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Article

# AC Microgrids Protection: A Digital Coordinated Adaptive Scheme

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**Abstract:** A significant challenge for designing a coordinated and effective protection architecture of a microgrid (MG) is the aim of an efficient, reliable, and fast protection scheme for both the grid-connected and islanded modes of operation. To this end, bidirectional power flow, varying short-circuit power, low voltage ride-through (LVRT) capability, and the plug-and-play characteristics of distributed generation units (DGUs), which are key issues in a MG system must be considered; otherwise, a mal-operation of protection devices (PDs) may occur. In this sense, a conventional protection system with a single threshold/setting may not be able to fully protect an MG system. To tackle this challenge, this work presents a comprehensive coordinated adaptive protection scheme for AC MGs that can tune their protection setting according to the system states and the operation mode, and is able to switch the PDs' setting. In the first step of the proposed adaptive algorithm, an offline setting will be adopted for selective and sensitive fault detection, isolation, and coordination among proposed protective modules. As any change in the system is detected by the proposed algorithm in the online step, a new set of setting for proposed modules will be performed to adapt the settings accordingly. In this way, a new set of settings are adapted to maintain a fast and reliable operation, which covers selective, sensitive, and adaptive requirements. The pickup current ( $I_p$ ) and time multiple settings (TMS) of directional over-current relays (DOCR), as well as coordinated time delays for the proposed protection scheme for both of the grid-connected and islanded modes of operation, are calculated offline. Then, an online adaptive protection scheme is proposed to detect different fault types in different locations. The simulation results show that the proposed method provides a coordinated reliable solution, which can detect and isolate fault conditions in a fast, selective and coordinated adaptive pattern.

**Keywords:** adaptive protection; digital protection; directional over-current relay; fault detection; microgrids; symmetrical/asymmetrical faults



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## 1. Introduction

Low-voltage active networks and microgrids (MGs) are often asymmetric and unbalanced three-phase systems including distributed generation units (DGUs), storage systems, and loads, which can act as a controllable entity. They can disconnect from/connect to the grid at the point of common coupling (PCC) to operate in islanded and grid-connected modes [1,2]. Although MGs have proposed a large number of benefits from distributed generation architecture for conventional distribution networks and power systems, they have changed fundamental concepts for protection and control methods, which implies that

more sophisticated methods for the control, monitoring, energy management [3,4], cyber security [5], and especially protection of MG for a reliable and safe operation need to be investigated, such that DC MGs protection is reviewed in [6]. The concepts to be considered in the MG protection are explained in detail in [7]. In the same way, recent developments and challenges in MG protection [8], advances in conventional and adaptive protection schemes [9], and a review on the protection of MG and its difference with conventional power systems [10] have been proposed so far.

The protection of an MG is a complex and challenging task, because of different factors such as the MG operation modes and its bidirectional power flow, varying fault current contribution, limited and low level of fault current in power electronics-based power converter DGUs, high impedance faults (HIF), variable configuration of MG due to plug and play characteristics of DGUs [11,12], and low-voltage ride through (LVRT) requirements during a fault to prevent from system collapse [13]. In addition, the capacity and location of DGUs are important to define the setting of directional over current relays (DOCR) [14], which may influence the setting of protection devices (PD), such as pickup current ( $I_p$ ), and time multiplier setting (TMS). Moreover, different connection mode of an MG may cause different challenges. For instance, in the grid-connected mode, a large current amplitude contribution of the grid may lead to the malfunction of in-coordination of PDs of MG side including fully power electronic-based DGUs [15]. In the islanded mode, conventional PDs such as fuses and overcurrent relays (OCRs) may not properly operate [16], due to significant decrease in DGUs fault current in high penetrated power electronic converters [17] and current limitation block in the primary inner current control loop [18].

Various research works have been conducted in the area of protection of MGs. However, there are still many challenges and issues that need to be investigated for having an effective and comprehensive protection scheme, i.e., a mechanism that can detect and isolate faults in a fast and coordinated way for both of the operation modes [19,20]. In this way, group setting of DOCRs by using the sensitivity matrix is proposed by [21]. The dual setting of DOCR for protection and coordination of MGs is presented in [22]. The coordination of the over-current relay (OCR) is being studied by different researchers to minimize the operating time of the primary and backup relay [23,24]. A communication-assisted protection scheme for MGs is proposed for both the grid-connected and islanded modes of operation in [25]. The dual setting of DOCR by considering multiple fault locations is investigated and the protection coordination problem is solved by using optimization algorithms with voltage constraints [26,27].

It should be noted here that when the fault path impedance is high, the current direction may not change, which makes the directional protection ineffective. To address this concern, recently, the superimposed component-based DOCR setting methods have gained attention from researchers. In [28], a superimposed current-based DOCR protection is proposed while the superimposed component of transient energy has not been utilized for DOCR protection. The DOCR protection scheme proposed in [29] is based on the modified squared poverty gap (MSPG) index calculated using the superimposed component of current.

Moreover, a fault current limiter (FCL) based approach is proposed for coordination of DOCR in [18]. In [30,31], a protection system by using DOCR and an FCL is proposed for both of the connection modes of operation. In [32], by employing artificial neural networks (ANNs) and a transient monitoring function (TMF), fault is detected discriminated that the output current magnitudes of DER units are limited, and after fault clearance, the microgrid is restored to its normal operating conditions.

An adaptive OCR protection based on micro-phasor measurement units ( $\mu$ PMUs) for MGs system is proposed in [33]. The  $\mu$ PMUs are installed at PCC and other parts of the MGs system to detect any change in the system and outage of line. The monitored data by  $\mu$ PMUs are sent to the phasor data concentrators and then OCRs coordination is updated accordingly. The line outage, DG disconnection, and network configuration

changes are monitored by Thevenin impedance estimation at PCC. An adaptive zonal protection algorithm is proposed for ring MGs that updates the relay settings according to the line current and DG status [34]. Moreover, an adaptive protection scheme for MGs is proposed by using a signal processing-based fault detection method to detect the changes in the system network and optimally identify the pickup current. This method is implemented by using a fast recursive discrete Fourier transform (FRDFT) algorithm and fuzzy logic interface for a fast and effective fault detection [35].

Lack of a comprehensive protection scheme is sensed in most of the MG protection researches. For example, ref. [36] proposes a voltage-based protection scheme for an inverter-based MGs; however, it only considers the islanded mode of operation. In [37,38], sequence components of current are used for fault detection of islanded MGs. In a similar manner, authors in [39] have proposed a protection scheme for LV MGs, which is applicable for autonomous operation of an MG. In addition, single-phase tripping is supported. However, all of the downstream elements of a feeder should be tripped of a fault in the feeder's zone, which is a drawback and undesirable for sensitive loads. In [40], a comprehensive protection scheme is proposed, although its parameters are not set properly based on the system's feature.

The communication system failure and its impact on adaptive protection of MGs are investigated in [41], where MGs fault detection and recent development in protection systems along with adaptive protection have been briefly reviewed. Authors have shown studies carried out to identify the optimal pickup current ( $I_p$ ) setting and minimized approaches of coordination time interval (CTI) of the primary and backup relays. It has been revealed that a number of the reviewed methods are depended to the operation mode, and in some others, because of employing one directional OCRs, all of the downstream DGUs are tripped. In this regard, a fast and reliable protection scheme for MGs system identify, and isolate fault conditions in a coordinated manner is required.

In this paper, a comprehensive and coordinated protection scheme based on digital PDs to efficiently satisfy protection coordination requirements in both the grid connected and islanded modes of operation of AC microgrids is proposed. The proposed scheme covers PCC, feeders, lines, and DGU protection requirements for various type of fault. Its coordination settings are set adaptively, according to the MGs and DGU features. To do so, in an offline procedure, coordinated time delays for various type of employed relays are defined; then, an online adaptive protection algorithm is developed so that switch the PD setting automatically based on the information received by the system, and meanwhile, the algorithm calculates the optimal pickup current and TMS setting in a real-time progress. It means that an offline (calculated and stored) as well an online (measured and calculated in real-time) data are used for reliable, coordinated, and fast fault detection. Briefly, the main contributions of the proposed protection scheme are:

- A coordinated adaptive digital protection scheme is derived. The proposed scheme contains various protective modules such as DOCR, DOCR-NSC, DOCR-THD, DFRs and UVRs, which facilitate detecting various faults.
- Coordinated protection modules for different modes of an MG results in reliable, selective, and coordinated protection, which is appropriate to detect all types of faults.
- In addition to coordinate the DOCRs, coordination of the NSC, THD, and UVR modules have been conducted through appropriate time delays tuned by an adaptive algorithm.
- The coordination is performed through an adaptive scheme, which includes offline and online steps. In the offline step, as the first step of the proposed adaptive scheme, all the settings are adopted for a selective and coordinated scheme among proposed protective modules. Then, in the online procedure, after detection any change in the system topology, a new set of setting for proposed modules will be performed to adapt the settings accordingly.
- The proposed method is appropriate not only for the grid-connected mode, but also for the islanded-mode of the operation.

The rest of the paper is organized as follows. Section 2 proposes protective modules for each region of an MG, with the implementation of them. Section 3 presents the proposed coordination algorithm. Simulations have been performed to validate the merits of the proposed protection scheme in Section 4. Furthermore, lastly, the conclusion and potential directions are discussed in Section 5.

## 2. Proposed Protection Schemes

MG systems as active distribution networks are needed to be protected in directional way, such that the employed PDs should be coordinated to isolate the faulted area. To this end, upstream relay trip signal is transmitted to all of the downstream DGUs. The following coordinated scheme not only supports directional requirements for MG protections, it also employs single-phase trip commands which are an appropriate solution for low-voltage MGs including unbalanced loads.

### 2.1. PCC Protection

As mentioned before, due to operational situations, an MG can be operated in both the grid connected and islanded modes. However, to improve the power quality of loads in faulty conditions or abnormal events of the up-stream grid, the MG can be disconnected through an intentional or unplanned manner. Isolation detection procedure is mainly performed by PCC relays. Conventional OCRs, which are solely sensitive to the fault current amplitude, are not a suitable fault detector. To deal with this problem, the comprehensive fault detection scheme for the PCC relay shown in Figure 1 is presented. The PCC relay involves the following three main relays.

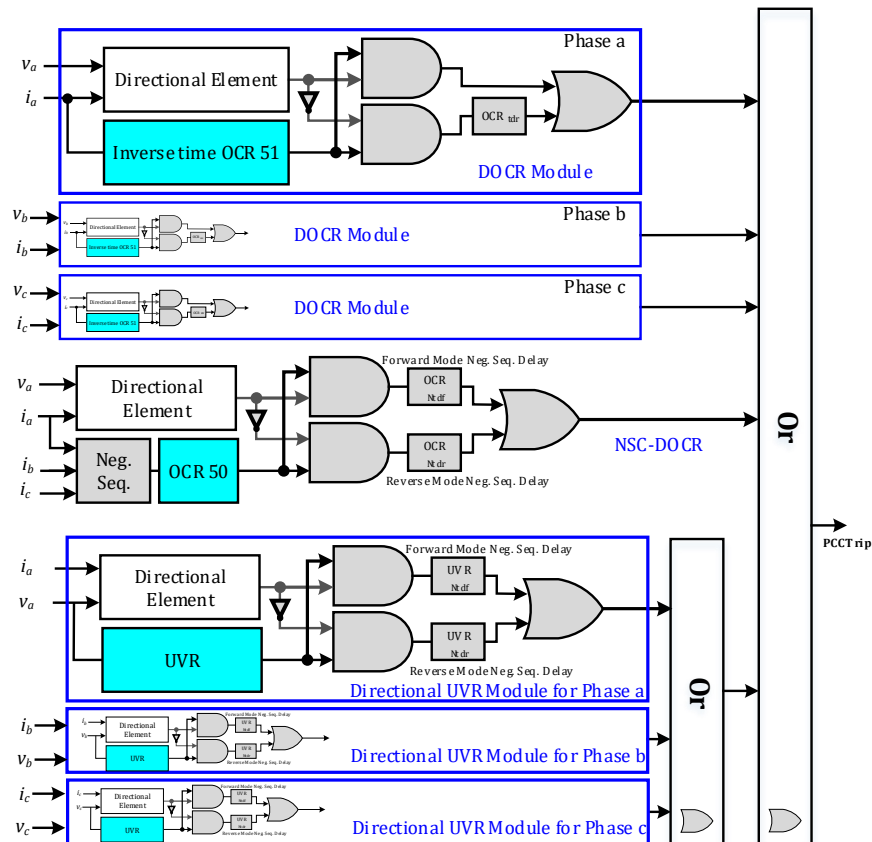


Figure 1. The proposed PCC protection scheme.

#### 2.1.1. Inverse Time DO CR

Due to the large current contribution of the main grid for faults occurring in the MG, inverse time OCR is employed. In the proposed scheme, an inverse time OCR is used for

each of the phases. The inverse time OCR relay per phase outputs join to a logical OR gate, then the trip signal is prepared.

### 2.1.2. Instantaneous DOCR for Negative Sequence of Current

By this module, the negative sequence of component (NSC) of current is used as a detection tool for asymmetrical faults. It is worth highlighting that the reason for employing a directional element is to discriminate between the faults occurring in the main grid (upstream) and the MG (downstream). Consequently, respective CTIs are tuned in offline mode in Section 3. For the grid side faults, a very small CTI as the forward time delay is defined, i.e.,  $CTI = 0.12\text{ s}$ , which is responsible for fast isolation of the MG from the main grid. For the faults occurring in the MG-side,  $CTI = 0.5\text{ s}$ . for this direction is employed long enough, such that it keeps the coordination between the PCC and other MG protection relays.

### 2.1.3. Directional UVR

During three-phase symmetrical voltage sags or faults in the grid-side, both of the relays mentioned in the PCC protection scheme fail to detect the fault or voltage drops. To cope with this issue, a directional UVR for each phase is employed, which is based on the grid codes and appropriate coordination between the PCC and MG relays, and appropriate time delays for reverse and forward directions are defined.

## 2.2. Feeder Protection

Figure 2 shows the proposed digital protection scheme suggested as backup protection for lines and loads. As it can be observed, this protection scheme is installed at the beginning of feeders, and generates feeder protection trip. During a faulty condition, When the feeder protection relay trips, the corresponding feeder will be disconnected and a the generated trip signal FPTrip will be sent to all downstream DGUs and lines on the feeder. As can be observed, the feeder protection relay consists of a directional OCR and a directional NSC-OCR, which are described in the following.

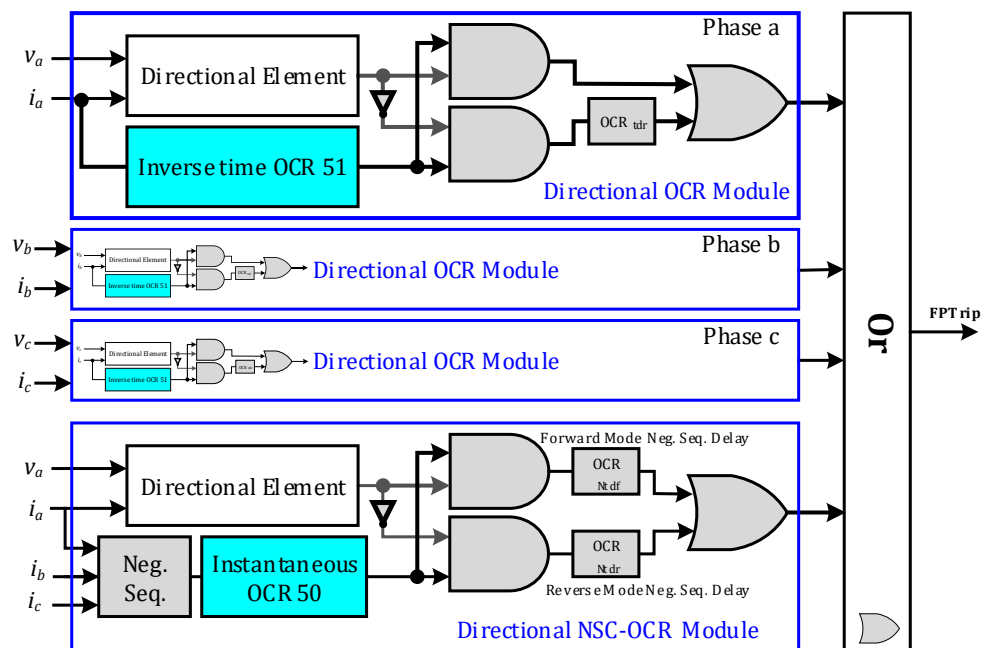


Figure 2. The proposed Feeder protection scheme.

#### 2.2.1. Directional Inverse Time OCR

The proposed directional inverse time OCR not only can properly detect the grid-side faults but can also, by an appropriate time delay definition for reverse mode, achieve a

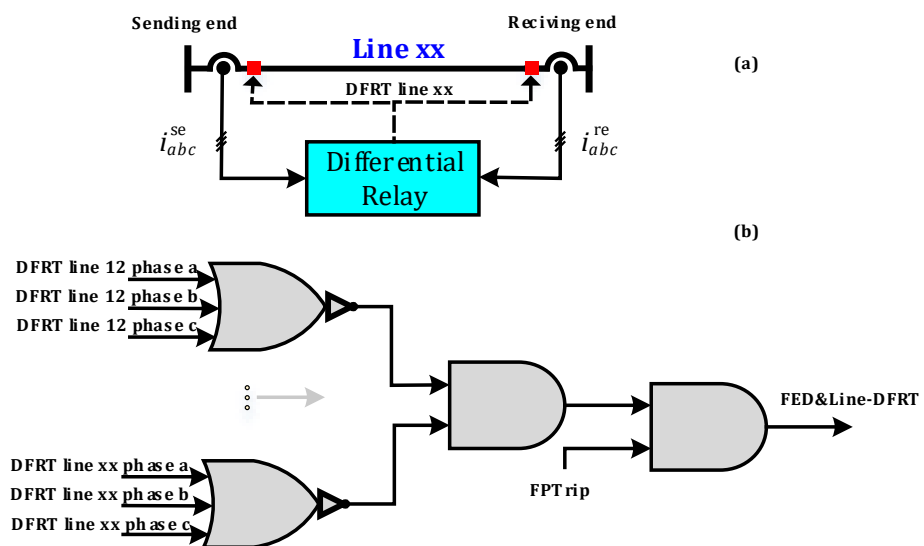
proper coordination. Then, per phase directional OCR signals join to a logical OR gate to generate the trip signal. By the inverse time feature of the relay, grid-side faults, which have a large fault current contribution, will be detected faster. It is worth highlighting here that due to the reduced fault current in MG-side in islanded mode, this module cannot operate properly and in a reasonable time. This issue is addressed by the next module, described in the following section.

### 2.2.2. Directional Negative Sequence Current OCR

An NSC is employed here to detect asymmetrical faults in both of the reverse and forward directions. By passing the output signals of the OCR 50 and directional element through a logical AND gate, fault direction is discriminated as well. Lastly, appropriate time delays are defined to provide the relay coordination.

### 2.3. Line Protection

Differential current-based relays (DFRs) are employed for protecting the all lines to which, in their downstream at least, a grid-forming DGU is connected [42]. As can be observed from Figure 3, all communicated signals from line DFRs join to a logical AND gate, and then they join again with the feeder protection trip signal FPTrip to generate the line and feeder’s trip command FED& LineDFRT.



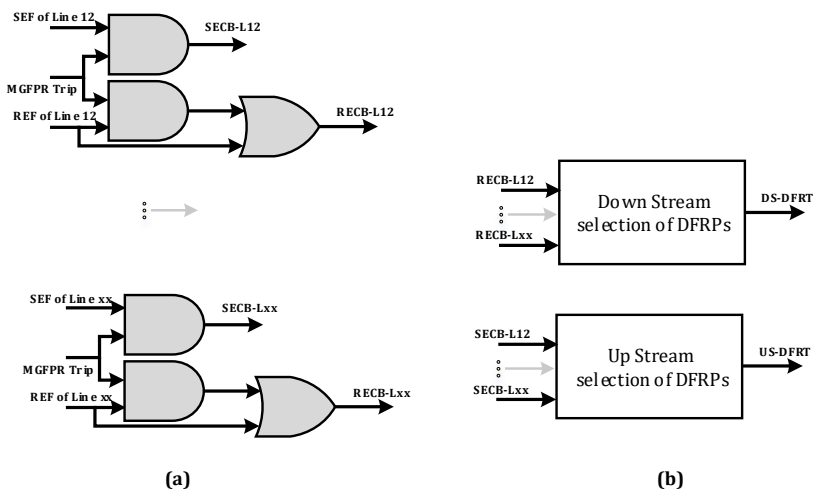
**Figure 3.** The proposed protection scheme for lines. (a) DFR protection scheme for line protection as main protection, and (b) FED&Line-DFRT signal command creating for DGU’s back up protection.

### 2.4. DGU Protection

In order to provide comprehensive DGU protection, communication-based trip commands as external command, and local-based trip commands as internal commands, are provided as follows.

#### 2.4.1. DGU External Trip Command

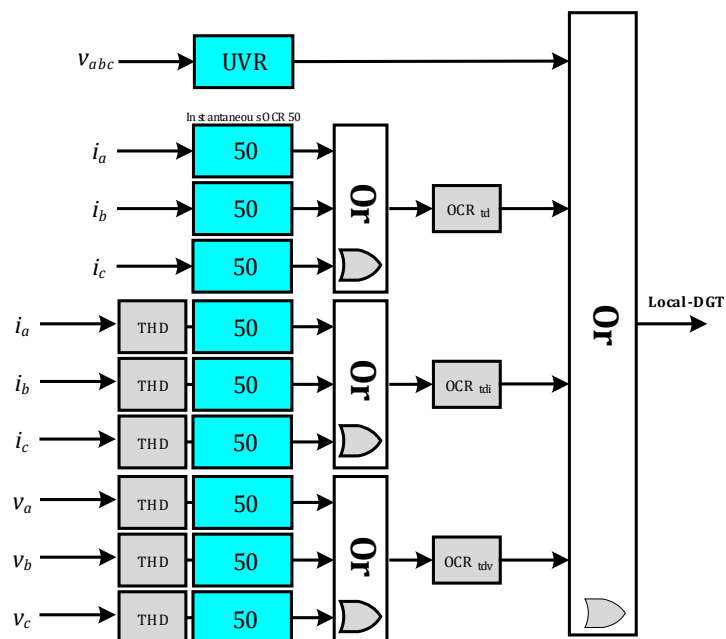
These commands come from the feeder and line protection schemes through a communication infrastructure, to all DGUs located in the feeder/line downstream. It is worth noting that if each one of the sending end circuit breakers fails to operate, the faulty line will be disconnected from the downstream, while it will still be fed from its upstream. In this condition, downstream loads are fed by downstream DGUs; however, a DS-DFRT trip command should be sent to its relevant DGU. The same procedure will be performed when a receiving end circuit breaker faces with a fault, and consequently, a US-DFRT should be used as an interruption for the downstream DGUs, as shown in Figure 4.



**Figure 4.** The proposed external protection scheme for DGUs. (a) sending-end and receiving-end protection commands, and (b) upstream and downstream command selection for DGU external command purposes.

#### 2.4.2. DGU Local Trip Command

As can be observed from Figure 5, the employed structure for grid-forming power converters protection scheme is utilized as explained in the following. A UVR for detecting voltage sags and solid faults is employed. Then, an OCR is utilized for high impedance and overload conditions. Due to the heating effect of the fault current during high impedance faults or overload conditions, a long delay is considered here, such that for each phase, an OCR and a long enough delay are considered. The proposed OCR per phase module can detect asymmetrical overcurrent and faults as well. The last module presented in the local trip command for DGUs is voltage and current THD blocks, which protects the inverter from distorted voltage and currents. The importance of this block is not only for fault condition, but is also for overload conditions, when the inner current control loop of the inverter limits the current amplitude and leads the DGU to a distorted current and voltage waveforms. Figure 6 shows a complete DGU trip command which includes local and external trip commands.



**Figure 5.** The proposed local DGU protection scheme.



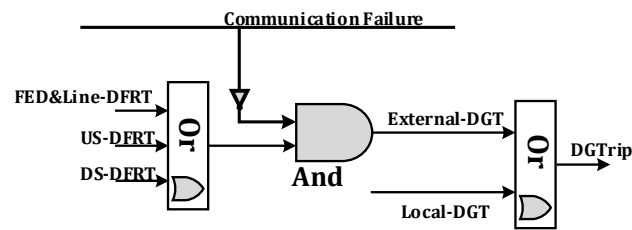


Figure 6. The proposed comprehensive DGU protection scheme configured by external and local trip commands.

### 3. Relays Coordination

In the previous section, we presented a comprehensive protection scheme not only for PCC, feeders and lines, but also for DGUs. In order to provide reliable protection, all the protection relays must be coordinated properly; otherwise, it leads to unwanted trips of out-of-zone faults. It is worth highlighting that PDs of line and loads are the fastest PDs, which independently operate from the other PDs. On the other side, the rest of protection schemes such as PCC, feeder, and DGUs, as backup protection for loads and lines, are coordinated regarding them.

The proposed coordination method works based on two different approaches—an offline method and online approach in real-time. According to the first approach, adequate time delay settings for each one of the forward and reverse relays are determined offline according to the structure of the MGs system configuration with the help of load flow and circuit analysis. The generated data are stored. Then, by using these data, the pickup current ( $I_p$ ) for each upstream and downstream relay are calculated by utilizing the load current and fault current considerations. Next, the TMS for each forward and reverse relay are chosen in such a way each relay works as primary protection and provides a backup protection to upstream and downstream relay for forward and the reverse relay. Different settings for the defined network structure of MGs system are stored in each determined time delay unit. In the second approach, an adaptive technique for online calculation method is adopted that can calculate the pickup for each DOCR relay in real-time and the result of both approaches is compared and the best of these or nearest time delay is adopted for fast fault detection isolation. The flow chart of offline and online approaches is shown in Figure 7, respectively. In addition, the time-current characteristics of DOCR relays located in the PCC and feeders are depicted in Figure 8. The following sections briefly describe the proposed offline Dual setting of DOCR and its implementation along with the online adaptive protection approach.

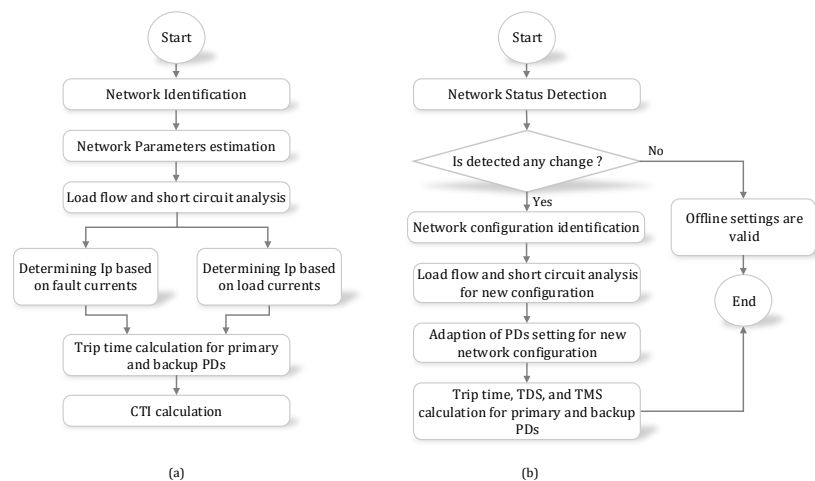


Figure 7. The proposed algorithm for MG protection: (a) offline mode setting, and (b) adaptive online mode for setting DOCRs.

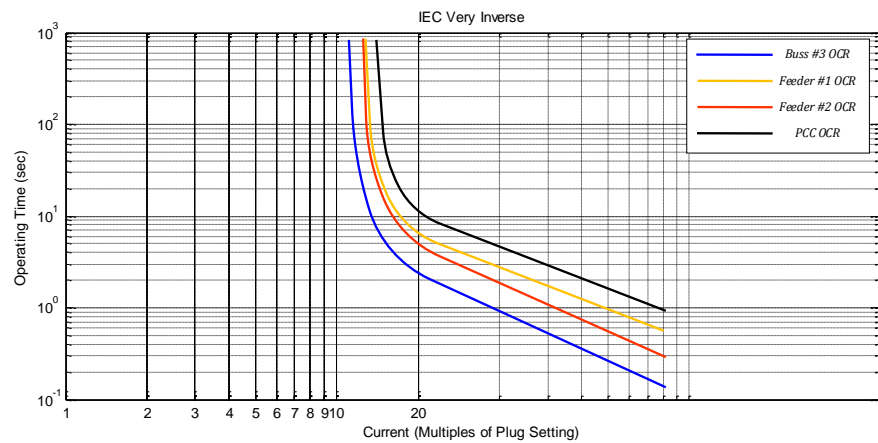


Figure 8. Time-current characteristics of DOCR relays.

### 3.1. Offline Analysis and Setting

In the offline setting, after simulating the MG system shown in Figure 9 with the electrical and control parameters listed in Table 1 for both of the grid connected and islanded modes, the load flow and short circuit faults shown in Figure 7 are carried out to calculate the pickup current ( $I_p$ ) and time dial setting (TDS) by using IEC characteristics (2). For each case study,  $I_p$  and TDS parameters are stored in relay settings as the offline condition mode. As can be observed, in the first step, the network configuration is considered, which defines the MGs system connection and structure identification. Next, the capacity of each source such as grid and DGU, lines, and load is identified; after that, the load flow analysis is considered for normal condition, and then regarded data is recorded and sorted. After simulating shown faults in Figure 9, the short circuit analysis data are recorded and stored. Then, the normal load flow data and by using the maximum fault current, minimum fault current, the pickup current ( $I_p$ ) for each forward as well reverse relay are calculated, and appropriate time delays for NSC, THD, and UVR modules are defined. In the next step, the TDSs for each pair of forward as well as reverse relay trip time are calculated, as described in Section 3.3.

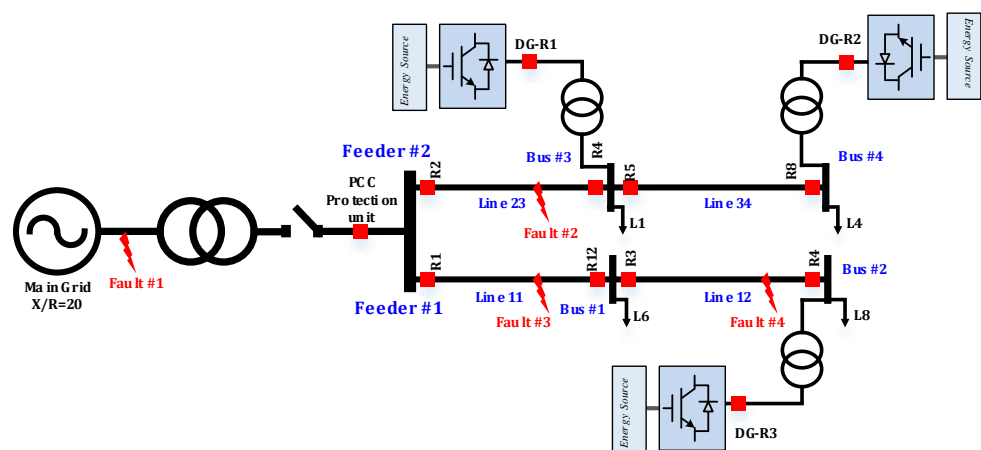


Figure 9. Configuration of AC MG test system and fault locations.

**Table 1.** Parameters of the test system.

Electrical Parameters		
Parameters	Symbol	Value
DC Source Voltage	$V_{DC}$	650 V
Nominal voltage magnitude	$V_{MG}$	325 V
Nominal Frequency	$f$	50 Hz
Switching Frequency	$f_s$	10 kHz
Capacitance of LCL filter	$C_f$	25 $\mu$ F
Inductances of LCL filter	$L_i/L_o$	1.8 mH
Load 1 and Load 4	$Z_1$ and $Z_4$	43 $\Omega$ , 0.3 H
Load 2 and Load 3	$Z_2$ and $Z_3$	124 $\Omega$ , 0.1 H
Line 11	$Z_{11}$	0.4 $\Omega$ , 3.6 mH
Line 12	$Z_{12}$	0.8 $\Omega$ , 1.8 mH
Line 23	$Z_{23}$	0.4 $\Omega$ , 1.2 mH
Line 34	$Z_{34}$	0.8 $\Omega$ , 3.6 mH
Inner loop coefficients and other control parameters		
Control Parameters	DGU: 1 and 3	DGU: 2
$P - \omega$ droop coefficient	0.001 rad/W.s	0.002 rad/W.s
$Q - v$ droop coefficient	0.005 V/VAr	0.01 V/VAr
Current proportional/resonance terms	1000/0.5	1000/0.5
Voltage proportional/resonance terms	120/0.05	120/0.05

### 3.2. Online Settings and Switching Mechanism

For the online setting phase, the real-time measurement and adoption algorithm is implemented to achieve a coordinated backup and selective protection scheme. In the first step of the proposed adaptive algorithm shown in Figure 7, the offline setting will be adopted for selective and sensitive fault detection, isolation, and coordination among proposed modules. As any change in the system is detected by the proposed algorithm. Then, a new set of settings for proposed modules will be performed to adapt the settings accordingly. This approach is mainly based on the information received by DGUs, lines, feeders, PCC, and load. It should be noted that the minimum trip time (TT) of 80 ms is selected for the first back up feeder, i.e., Feeder #1 or Feeder #2. Then, the coordination of back up setting is performed for them. Relays coordination among PCC and Feeder devices are given in Table 2.

**Table 2.** Time delays and protective parameter descriptions.

Protection Module	Parameter	Description	Value	
PCC	Time Delay (TD)	$OCR_{Ntdf}$	TD for NSC Instantaneous OCR 50 in forward direction	0.035 s
		$OCR_{Ntdr}$	TD for NSC Instantaneous OCR 50 in reverse direction	0.350 s
		$UVR_{Ntdf}$	TD for PCC UVR in forward direction	0.005 s
		$UVR_{Ntdr}$	TD for PCC UVR in reverse direction	0.200 s
	Current Settings	$I_p$	Pick-up current for OCR	10 A
$I_{p-NSC}$		Pick-up current for NSC-OCR	1 A	
TMS		OCR Time multiplier setting	1.06	
(Feeder #1, Feeder #2, Bus #3)	Time Delay (TD)	$OCR_{tdr}$	TD for Inverse time OCR 51 in reverse direction	(0.3, 0.3, 0.5) s
		$OCR_{Ntdf}$	TD for NSC Instantaneous OCR 50 in forward direction	(0.08, 0.12, 0.08) s
		$OCR_{Ntdr}$	TD for NSC Instantaneous OCR 50 in reverse direction	(0.35, 0.35, 0.50) s
Current Settings	$I_p$	Pick-up current for OCR	(12, 10, 9) A	
	$I_{p-NSC}$	Pick-up current for NSC-OCR	(1.2, 1, 1) A	
	TMS	OCR Time multiplier setting	(0.8, 0.93, 0.86)	
DGUs	Time Delay (TD)	$OCR_{td}$	TD for Instantaneous OCR 50	2.00 s
		$OCR_{tdi}$	TD for Instantaneous current THD OCR 50	0.15 s
		$OCR_{tdv}$	TD for Instantaneous voltage THD OCR 50	0.15 s
	Current Settings	$I_p$	Pick-up current for OCR	10 A
$I_{p-ithd}$		Pick-up current for Instantaneous current THD OCR 50	1.1 A	
Lines	Current Settings	$I_{p-vthd}$	Pick-up current for Instantaneous voltage THD OCR 50	1.1 A
		$I_{min}$	Minimum differential current required to operate the DFR	(0.2, 0.15, 0.22, 0.15) A

### 3.3. DOCR Principle and Setting

In order to minimize the overall clearing time for different faults in the online procedure, the following objective function for coordinating the DOCR is employed. Based on

the linear or nonlinear modeling, different optimization tools can be used. The expressed optimization problem is a function of two variables, i.e., the pickup current ( $I_p$ ) and time dial setting ( $TDS$ ).

$$\min_{\{TDS_i^{pm}, TDS_i^{bk}, I_{p_i}\}} \sum^{(c,i,j)} (t_i^{pm}(I_{j,c}^{SC})) + \sum_{k=0}^K (t_i^{bk}(I_{k,c}^{SC})) \quad (1)$$

subject to the IEC 60255 standard inverse time relays characteristic, expressed as follows:

$$t_{ij} = TDS_i \frac{A}{(I_{ij}^{SC}/I_{p_i})^B - 1} \quad (2)$$

where  $I^{SC}$  is the short circuit current,  $i$  and  $j$  are the relay and fault location indices, and  $k$  stands for the backup relay numbers. Superscripts  $pm$  and  $bk$  stand for primary and backup protection, and  $c$  determines the operation mode of the MG, such that for grid connected has a zero value, while it is set to one for islanded mode.  $t_{ij}$  is the operating time of relay  $i$  when a fault is happened in location  $j$ .  $A$  and  $B$  are relay's tripping curve coefficients, whose values are 0.14 and 0.02, respectively, [43]. In addition, the expressed objective function should fulfill the following constraint in both of the grid connected and islanded modes.

$$t_i^{bk}(I_{SC}^{k,c}) - t_i^{pm}(I_{SC}^{j,c}) \geq CTI \quad \forall i, j \quad (3)$$

where  $CTI$  stands for the minimum coordination time interval required for discriminating between  $pm$  and  $bk$  for the same fault in  $j$ , recommended to be  $CTI \in [0.2-0.5]$  in most of the contexts, as [43]. In the same way, for the pickup setting and TDS of DOCRs, following constraints should be considered.

$$1.1 \cdot I_i^L \leq I_{p_i}^{bk} \leq I_{SC}^j \quad (4)$$

$$1.1 \cdot I_i^L \leq I_{p_i}^{pm} \leq I_{SC}^j \quad (5)$$

$$TDS_{\min} \leq TDS_i^{bk} \leq TDS_{\max} \quad (6)$$

$$TDS_{\min} \leq TDS_i^{pm} \leq TDS_{\max} \quad (7)$$

where  $I_i^L$  is the maximum load current sensed by relay  $i$ .  $TDS_{\min}$  and  $TDS_{\max}$  stand for the minimum and maximum values for  $pm$  and  $bk$  relay's TDS.

#### 4. Case Studies and Simulation Results

In this study, a modified test system, as shown in Figure 9, is used. In the studied MG, three DGUs operated as droop-based grid forming power converters, controlled by hierarchical droop, voltage, and current controller, are employed. A current saturation block is utilized for safe operation of power electronic converters in the current control layer. The electrical parameters of the system are shown in Table 1. It is worth noting that some concepts and control strategies such as type of earthing system [44], hierarchical control and operation of MG systems have been explained and described before in most contexts such as [4]. In comparison with the comprehensive method in [40], the proposed method not only presents an adaptive scheme for coordination, but also hierarchical control as well as current limitation of DGUs are considered in the simulations, which leads the case studies to be closer to the real world operational MGs.

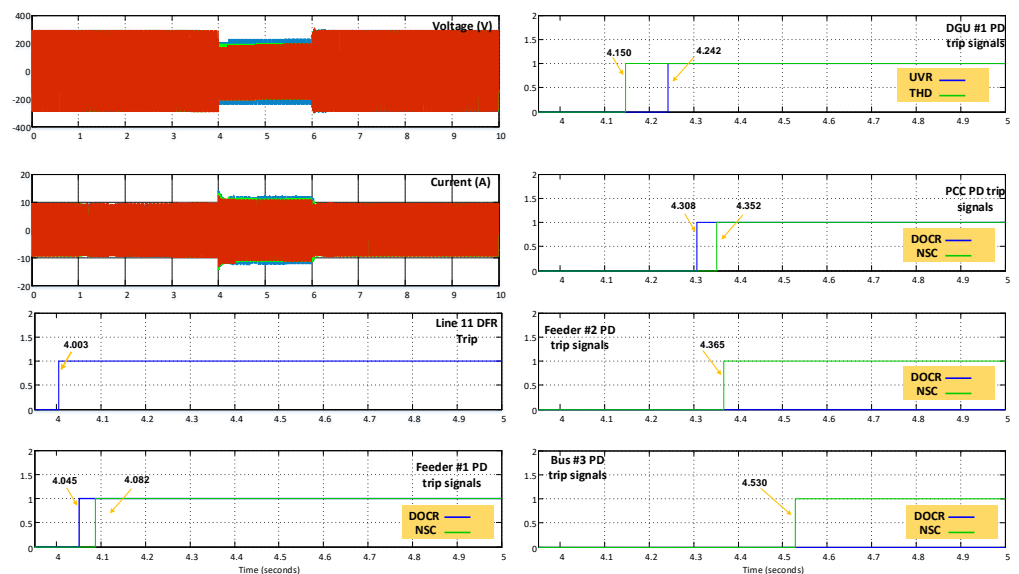
In order to evaluate the merits and effectiveness of the proposed comprehensive MG protection scheme, the illustrated MG in Figure 9 is simulated in Matlab/sim-power systems environment. Then, all types of fault such as LG, LL, LLG, and three-phase fault are examined in different locations for both of operation mode, i.e., islanded and grid-connected modes. By employing the proposed protection scheme, all the PDs operate and

isolate the faults in a coordinated scheme. Furthermore, DGUs and loads are allowed by the proposed protection scheme to service after clearing the fault.

#### 4.1. Grid Connected Mode

For line faults, DFR current-based PDs operates as main PD. These devices detect the fault conditions in one cycle. The PCC and feeder protection relays are considered as back up protections.

In the grid connected mode, Fault #1 in the grid-side, Fault #2 occurred in Feeder #2 and Bus #3, and Fault #3 occurred between Feeder #1 and Bus #1 are investigated. Although all results are extracted for different types of faults, waveform results of an ABG fault at the location of Fault #2 is depicted in Figure 10.



**Figure 10.** Voltage and current waveforms of DGU #2 during an ABG fault and coordinated trip signals for Fault #2 in grid-connected mode.

As can be observed from Figure 10, the upstream grid experience a voltage sag with 30% voltage drop in the location of Fault #1. Injected current from DGU #1 is shown in which, in its inner loop, a current limitation block is employed. The current limitation allows 20% over-current for fault and overload steady-state conditions, as it can be observed from the current wave forms. For the mentioned fault, DGU #1 feeds the fault. As can be expected, the current saturation of the DGU's inner loop, limits the fault current, and it leads to distortion of current waveforms. As can be observed from Boolean type waveform trip signals, the trip command coordination can be observed for Feeder PD, DGU PD, and PCC PD. They are coordinated based on their contribution for feeding the faults. It is worth highlighting that to analyze all the protection schemes, all the trip commands have been intentionally blocked, and thereby, the faults remains active for 2 s, which leads us to check the coordination procedure. As shown in subplots, after the occurred fault at  $t = 4$  s, the DFR protection scheme for Line #11 issues the trip command after 0.003 s; then, the protection scheme for Feeder #1 operates, due to its directional OCR at  $t = 4.056$  s, and consequently, Feeder #1's NSC protection scheme trips at  $t = 4.083$  s. After that, the first DGU which contributes in feeding the faults is recognized as DGU #1 which its UVR and THD protection schemes trip at 4.112 and 4.150 s. After these, the protection schemes of the PCC relay, Feeder #2 and Bus #3 respond to the fault as the can be observed from Figure 10. The illustrated sequence of trip commands demonstrates a coordinated protection manned for an L-L grid-side fault.

More faults in grid connected mode are also investigated to verify the proposed protection scheme. The investigated faults are not only symmetric/asymmetric faults in

the grid-side location, but also include faults occurred in the MG and downstream region. These faults and coordination assessing are given in Table 3, where for Fault #1 located in the grid side, all the fault types are considered. Faults #2 and #3 located in the downstream, as shown before in Figure 9, are also investigated the coordination point of view of the proposed protection scheme in the grid connected mode. As can be seen, DFR protection is the main PD, and all the backup PDs can operate in a coordinated way based on their contribution in feeding the fault.

**Table 3.** Simulation results under different fault conditions in grid connected mode.

Fault Location: Fault Type:	Fault #1		Fault #2		Fault #3	
	Main and Backup Relays	OT (s)	Main and Backup Relays	OT (s)	Main and Backup Relays	OT (s)
AG	PCC Trip (NSC Module)	4.039	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003
	Feeder #2 Trip	4.355	Feeder #1 DOCR Trip	4.035	Feeder #2 DOCR Trip	4.055
	Feeder #1 Trip	4.357	Feeder #1 NSC Trip	4.085	Feeder #2 NSC Trip	4.123
	PCC Trip (UVR Module)	4.505	DGU Trip #1 (OCR-THD)	4.150	DGU Trip #1 (OCR-THD)	4.179
	Bus #3 Trip	4.504	DGU Trip #1 (UVR)	4.185	PCC Trip (NSC)	4.355
			PCC Trip (DOCR)	4.245	Feeder #2 Trip	4.367
			Feeder #2 Trip	4.353	PCC Trip (DOCR)	4.393
		Bus #3 Trip	4.535	Bus #3 Trip	4.505	
AB	PCC Trip (NSC Module)	4.038	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003
	PCC Trip (UVR Module)	4.118	Feeder #1 DOCR Trip	4.056	Feeder #2 DOCR Trip	4.062
	Feeder #2 Trip	4.354	Feeder #1 NSC Trip	4.086	Feeder #2 NSC Trip	4.123
	Feeder #1 Trip	4.356	DGU Trip #1 (UVR)	4.112	DGU Trip #2 (OCR-THD)	4.225
	Bus #3 Trip	4.506	DGU Trip #1 (OCR-THD)	4.150	PCC Trip (NSC)	4.353
			PCC Trip (DOCR)	4.308	PCC Trip (DOCR)	4.358
			Feeder #2 Trip	4.350	Feeder #1 Trip	4.363
		Bus #3 Trip	4.530	Bus #3 Trip	4.504	
ABG	PCC Trip (NSC Module)	4.037	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003
	PCC Trip (UVR Module)	4.117	Feeder #1 DOCR Trip	4.045	Feeder #2 DOCR Trip	4.068
	Feeder #2 Trip	4.355	Feeder #1 NSC Trip	4.082	Feeder #2 NSC Trip	4.128
	Feeder #1 Trip	4.359	DGU Trip #1 (THD)	4.150	DGU Trip #2 (OCR-THD)	4.175
	Bus #3 Trip	4.508	PCC Trip (DOCR)	4.242	PCC Trip (NSC)	4.352
			DGU Trip #1 (UVR)	4.308	Feeder #1 Trip	4.360
			PCC Trip (NSC)	4.352	PCC Trip (DOCR)	4.383
		Feeder #2 Trip	4.365	Bus #3 Trip	4.504	
		Bus #3 Trip	4.530			
ABC	PCC Trip (UVR Module)	4.035	DFR Line #11 Trip	0.003	DFR Line #21 Trip	4.003
			Feeder #1 DOCR Trip	4.045	Feeder #2 DOCR Trip	4.058
			DGU Trip #1 (UVR)	4.116	DGU Trip #2 (OCR-THD)	4.175
			PCC Trip (DOCR)	4.235	Feeder #1 Trip	4.360
			PCC Trip (UVR)	4.705	PCC Trip (DOCR)	4.383
				Bus #3 Trip	4.504	

#### 4.2. Islanded Mode

The same fault types have been also considered to investigate proper cooperation of the proposed protection scheme in the islanded mode. It is worth noting again that the DFR devices are the primary PDs which detect the fault, and then the cooperated backup protections operate. To show the coordinated results, a number of simulations for islanded mode are carried out, and results are shown in Table 4. In the following, one of the LG fault (for example phase A to ground fault) occurred in the location of Fault #2 is explained.

After the AG fault occurred in the fault location #2, the DFRs for line protection trip the fault signals in 4.003 s. As with the grid connected mode, to analyze the coordination of PDs, the trip command of the protection relays have been blocked during the fault and, thereby, the fault is continued. Feeder #1's NSC protection scheme trips at 4.073 s, then the OCR-THD and UVR employed in DGU #1 create trip signals at 4.150 s and 4.185 s. Subsequently, trip commands from Feeder #2, Bus #3, and DOCR of Feeder #1 send out their trip commands at  $t = 4.353$  s,  $t = 4.503$  s, and  $t = 6.352$  s, respectively.

It is worth highlighting that the proposed protection scheme works in the both grid-connected and islanded modes, without a mode switching procedure and recalculation. These validated features for both of the grid connected and islanded mode operation of MGs, as well as its comprehensiveness, specify the proposed protection scheme for practical applications as a comprehensive adaptive digital protection scheme.

**Table 4.** Simulation results under different fault conditions in island mode.

Fault Location: Fault Type	Fault #1		Fault #2		Fault #3	
	Main and Backup Relays	OT (s)	Main and Backup Relays	OT (s)	Main and Backup Relays	OT (s)
AG	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003	DFR Line #12 Trip	4.003
	Feeder #1 NSC Trip	4.073	Feeder #2 NSC Trip	4.124	Feeder #1 NSC Trip	4.083
	DGU Trip #1 (OCR-THD)	4.150	DGU Trip #1 (OCR)	4.181	DGU Trip #1 (OCR-THD)	4.152
	DGU Trip #1 (UVR)	4.185	Feeder #2 Trip	4.361	Feeder #2 Trip	4.352
	Feeder #2 Trip	4.353	Bus #3 Trip	4.505	Bus #3 Trip	4.512
	Bus #3 Trip	4.503				
	Feeder #1 DOCR Trip	6.325				
AB	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003	DFR Line #12 Trip	4.003
	Feeder #1 NSC Trip	4.073	Feeder #2 NSC Trip	4.123	Feeder #1 NSC Trip	4.083
	DGU Trip #1 (UVR)	4.150	DGU Trip #1 (OCR)	4.233	DGU Trip #1 (OCR-THD)	4.150
	DGU Trip #1 (OCR-THD)	4.183	Feeder #1 NSC Trip	4.358	Feeder #2 Trip	4.352
	Feeder #2 Trip	4.353	Bus #1 NSC Trip	4.504	Bus #3 Trip	4.510
	Bus #3 Trip	4.503				
	Feeder #1 DOCR Trip	5.669				
ABG	DFR Line #11 Trip	4.003	DFR Line #21 Trip	4.003	DFR Line #12 Trip	4.003
	Feeder #1 NSC Trip	4.073	Feeder #2 NSC Trip	4.123	Feeder #1 NSC Trip	4.083
	DGU Trip #1 (UVR)	4.150	DGU Trip #1 (OCR)	4.179	DGU Trip #1 (OCR-THD)	4.163
	DGU Trip #1 (OCR-THD)	4.183	Feeder #1 Trip	4.358	Bus #3 Trip	4.510
	Feeder #2 Trip	4.353	Bus #1 Trip	4.504	Feeder #2 Trip	4.523
	Bus #3 Trip	4.503				
	Feeder #1 DOCR Trip	5.335				

## 5. Conclusions

In this paper, a digital adaptive protection scheme for low voltage MGs was provided. In the proposed method, different protective digital relay schemes for different locations of MGs, such as the PCC, feeders, lines, and grid-forming droop based DGUs, were introduced and they have been coordinated through an adaptive scheme. The proposed adaptive scheme includes two steps. First, the offline step, as the first step of the proposed adaptive scheme, wherein all the settings are adopted for selective and sensitive fault detection, isolation, and coordination among proposed protective modules. Then, in an online procedure, any change in the system is detected, and thus a new set of setting for proposed modules will be performed to adapt the settings accordingly. The proposed digital protection modules covers various fault types, such as DOCR, NSC, THD, and UVR relays, which facilitates detecting various faults. Offline and online algorithms for adaptive setting and coordination of the proposed relays were developed. Due to its credible capability of the proposed method for operation in both of the grid-connected and islanded mode, it presents a free-mode switching feature, which is able to clear the faults from double sides as well as single phase faults. Protection modules for different nodes of the MG system were introduced as one of the main contributions, which results a reliable, selective, and coordinated protection, and facilitates detecting several types of faults, for grid-connected and islanded modes of the operation. In order to show the effectiveness of the proposed method, various simulations were performed. Simulation results show a safe, selective, reliable, and coordinated protection under several fault scenarios. The future of research mainly focuses on the convex optimization approaches to find a strict optimal point for the DOCR relays, as well as extending the proposed method for interconnected MGs with meshed topology.

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### Abbreviations

The following abbreviations are used in this manuscript:

CTI	Coordination time interval
DFR	Differential current-based relay
DGU	Distributed generation unit
DOCR	Directional over-current relay
DOCR-NSC	Directional over-current relay for negative sequence current
DOCR-THD	Directional over-current relay for total harmonic distortion
HIF	High impedance faults
ESSs	Energy storage systems
FRDFT	Fast recursive discrete Fourier transform
LVRT	low voltage ride-through.
MG	Microgrid
NSC	Negative sequence current
$\mu$ PMU	Micro-phasor measurement unit
OCR	Over-current relay
OT	Operating Time
PD	Protective device
PCC	Point of common coupling
PI	Proportional integral
PR	Proportional Resonant
PC	Primary control
RES	Renewable energy source
THD	Total harmonic distortion
TMS	Time multiple settings
TMF	Transient monitoring function
UVR	Under voltage relay
VSC	Voltage source converter

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