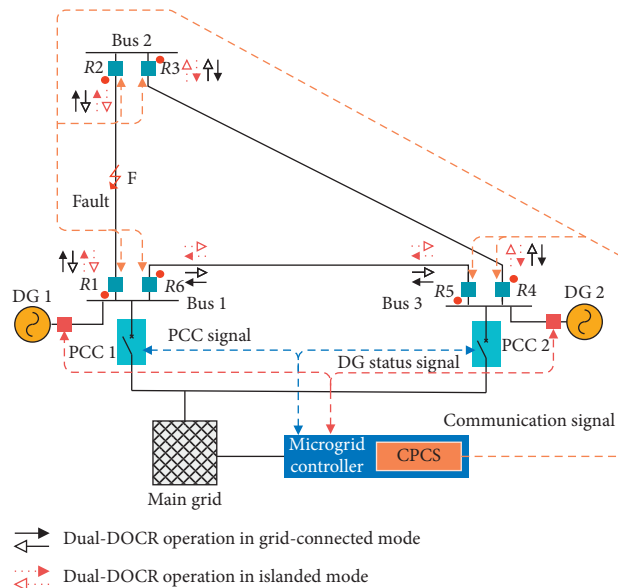
FIGURE 6: Structure of the centralized protection system control.
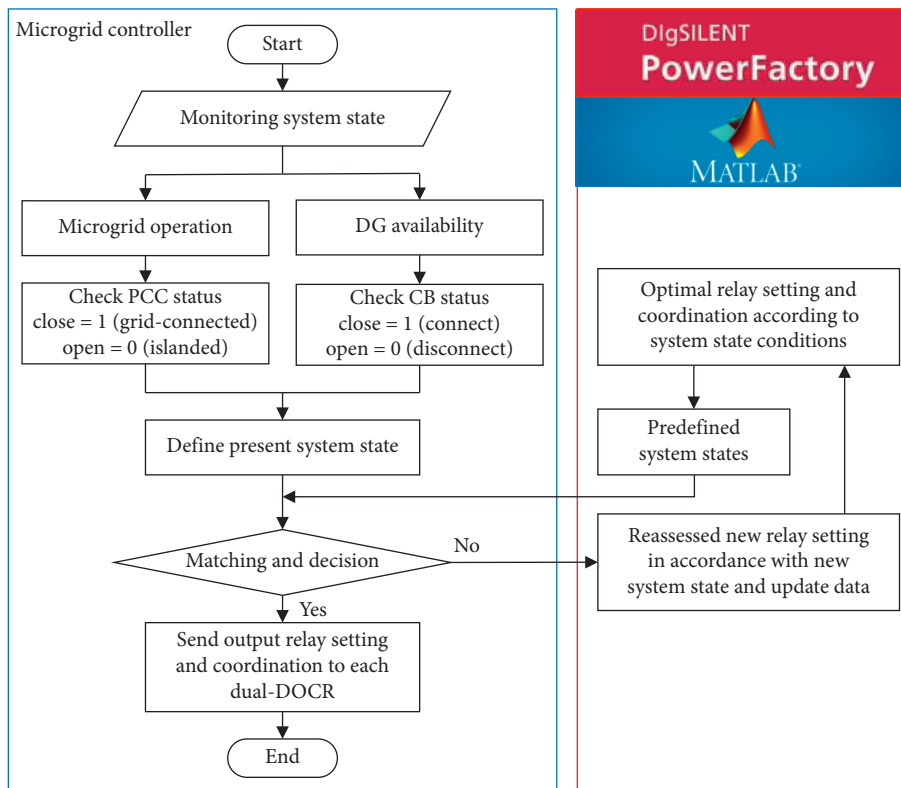
FIGURE 7: Protection system control strategy.

direction or a polarity mark can be considered to be the forward direction; otherwise, it is the reverse direction. With this approach, the dual-DOCR can respond differently for faults in both directions.

Figure 6 demonstrates a meshed microgrid operated in an islanded mode connected with two DGs. The CPCS will determine the present state of the system from the PCC status and the DG status, and then the individual relay setting group is assigned to each dual-DOCR. The protective relay is ready to operate as soon as a fault occurs in the system. In the event that a fault occurs at point F, the primary relay $R1$ will operate using the R_{set}^4 operation setting of its relay setting group. The backup relay $R6$ will operate using R_{set}^4 of its relay setting group. Besides, the primary relay $R2$ and the backup relay $R3$ will operate using the R_{set}^3 operation setting of each relay setting group.

FIGURE 8: Set of relay setting groups for each dual-DOCR.

FIGURE 9: Symbolic decision-making logic for the operation of dual-DOCR.

4. Case Studies and Results

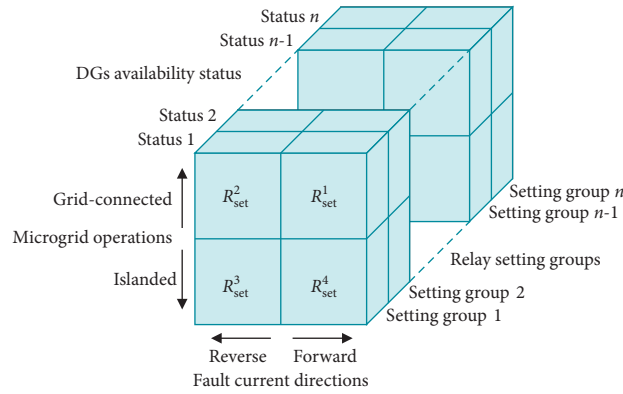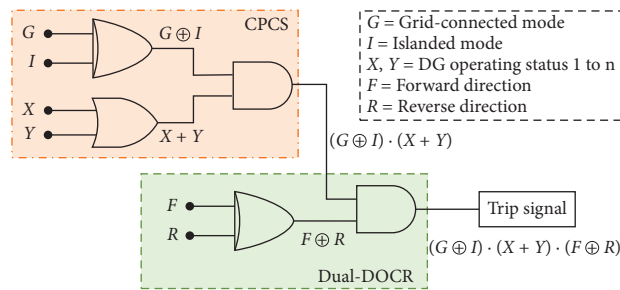In this section, the proposed quaternary protection scheme implemented with the optimal setting and coordination of dual-DOCRs is evaluated and compared with the conventional protection scheme equipped with DOCRs for protecting microgrids taking into account the variation of DGs interconnection. The simulation case studies of the protection schemes are performed using the IEEE 14-bus test system with a mesh structure of 132/33 kV, as shown in Figure 10. The system structure is divided into two main parts: a 132 kV transmission system and a 33 kV distribution system. Further system parameters and configuration are available in [25].

The 33 kV distribution system portion equipped with two DGs, DG1 connected at bus 0006 and DG2 connected at bus 0007, is modified as a meshed microgrid that can be operated in both grid-connected and islanded modes. The microgrid connects with the main grid at the PCC located at bus numbers 0004 and 0005. Each DG is defined as a 100 MVA synchronous-based generator operated at 1.0 power factor. It is assumed that the installed DGs can supply the total system demand and the microgrid must have at least one DG to operate in the islanded mode.

The conventional protection scheme equipped with six DOCRs (R1 to R6) is implemented in the microgrid area, with the direction of each relay, which is determined according to the scheme as shown in Figure 1. On the other hand, the proposed quaternary protection scheme installed with six dual-DOCRs (R1 to R6) is implemented in the same microgrid area, with the direction of each dual-DOCR,

which is defined in accordance with the proposed scheme shown in Figure 6. The fault events F-1 to F-3 are simulated as three-phase faults occurring at the middle point of the distribution lines in the microgrid. It should be mentioned that the relay coordination needs to be considered the worst fault events at the ends of the lines. However, in the case studies, fault occurrences are simulated at the middle point of the lines to represent any faults that may occur at any location throughout the line length in meshed microgrids. In addition, the middle point fault simulation in accordance with the examples presented in Figures 2 and 4 will make it easier to understand the proposed protection approach.

System modeling and simulation are performed using DIgSILENT PowerFactory software. To study the effects of DG connection and disconnection, the simulation case studies will determine the DGs availability according to the operating status shown in Table 2. System scenarios are classified in accordance with the different operating conditions of DGs availability, protection schemes, relay settings, and protective devices, as shown in Table 3. Tables 4 and 5 show the relevant fault currents in the grid-connected and islanded microgrid, respectively.

4.1. Conventional Protection Coordination Scheme with Directional Overcurrent Relay. These case studies demonstrate the implementation of the conventional protection scheme with DOCRs in the modified IEEE 14-bus test system. The relay settings shown in Table 6 are determined based on the IEC 60255 for the grid-connected and islanded microgrid.
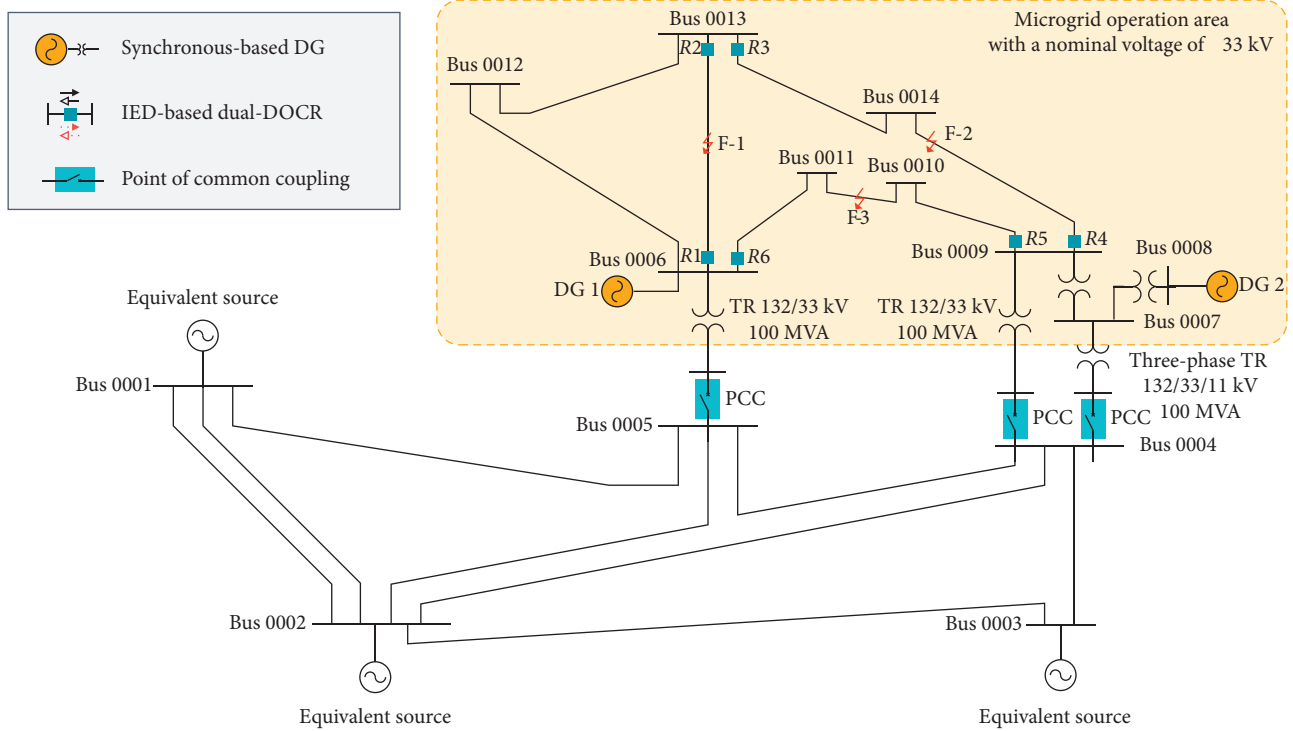
FIGURE 10: The modified distribution portion of the IEEE 14-node test feeder.

TABLE 2: Available operating status of DGs for the microgrid.

DG availability status	DG 1	DG 2
Status 1	ON	ON
Status 2	ON	OFF
Status 3	OFF	ON

TABLE 3: Classification of the comparative case studies.

Case study	DG operating condition	Protection scheme	Optimal relay setting	Protective device
1	Status 1 Status 2 Status 3	Conventional	No	DOCR
2	Status 1 Status 2 Status 3	Quaternary	Yes	Dual-DOCR

TABLE 4: Fault current magnitude in grid-connected microgrid.

DG operating status	Fault current (kA) in each fault location		
	F-1	F-2	F-3
Status 1	11.662	8.226	8.893
Status 2	11.181	7.366	8.110
Status 3	7.310	7.156	7.269

TABLE 5: Fault current magnitude in islanded microgrid.

DG operating status	Fault current (kA) in each fault location		
	F-1	F-2	F-3
Status 1	8.716	5.992	6.664
Status 2	6.902	3.559	4.214
Status 3	2.431	3.213	3.040

Tables 7 and 8 show the primary and backup relay coordination and relay operating times while protecting against fault events at F-1 to F-3 in the grid-connected and islanded microgrid. For the test results, each primary relay has more than one backup relay, according to the coordination and the protection zone setting of each relay. The simulation results presented only the coordination between the primary relay and its first backup relay.

TABLE 6: DOCR settings for conventional protection scheme.

Relay	I_s (pu)	TMS (s)
R1	0.5767	0.1400
R2	0.5767	0.0500
R3	0.7150	0.0800
R4	0.6150	0.1300
R5	0.7000	0.1700
R6	0.6160	0.1300

TABLE 7: Directional primary and backup relay operating times for conventional scheme in grid-connected microgrid.

DG operating status	Fault location	Operating times (t) of relay in second (R_P = primary relay; R_b = backup relay)		
		R_p	R_{b1}	R_{b2}
Status 1	F-1	R1	R5	R3
		0.278	0.489	0.577
		R2	R4	R6
		0.129	0.349	0.446
	F-2	R3	R1	R5
		0.200	0.415	0.514
		R4	R6	R2
		0.259	0.471	0.499
	F-3	R5	R3	R1
		0.338	0.548	1.236
		R6	R2	R4
		0.272	0.580	0.799
Status 2	F-1	R1	R5	R3
		0.278	0.546	0.586
		R2	R4	R6
		0.133	0.369	0.509
	F-2	R3	R1	R5
		0.202	0.420	0.484
		R4	R6	R2
		0.259	0.439	0.591
	F-3	R5	R3	R1
		0.338	0.550	1.048
		R6	R2	R4
		0.274	0.522	0.636
Status 3	F-1	R1	R5	R3
		0.278	0.493	0.602
		R2	R4	R6
		0.142	0.360	0.397
	F-2	R3	R1	R5
		0.226	0.480	0.833
		R4	R6	R2
		0.259	0.649	0.679
	F-3	R5	R3	R1
		0.338	0.553	0.812
		R6	R2	R4
		0.309	0.525	0.788

TABLE 8: Directional primary and backup relay operating times for conventional scheme in islanded microgrid.

DG operating status	Fault location	Operating times (t) of relay in second (R_P = primary relay; R_b = backup relay)		
		R_p	R_{b1}	R_{b2}
Status 1	F-1	R1	R5	R3
		0.278	0.549	0.637
		R2	R4	R6
		0.145	0.392	0.507
	F-2	R3	R1	R5
		0.210	0.438	0.466
		R4	R6	R2
		0.259	0.490	0.518
	F-3	R5	R3	R1
		0.338	0.582	1.018
		R6	R2	R4
		0.286	0.601	0.691
Status 2	F-1	R1	R5	R3
		0.278	1.106	1.188
		R2	R4	R6
		0.203	0.995	1.139
	F-2	R3	R1	R5
		0.216	0.460	0.493
		R4	R6	R2
		0.333	0.557	0.611
	F-3	R5	R3	R1
		0.508	0.873	0.893
		R6	R2	R4
		0.291	0.517	0.556
Status 3	F-1	R1	R5	R3
		0.474	0.696	0.699
		R2	R4	R6
		0.189	0.418	0.443
	F-2	R3	R1	R5
		0.616	2.000	2.010
		R4	R6	R2
		0.283	1.090	1.102
	F-3	R5	R3	R1
		0.363	0.601	1.252
		R6	R2	R4
		0.867	1.086	1.099

the primary relay R6 and its backup relays R2 and R4 is 0.272, 0.580, and 0.799 sec, respectively. Besides, in Table 8, when the fault occurs in the islanded microgrid, the time of the primary relay R6 and its backup relays R2 and R4 is 0.286, 0.601, and 0.691 sec, respectively. The operating time of the primary relay which is less than that of the secondary relay indicates that the primary relay will operate before its backup in accordance with the principle of protection coordination.

For the grid-connected operation with only one DG connected to the microgrid, DG operating status 2 and 3, test results in Table 7 show that all primary and backup relays can be still coordinated. For example, when a fault occurs at F-3 in the grid-connected microgrid with DG operating status 3, the operating time of the primary relay R6 and its backup relays R2 and R4 is 0.309, 0.525, and 0.788 sec,

When the microgrid operates in either grid-connected or islanded mode with both DGs supplying power to the system, the operating times of the DOCRs for protecting against faults show that all relays in the microgrid are coordinated correctly without violating the CTI constraint. For example, in Table 7, when a fault occurs at F-3 in the grid-connected mode with DG status 1, the operating time of

TABLE 9: Dual-directional overcurrent relay settings for the quaternary protection coordination scheme.

Relay	DG operating	Grid-connected microgrid in forward direction		Grid-connected microgrid in reverse direction		Islanded microgrid in forward direction		Islanded microgrid in reverse direction	
		I_s (pu)	TMS (s)	I_s (pu)	TMS (s)	I_s (pu)	TMS (s)	I_s (pu)	TMS (s)
R1	Status 1	0.908971	0.050000	0.830400	0.050000	0.870798	0.065532	0.774000	0.050000
	Status 2	0.920024	0.050000	0.752000	0.050000	0.926764	0.050706	0.812000	0.050000
	Status 3	0.816757	0.050000	0.891734	0.050000	0.651192	0.057826	0.578151	0.386953
R2	Status 1	0.842845	0.134825	0.961430	0.050535	0.774384	0.096503	0.892387	0.056220
	Status 2	0.772070	0.128937	0.832167	0.050000	0.813987	0.094885	0.822938	0.050000
	Status 3	0.851258	0.118257	0.970237	0.050000	0.552425	0.192863	0.582199	0.050016
R3	Status 1	0.922905	0.050000	0.870209	0.143880	0.841449	0.050000	0.857803	0.074514
	Status 2	0.808935	0.050000	0.888088	0.120719	0.902977	0.050000	0.803077	0.050000
	Status 3	0.859760	0.050000	0.929486	0.139762	0.895631	0.050187	0.819987	0.111881
R4	Status 1	0.738000	0.057891	0.771048	0.050004	0.761133	0.056368	0.767017	0.055154
	Status 2	0.847584	0.077759	0.869435	0.050000	0.804075	0.167440	0.859151	0.052559
	Status 3	0.811748	0.050000	0.850455	0.050000	0.769846	0.050000	0.880659	0.050052
R5	Status 1	0.990237	0.056325	0.901277	0.115700	0.833758	0.052783	0.890626	0.050322
	Status 2	0.729298	0.050000	0.728047	0.159616	0.796449	0.050000	0.901522	0.086345
	Status 3	0.818587	0.050000	0.726000	0.064150	0.869643	0.056577	0.801000	0.050000
R6	Status 1	0.739626	0.102973	0.777452	0.050251	0.811765	0.050000	0.869746	0.064470
	Status 2	0.750279	0.078815	0.850592	0.050000	0.800000	0.050000	0.953794	0.050007
	Status 3	0.715141	0.122780	0.760580	0.050000	0.860723	0.084716	0.810000	0.050000

respectively. It is observed that the relay operating times obtained from the DG status 2 and 3 are close to the times obtained from the DG status 1. These results indicate that when a fault occurs in the grid-connected microgrid, the dominated fault currents are from the main grid, which is higher than those from DGs. Disconnecting one of the DGs from the microgrid has little impact on the total system fault current magnitudes. The protective relays can still operate normally with the corresponding relay operation times.

For the islanded operation with only one DG connected to the microgrid, DG status 2 and 3, test results in Table 8 show that all relay coordination can be satisfied. For example, when a fault occurs at F-3 in the islanded microgrid with DG operating status 3, the operating time of the primary relay R6 and its backup relays R2 and R4 is 0.867, 1.086, and 1.099 sec, respectively. It is observed that the relay operating times obtained from the islanded microgrid are higher than those from the grid connection.

These results indicate that when a fault occurs in the islanded microgrid, all fault currents are from the DGs, which are much lower compared to the grid-connected operation. Disconnecting one of the DGs from the islanded microgrid has much impact on the total system fault current levels and magnitudes. Using relay settings based on grid-connected mode causes the operating time of the relays to slow down when protecting the islanding, especially for the backup relays, which may lead to protection blinding problems.

4.2. Quaternary Protection Coordination Scheme with Dual-Directional Overcurrent Relay. For evaluating the performance of the quaternary protection scheme presented in Section 3, the implementation of the proposed scheme with dual-DOCRs in the IEEE 14-bus test system is demonstrated

in this section. Each dual-DOCR is equipped with a relay setting group that is optimally determined according to the present system state. Each relay setting group consists of four pairs of relay setting values (I_S^n, TMS^n) in accordance with the microgrid operations and the fault current directions.

The optimal dual-DOCRs settings shown in Table 9 are determined based on system state variations that take into account the microgrid operations, DG availability, and fault current directions. It can be seen that each dual-DOCR has three relay setting groups according to the operating status of the DGs availability. Each relay setting group will have different relay setting values depending on the short-circuit current level and magnitude that are caused by the operations of the microgrid and DGs. In particular, the short-circuit current level in the islanded mode, which is lower than that of the grid-connection mode, causes the relay setting values to be reduced accordingly to improve the sensitivity of the protection system. Thus, the protective relay settings obtained from the proposed scheme are more suitable and responsive to the flexible operations of the microgrid with DGs, which have dynamic variations of short-circuit current levels, magnitudes, and directions.

Tables 10 and 11 show the primary and backup relay coordination and relay operating times while protecting against fault events at F-1 to F-3 in the grid-connected and islanded microgrid.

For example, in Table 10, when a fault occurs at F-3 in the grid-connected microgrid with DG status 1, the operating time of the primary relay R6 and its backup relays R1 and R2 is 0.124, 0.466, and 0.475 sec, respectively. Besides, in Table 11, when the fault occurs in the islanded microgrid, the time of the primary relay R6 and its backup relays R1 and R2 is 0.196, 0.531, and 0.548 sec, respectively. The simulation results of the relay operating times show that the optimal protection coordination obtained from the proposed approach can be successfully used

TABLE 10: Dual-directional primary and backup relay operating times for quaternary scheme in grid-connected microgrid.

DG operating status	Fault location	Operating times (t) of relay in second (R_p = primary relay; R_b = backup relay)		
		R_p	R_{b1}	R_{b2}
Status 1	F-1	R1	R6	R5
		0.099	0.399	0.410
		R2	R3	R4
		0.163	0.453	0.466
	F-2	R3	R2	R1
		0.139	0.440	0.454
		R4	R5	R6
		0.099	0.408	0.421
	F-3	R5	R4	R3
		0.119	0.425	0.440
		R6	R1	R2
		0.124	0.466	0.475
Status 2	F-1	R1	R6	R5
		0.099	0.405	0.418
		R2	R3	R4
		0.157	0.473	0.492
	F-2	R3	R2	R1
		0.146	0.450	0.463
		R4	R5	R6
		0.099	0.393	0.412
	F-3	R5	R4	R3
		0.099	0.394	0.404
		R6	R1	R2
		0.126	0.580	0.601
Status 3	F-1	R1	R6	R5
		0.104	0.412	0.425
		R2	R3	R4
		0.167	0.468	0.472
	F-2	R3	R2	R1
		0.153	0.461	0.478
		R4	R5	R6
		0.099	0.404	0.417
	F-3	R5	R4	R3
		0.102	0.448	0.466
		R6	R1	R2
		0.129	0.461	0.474

TABLE 11: Dual-directional primary and backup relay operating times for quaternary scheme in islanded microgrid.

DG operating status	Fault location	Operating times (t) of relay in second (R_p = primary relay; R_b = backup relay)		
		R_p	R_{b1}	R_{b2}
Status 1	F-1	R1	R6	R5
		0.172	0.499	0.518
		R2	R3	R4
		0.138	0.522	0.532
	F-2	R3	R2	R1
		0.259	0.532	0.553
		R4	R5	R6
		0.152	0.439	0.461
	F-3	R5	R4	R3
		0.212	0.501	0.505
		R6	R1	R2
		0.196	0.531	0.548
Status 2	F-1	R1	R6	R5
		0.144	0.484	0.497
		R2	R3	R4
		0.540	0.787	0.805
	F-2	R3	R2	R1
		0.309	0.610	0.623
		R4	R5	R6
		0.179	0.465	0.476
	F-3	R5	R4	R3
		0.406	0.715	0.728
		R6	R1	R2
		0.264	0.564	0.578
Status 3	F-1	R1	R6	R5
		0.136	0.432	0.445
		R2	R3	R4
		0.117	0.428	0.443
	F-2	R3	R2	R1
		0.514	0.828	0.837
		R4	R5	R6
		0.219	0.509	0.530
	F-3	R5	R4	R3
		0.296	0.601	0.620
		R6	R1	R2
		0.238	0.548	0.561

to coordinate the primary and backup relays without violating any coordination constraints. In addition, the relay operating times obtained from the quaternary scheme are lower than those from the conventional scheme, which indicates the improving sensitivity and speed of the protection system.

For the grid-connected operation with only one DG connected to the microgrid, DG operating status 2 and 3, test results in Table 10 show that all primary and backup relays are coordinated correctly. For example, when a fault occurs at F-3 in the grid-connected microgrid with DG status 3, the operating time of the primary relay R6 and its backup relays R1 and R2 is 0.129, 0.461, and 0.474 sec, respectively. In addition, for the islanded operation with only one DG connected to the microgrid, DG status 2 and 3, test results are shown in Table 11. For example, when a fault occurs at

TABLE 12: Comparison of the total relay operating times of different protection schemes in grid-connected microgrid.

DG operating status	Total relay operating times (s)		Percentage of reduction
	Conventional scheme	Quaternary scheme	
Status 1	8.399	6.000	28.56
Status 2	8.184	6.211	24.11
Status 3	8.723	6.140	29.61

F-3 in the islanded microgrid with DG operating status 3, the operating time of the primary relay R6 and its backup relays R1 and R2 is 0.238, 0.548, and 0.561 sec, respectively.

The comparison of the total relay operating times obtained from the conventional and the proposed protection

TABLE 13: Comparison of the total relay operating times of different protection schemes in islanded microgrid.

DG operating status	Total relay operating times (s)		Percentage of reduction
	Conventional scheme	Quaternary scheme	
Status 1	8.405	7.270	13.50
Status 2	11.217	9.174	18.21
Status 3	15.288	8.302	45.70

schemes is summarized in Tables 12 and 13 for the grid-connected and islanded modes of operation, respectively. It is observed that the coordination of all relays can be achieved efficiently, as seen from the much faster operating time of the protective relays when compared with the conventional scheme.

5. Conclusion

The operation of microgrids in islanded mode causes the short-circuit current to be lower than the operation in grid-connected microgrid due to only the DGs installed in the islanding, which supplies the fault current. In addition, the existence of DGs in the microgrids causes changes in the short-circuit current magnitudes and directions from the connection and disconnection of the DGs. These changes affect the performance of conventional protection systems that are designed based on the grid-connected microgrid. In this paper, the quaternary protection scheme with dual-DOCRs is proposed for protecting against faults in meshed microgrids with the interconnection of DGs. The optimal relay setting and coordination are determined using an EP approach to minimize the relay operating times, improving the speed of the protection system operation. The proposed protection approach is implemented with a centralized protection control system based on the smart grid concept to increase the adaptability of the dual-DOCRs. The simulation case studies of the protection scheme are performed using the modified IEEE 14-bus test system. Scenarios, including possible operations of microgrids, DGs availability, and different fault events, are analyzed and discussed.

The simulation results and analytical studies show that the use of the quaternary protection scheme with dual-DOCRs coordinated optimally according to the operations of microgrids and DGs availabilities can increase the response-ability of the protection system, which can be observed from the significant reduction in the relay operating times. In addition, the primary and backup relays can be coordinated efficiently for protecting microgrids and DGs without violating protection system constraints. These performances led to the enhancement of selectivity, sensitivity, and speed of the microgrid protection system.

Data Availability

All relevant data including relay setting and coordination and relay operating time are included in the article. The additional data regarding the IEEE 14-bus test system and relay modeling in DigSILENT PowerFactory 2019, student license, used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare there are no conflicts of interest regarding the publication of this paper.

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