Protection of Networked Microgrids Using Relays With Multiple Setting Groups

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***Abstract*—The protection of multiple interconnected microgrids is a challenging task because of changes in the topology of the system. A microgrid can operate in an islanded mode or get connected to another autonomous microgrid or grid-connected microgrid or directly to the utility grid. The short-circuit currents can change widely because of the connection status of a microgrid in the system of multiple or networked microgrids. In this article, a novel setting groups based scheme is presented for the protection of networked microgrids using directional overcurrent relays. The developed scheme can provide adequate protection to all microgrids under all possible interconnection among the microgrids and utility grid. A vector is generated for each possible interconnection of microgrids in the system to categorize them into four groups using *k*-means clustering. The optimum settings of relays considering all operational aspects of each group are calculated using a nonlinear programming based algorithm. Based on the topological interconnections of microgrids in the system, one of the setting groups can be enabled using a low-bandwidth communication link. The proposed protection approach has been validated on a benchmark test system for networked microgrids. The suitability and the effectiveness of the developed settings of the relays have been analyzed adequately.**

***Index Terms*—Directional overcurrent relays (DOCRs), feeder reconfiguration, numerical relays, photovoltaic (PV) system, protection coordination.**

I. Introduction

HIGH penetration of renewable energy sources (RESs) to power distribution networks (DNs) is becoming a reality throughout the world, mainly because of no fuel cost, absence of harmful emissions, and worldwide availability [1]. According to the International Energy Agency report 2019, the renewable power capacity is set to expand by 50% between 2019–2024, led by solar photovoltaic (PV) power. The solar PV alone accounts for almost 60% of the expected growth, with onshore wind turbines (WTs) representing about 25%, and total addition is expected to be 1200 GW [2]. However, such a high penetration of distributed energy resources (DERs) in the existing system may cause several issues. System stability, coordinated control, and adequate protection coordination are some of the major challenges [3].

Networking of multiple self-governed microgrids (MGs) is emerging as one of the best alternatives to utilize locally available cost-effective and environment-friendly electric power generated from DERs [4]. It is more commonly known as networked MGs (NMGs). Advanced control and communication technologies enable the operation of multiple MGs with the DNs to supply day-to-day growing electrical energy requirements economically and efficiently. Networking of multiple MGs either to the grid or another grid-connected or isolated MG can enable a more resilient, reliable, and economic power supply to the consumers. During emergencies, multiple MGs may continue to supply energy to the critical loads for longer periods, depending on the capacity of the energy storage system of each MG, and help to restore supply quickly by providing black-start support to the conventional power stations [4]. Also, it can provide the opportunity for a competitive ancillary market [5]. The overall operation of the NMG system is performed through the energy management system (EMS), which is called NMG-EMS [1], [4], [5]. However, the successful operation of NMGs has several challenges. The development of a suitable protection coordination scheme is one of the major challenges to such networks [6].

Overcurrent protection is predominantly used for the protection of DNs [7]. The conventional protection schemes used for the protection of interconnected systems are not suitable in a system of MGs or multiple MGs [8]. In the literature, several studies have been presented to solve the issues related to the protection of MGs [9]. These studies suggest developing a more sophisticated protection scheme to tackle issues of islanded and grid-connected operation of MGs. Distance protection and line differential protection are mostly used for the protection of transmission networks [7]. The zone-1 reach of distance relays is to be set lower while protecting interconnected lines of short distance as it poses a higher source impedance ratio (SIR), which is defined as the ratio of source impedance to the line impedance at the relay location [10]. Any error in voltage transformer

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(VT) or capacitive VT further complicates the issue [11]. MGs often have short lines/cables and consequently higher values of SIR, which causes underreach issues with distance relays. Converter fed sources, widely used in MGs, often pose higher SIR. As a result, distance protection is not a very attractive choice for the protection of MGs [12]. Line differential relay is relatively a better choice as compared to the distance relay for the protection of MGs [12]. However, line differential protection does not provide backup protection, and its failure because of any reason can compromise the protection of MGs. On the other hand, directional overcurrent relays (DOCRs) based protection schemes have been widely studied for providing protection of MGs under different operating conditions [13]–[15].

For the protection of interconnected DNs with an MG, several studies have been presented [16]–[18]. In [16], the protection of MG using DOCRs with agent-based communication has been proposed. Proper coordination is dependent on a reliable communication link in this scheme. Also, intelligent electronic devices, synchrophasor, and supervisory control and data acquisition systems are required, which may make the overall scheme uneconomical for MGs of small size. In [17], protection coordination of DOCRs has been proposed for the protection of DN with the grid-connected and islanded mode of operation of MG by utilizing fault current limiter at the point of common coupling (PCC). In [18], an improved protection coordination scheme by utilizing dual-setting DOCRs has been discussed for the protection of DN with both grid-connected and islanded modes of MG operation without fault current limiter. A significant reduction in the overall operating time of primary and backup relays has been achieved in this article. However, in all these studies, only one MG has been considered, whereas NMGs may have several MGs [19]. Recently, a setting groups based protection scheme of DOCRs has been presented for the protection of meshed DNs in [20]. In this scheme, possible topologies have been clustered into three groups, and the settings of DOCRs have been developed for each one of them. One of the setting groups can be enabled through a communication link based on topological information of the network. This approach gives better protection coordination, which is suitable to power networks with high short-circuit current levels and grid-connected systems. However, directly applying the same approach to protect the NMG system is a challenging task. This is because of widely changing short-circuit current level from one configuration to another configuration in NMG system. The idea of setting groups can be extended for the protection of NMG systems.

From the aforementioned discussion, it is clear that the protection coordination issues of NMGs have not been fully addressed yet. A setting groups based DOCRs protection scheme can provide excellent protection coordination for meshed DNs with a change in possible topology. This scheme can be extended to the protection of NMGs. All possible interconnection of MGs in the system can be clustered into a few groups based on their short-circuit current levels. Subsequently, optimum settings of relays for these groups can be obtained by considering all possible operational aspects of the system in these groups. The major contributions of this article are as follows.

1) Introducing a new vector to represent each topology generated by the possible interconnection of MGs in the system for the *k*-means clustering algorithm.
2) Development of setting groups of DOCRs for protection of the NMG system considering all possible interconnection of MGs in the system.
3) Development of an overall setting group enabling framework for implementing the proposed protection scheme based on the interconnection status of MGs in the system.

The proposed protection scheme has been tested on the benchmark system of NMGs presented in [6]. The suitability and effectiveness of the proposed protection scheme have been demonstrated.

The rest of this article is organized as follows. Protection coordination issues of NMGs are discussed in Section II. The developed clustering approach is introduced in Section III. The proposed optimal protection scheme for setting groups is discussed in Section IV. Results and discussion are given in Section V. Finally, Section VI concludes this article.

II. Protection Issues With NMGs

DOCRs are said to coordinate well when coordination time interval (CTI) between the operating times of primary-backup relay pairs is more than a prespecified value. The CTI between the operating times of a relay pair is defined as follows:

$$\text{CTI} = t_{ob} - t_{op} \tag{1}$$

where t_{op} and t_{ob} are the operating times of primary and the corresponding backup relay, respectively.

The inverse definite minimum time type of DOCRs is predominantly used for protection of power distribution systems [21]. The operating time of a relay for a given value of fault current is dependent on its pickup current setting (PCS) and time multiplier setting (TMS). The operating time of a relay (primary/backup) is expressed as follows [21]:

$$t_{op} = \frac{0.14 \times \text{TMS}}{(I_F/\text{PCS})^{0.02} - 1} \tag{2}$$

where TMS is the time multiplier setting of the relay; PCS is the pickup current setting of the relay; and I_F is the fault current passing through the relay. The protection coordination status of a primary-backup relay pair is identified as follows:

1) $\text{CTI} \geq \text{MCT}$: coordination $holds$;
2) $\text{CTI} < \text{MCT}$: coordination $lost$.

Here, minimum coordination time (MCT) is the minimum time gap required between operating times of primary and its backup relay for proper coordination. The value of MCT lies within 0.2–0.3 s. In this study, 0.2 s has been considered as the value of the MCT.

Normally, there is no definite upper limit on CTI value for DOCRs' coordination. However, the value of CTI should not be very large because it may cause damage to the system if the primary relay fails to clear the fault. This simply indicates that the operating times of backup relays should not be very high and, thus, CTI values of all primary-backup relay pairs should be low but must be higher than MCT as discussed earlier.

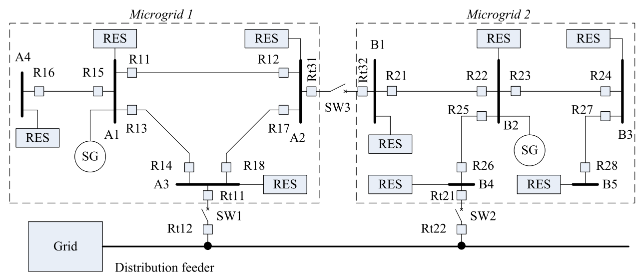

Fig. 1. Typical NMG system of two MGs.

TABLE I
CONNECTION STATUS OF NMG SYSTEM

Particular	Status of switches			Topological remarks
	SW1	SW2	SW3	
Case 1	OFF	OFF	OFF	Islanded MGs
Case 2	ON	OFF	OFF	MG1 grid-connected and MG2 islanded
Case 3	OFF	ON	OFF	MG2 grid-connected and MG1 islanded
Case 4	OFF	OFF	ON	Islanded but interconnected MGs
Case 5	ON	ON	OFF	Individually grid connected MGs
Case 6	ON	OFF	ON	Grid-connected MGs through MG1
Case 7	OFF	ON	ON	Grid-connected MGs through MG2
Case 8	ON	ON	ON	Fully meshed grid-connected MGs

To achieve this task, both inverse time element (i.e., 51) and instantaneous/definite time element (i.e., 50) should be used. The inverse time element will work as per the optimum settings, whereas the instantaneous/definite time element will work on the same PCS as the backup relay but with a time delay of no more than 1.5 s. The actual operating time of element 50 of the backup relay can be set as per its primary relay so that the MCT requirements are never violated.

Proper protection coordination is one of the key requirements to run NMGs with high reliability. Change in the network topology may be frequent in such systems, which causes protection coordination issues. The magnitude and direction of fault currents can be different in various topologies of the system. Widely varying fault current is one of the main reasons for such issues. It can be understood through an example.

A. Example of NMG System

Let us consider a typical NMG system shown in Fig. 1. This system consists of two MGs and a distribution feeder through which these MGs can be connected to the grid. All buses of these MGs get power from the locally available RES. There is a synchronous generator (SG) in each MG to provide power balance and load-frequency control during extreme events [22]. There are three switches to enable the connection of MGs among themselves and with the DN. The total number of possible topologies in the NMG system is obtained using the following equation as discussed in [1]:

$$P_T = 2^{N_{\mathrm{TSW}}} \quad (3)$$

where N_{TSW} is the total number of switches or PCCs and P_T is the total number of possible topologies. MGs can be connected to each other through switches, which are typically known as PCC. This topological information of the NMG system of the two MGs with the DN is given in Table I.

TABLE II
FAULT CURRENT PATTERNS IN NMG SYSTEM

Particular	Relay pair (Primary-backup)	Fault currents		Remarks
		Primary	Backup	
Fig. 2(a), Fault 1	$R17 - R11$	$I_{a,R17}$	$I_{a,R11}$	–
Fig. 2(a), Fault 1	$R18 - R13$	$I_{a,R18}$	$I_{a,R13}$	–
Fig. 2(a), Fault 2	$R27 - R23$	$I_{a,R27}$	$I_{a,R23}$	–
Fig. 2(b), Fault 1	$R17 - R11$	$I_{b,R17}$	$I_{b,R11}$	$I_{b,R17} > I_{a,R17}$
Fig. 2(b), Fault 1	$R17 - Rt32$	$I_{b,R17}$	$I_{b,M2M1}$	Relay pair to MG2
Fig. 2(b), Fault 1	$R18 - R13$	$I_{b,R18}$	$I_{b,R13}$	–
Fig. 2(b), Fault 2	$R27 - R23$	$I_{b,R27}$	$I_{b,R23}$	$I_{b,R27} > I_{a,R27}$
Fig. 2(c), Fault 1	$R17 - R11$	$I_{c,R17}$	$I_{c,R11}$	–
Fig. 2(c), Fault 1	$R18 - R13$	$I_{c,R18}$	$I_{c,R13}$	$I_{c,R18} >> I_{a,R18}$
Fig. 2(c), Fault 1	$R18 - Rt12$	$I_{c,R18}$	$I_{c,M1}$	Relay pair to feeder and MG1
Fig. 2(c), Fault 2	$R27 - R23$	$I_{c,R27}$	$I_{c,R23}$	$I_{c,R27} >> I_{a,R27}$
Fig. 2(d), Fault 1	$R17 - R11$	$I_{d,R17}$	$I_{d,R11}$	$I_{d,R17} > I_{a,R17}$
Fig. 2(d), Fault 1	$R17 - Rt32$	$I_{d,R17}$	$I_{d,M2M1}$	Relay pair to MG2
Fig. 2(d), Fault 1	$R18 - R13$	$I_{d,R18}$	$I_{d,R13}$	$I_{d,R18} >> I_{a,R18}$
Fig. 2(d), Fault 1	$R18 - Rt12$	$I_{d,R18}$	$I_{d,M1}$	Relay pair to feeder and MG1
Fig. 2(d), Fault 2	$R27 - R23$	$I_{d,R27}$	$I_{d,R23}$	$I_{d,R27} >> I_{a,R27}$

From Table I, it is observed that there are some cases when one or more MGs are islanded, whereas in some cases, they are connected to the grid. Additionally, in Case 4, MGs are interconnected but islanded. All these topologies of the NMG system can have different types of protection coordination issues because the fault current pattern would be completely diverse when network topology gets changed.

B. Fault Currents Under Different Network Topologies

Fig. 2 shows four different NMG topologies selected from Table I. Two potential fault locations (one in each MG) are shown in various subfigures. Various fault currents passing through the responsible protective relays are indicated on them under that particular topology.

Faults under different network topologies result in widely varying magnitude of fault currents in any primary-backup relay pair as can clearly be observed from Table II. The fault currents passing through relay pairs $R17 - R11$, $R18 - R13$, and $R27 - R23$ in Fig. 2(a) are quite small because the short-circuit MVA of individual MGs are small. The same in Fig. 2(b) are relatively higher because of the interconnection of two MGs. On the other hand, in Fig. 2(c) and (d), the fault current passing through these relay pairs is very high because of the integration of MGs to the main grid. Additionally, the relay pair $R17 - Rt32$ because of the interconnection of the two MGs, and relay pair $R18 - Rt12$ because of the interconnection of MG1 to the distribution feeder for fault F1, as shown in Fig. 2, should also be considered for protection coordination. The remarks column of Table II indicates these observations. This widely varying magnitude of fault currents under different network topologies requires protective relays to adapt accordingly to provide adequate protection to the entire system. Different topologies of NMGs can be categorized into a few groups based on the magnitude of fault currents and settings of the relays can be provided for each group.

However, the classification of different topologies in a suitable number of groups is again a challenging task. The magnitude of various fault currents passing through the relays should be closer to each other in all the topologies of any classified group. These groups can also be termed clusters.

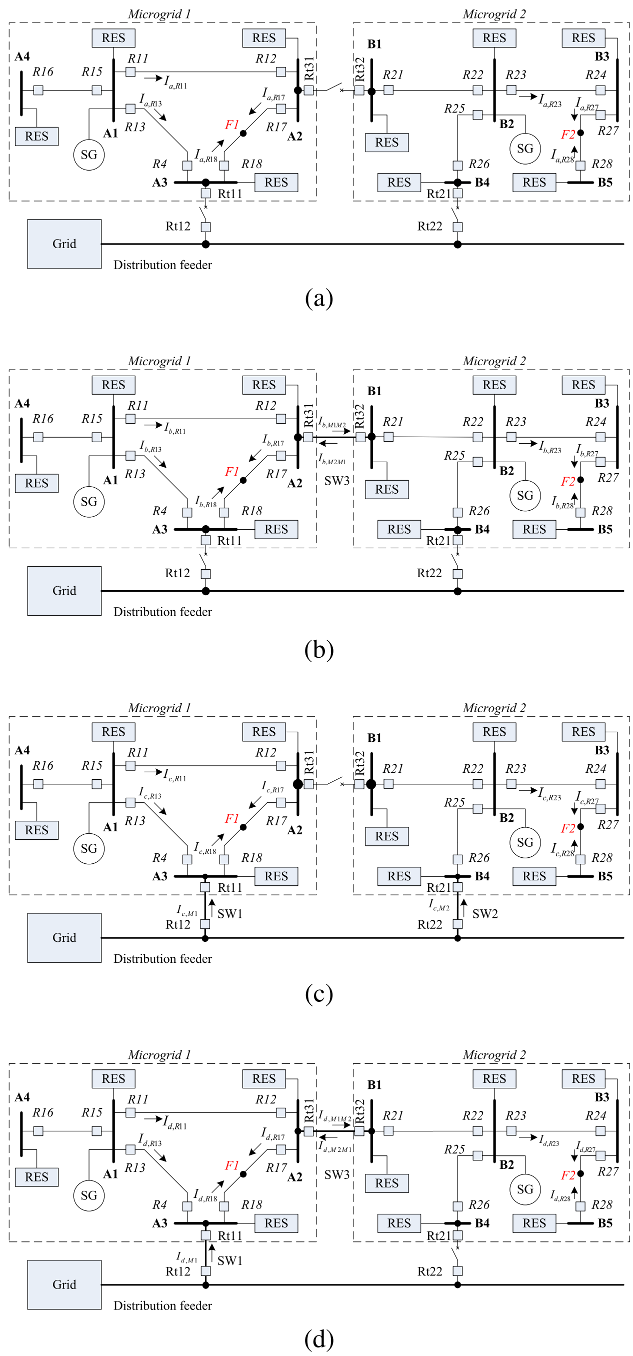

Fig. 2. Some possible topologies of NMG system, as mentioned in Table I. (a) Case 1. (b) Case 4. (c) Case 5. (d) Case 6.

III. Clustering of Topologies

One of the most widely adopted techniques for the classification of data into groups is k-means clustering. The algorithm of this technique is based on the minimization of the Euclidean distance between the center of a cluster and data points [23].

Selection of a data point that represents an NMG topology for the protection coordination issues is very important. Change in the maximum fault currents passing through each relay under different topologies is the key that causes miscoordination. Also, drastic changes in the magnitude of fault currents passing through each primary-backup relay pair under different topologies are observed, as mentioned in Table II. In this article, for clustering topologies into groups, each data point consists of the information regarding the maximum value of fault current passing through each relay and the values of fault currents passing through each relay pair in a given topology. A vector is formed with these fault current details corresponding to each NMG topology. It is named as topology fault current vector (TFCV) and defined as follows:

$$\text{TFCV}^k = [\mathbf{I}^k_{f\text{max}}, \mathbf{I}^k_{f\text{prim}}, \mathbf{I}^k_{f\text{back}}] \qquad (4)$$

where $\mathbf{I}^k_{f\text{max}}$ is the current vector of the maximum fault current passing through all the relays in kth topology; $\mathbf{I}^k_{f\text{prim}}$ and $\mathbf{I}^k_{f\text{back}}$ are near-end fault current vectors passing through all the primary and backup relays, respectively, in kth topology; and TFCV^k represents the kth topology of NMG system.

In this article, k-means clustering has been used to classify various topologies of the NMG system into a few groups. The effectiveness of clustered topologies has been checked by performing a silhouette plot [23]. The silhouette value ranges from -1 to $+1$. A high silhouette value indicates that a data point is well-matched to its own cluster and poorly matched to the neighboring clusters. The number of groups or clusters should be less than or equal to the number of setting groups allowed in the DOCRs. Modern numerical types of DOCRs may accept 2, 3, 4, or 8 setting groups [20]. The total number of setting groups considered in the presented scheme is 4. Depending on the network topology, one of these setting groups can be enabled through a low-bandwidth communication link.

IV. Proposed Optimal Protection Scheme for Setting Groups

The optimum settings of DOCRs need to be determined for all four groups. Here, the major task is to obtain values of TMS and PCS of DOCRs suitable for proper protection coordination under all the topologies considered in each group. This can be done by considering all the primary-backup relay pairs of all the topologies of a group so that the obtained optimum values of TMS and PCS can coordinate properly in these topologies. The objective function (OF) and constraints of this protection coordination problem are discussed in the next section.

A. Formulation of the Coordination Problem

Protection coordination problem of DOCRs for obtaining setting groups can be formulated for minimizing the summation of the operating times of all the relays while maintaining CTI between all possible primary-backup relay pairs of the considered topologies of the group. Mathematically, this problem can be expressed as [9]

$$\text{OF} = \min \sum_{k=1}^{T_N} \left(\sum_{i=1}^{m} \left(t_{op,ii,k} + \sum_{j=1}^{n_{i,k}} t_{ob,ij,k} \right) \right). \quad (5)$$

Subject to

$$t_{ob,ij,k} - t_{op,ii,k} \geq \text{MCT} \quad (6)$$

$$\text{PCS}_{i,\min} \leq \text{PCS}_i \leq \text{PCS}_{i,\max} \quad (7)$$

$$\text{TMS}_{i,\min} \leq \text{TMS}_i \leq \text{TMS}_{i,\max} \quad (8)$$

where m is the number of relays in the NMG system; T_N is the total number of possible topologies in the considered group of the system; $n_{i,k}$ is the number of backup relays for primary relay R_i in kth topology; $t_{op,ii}$ is the operating time of primary relay R_i in kth topology; $t_{ob,ij}$ is the operating time of backup relay R_j for relay R_i in kth topology; $\text{PCS}_{i,\min}$ is the lower limit on PCS of relay R_i; $\text{PCS}_{i,\max}$ is the upper limit on PCS of relay R_i; $\text{TMS}_{i,\min}$ is the lower limit on TMS of relay R_i; $\text{TMS}_{i,\max}$ is the upper limit on TMS of relay R_i; and MCT is the specified CTI requirement for proper coordination. $t_{op,ii}$ and $t_{ob,ij}$ are defined as follows:

$$t_{op,ii} = \frac{0.14 \times \text{TMS}_i}{(I_{F,ii}/\text{PCS}_i)^{0.02} - 1} \quad (9)$$

$$t_{ob,ij} = \frac{0.14 \times \text{TMS}_j}{(I_{F,ij}/\text{PCS}_j)^{0.02} - 1} \quad (10)$$

where $I_{F,ii}$ is the fault current passing through the primary relay R_i and $I_{F,ij}$ is the fault current passing through its backup relay R_j when the three-phase fault is at the middle of the line protected by the relay R_i.

In this article, all the DOCRs are considered to be allowing multiple setting groups, which can be enabled using a suitable communication link from the NMG control center. The lower and upper limits of TMS are considered in the range of [0.1, 1.1], whereas the lower and upper limits of PCS are calculated in terms of multiplication factors of CT secondary rating using the following equations:

$$\text{PCS}_{\min} = \max(0.25, 1.25 \times I_{L\max}/\text{CTR}) \quad (11)$$

$$\text{PCS}_{\max} = \min(2.00, 0.67 \times I_{f\min}/\text{CTR}) \quad (12)$$

where $I_{L\max}$ is the maximum load current, $I_{f\min}$ is the minimum fault current, and CTR is the current transformer (CT) ratio of the associated CT to the relay.

There are some primary-backup relay pairs in which backup relays may have much lesser fault currents passing through them relative to the corresponding primary relays. Such pairs always satisfy the MCT requirement. Such pairs need to be removed while solving the above-formulated protection coordination problem because they put an extra burden on the solver. These relay pairs satisfy the following condition:

$$I_{f\text{back}} < \max(2 \times I_{L\max}, I_{f\min}) \quad (13)$$

where $I_{f\text{back}}$ is the fault current passing through the backup relay of the primary-backup relay pair under consideration.

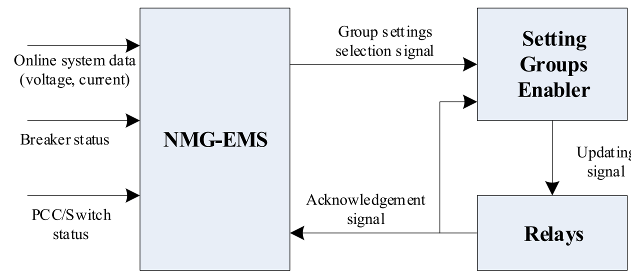

Fig. 3. Setting groups based protection scheme.

It is to be noted that (11)–(13) take care of the issues associated with the minimum fault current and the maximum load current in the proposed study. The selection of boundary limits on PCS is very important while protecting NMG systems because pickup current plays a crucial role to distinguish between a fault and overloading condition.

B. Selection of Current Transformer Ratio

The CT ratio is mostly selected based on the maximum load current. However, as the fault currents are on the rise in the grid-connected mode of NMGs because of additional current contributions from the DERs, CT saturation is possible during three-phase faults. To avoid CT saturation, its primary rating can be fixed based on the maximum load current and the maximum possible short-circuit current that can flow through it, as suggested in [21]. The primary side rating of the CT required for relay R_i is selected as the next higher standard value of CTP_i, which is calculated as

$$\text{CTP}_i = \max\left(I_{L\max,i}, \frac{I_{f\max,i}}{20}\right) \quad (14)$$

where $I_{L\max,i}$ is the maximum load current and $I_{f\max,i}$ is the three-phase fault current passing through relay R_i calculated under all possible topologies. Now, the ratio of the CT associated with relay R_i is equal to $\text{CTP}_i : 1$. It is assumed that all the CTs are of C100 class and these CT ratios remain constant.

C. Overall Protection Philosophy

Fig. 3 shows the overall setting groups based protection philosophy proposed for the protection of the NMG system. The real-time NMG system information is continuously received at the NMG-EMS center. This information includes system states, generation and load data, breaker status, and PCC/switch status. Based on topological information, NMG-EMS sends suitable setting group selection commands to the setting group enabler block, which has all the setting group enabling commands. After that, the setting group block sends updating signals to all the relays to enable a particular setting group. The relays, after enabling the selected setting group, acknowledge the settings information to NMG-EMS and setting groups enabler. From the control center, only one setting group of relays is enabled at a time to protect the system using a communication link from the control center to each relay. This adaptive protection

Algorithm 1: Setting Group Updating Strategy.

Result: Update setting group
initialize one setting group;
while *Once new data arrived at NMG-EMS* **do**
    Estimate network topology and inform to Setting Group Enabler;
    if *Topology is not within the enabled setting group* **then**
        identify correct setting group;
        select settings of relays of this setting group;
        send setting update signal to all relays;
        acknowledge to NMG-EMS and the Enabler;
    else
        no action (existing setting group retained);
    end
end

strategy is reliable and inexpensive as modern numerical relays are well-equipped with such facilities.

For proper operation of the NMG system, NMG-EMS continuously monitors and controls all the critical components of the system through a very reliable communication network. However, for implementing the proposed protection scheme, just an additional low bandwidth communication link is required for changing setting groups. This is because setting groups need to be changed only when system operating topology changes from one cluster to another cluster, which is relatively less frequent.

Settings of the relays from the existing setting group to another setting group are only changed once the latest network topology does not fall in the topology list of the cluster of the existing setting group. Setting group updating strategy in algorithm form is mentioned here to assist the overall understanding of the proposed scheme.

It is to be noted that the optimum setting calculation is an offline study. The appropriate number of setting groups are identified and the optimum settings of relays for each setting group are obtained using all topological and system details. Communication link does not have any role in obtaining optimum setting of the relays on a real-time basis. In the case of any communication failure, the existing settings of the relays will continue to protect the system. If faults occur to a few selected locations during this period, where setting group change was supposed to be required, there may be some possibility of miscoordination in a few primary-backup pairs in case of failure of their primary relays. Once the communication link is established, the required setting group can be enabled and the possibility of any such miscoordination can be nullified.

D. Solution Approach

The protection coordination problem formulated in the section is twice-continuously differentiable. Therefore, an analytical optimization method can solve this problem. In this article, the *interior-point* algorithm under $fmincon$ solver in MATLAB environment has been used to solve the developed optimum protection coordination problem of DOCRs. Simulation works have been performed on a personal computer of the Intel Core-2 Duo processor with 2-GB RAM and 2.67-GHz clock frequency.

TABLE III
TOPOLOGIES OF THE BENCHMARK TEST SYSTEM

Particular	PCC status					Topology indexing	
	PCC1	PCC2	PCC3	PCC4	PCC5	OFF-grid	ON-grid
1	OFF	OFF	OFF	OFF	OFF	1	33
2	OFF	OFF	OFF	OFF	ON	2	34
3	OFF	OFF	OFF	ON	OFF	3	35
4	OFF	OFF	OFF	ON	ON	4	36
5	OFF	OFF	ON	OFF	OFF	5	37
6	OFF	OFF	ON	OFF	ON	6	38
7	OFF	OFF	ON	ON	OFF	7	39
8	OFF	OFF	ON	ON	ON	8	40
9	OFF	ON	OFF	OFF	OFF	9	41
10	OFF	ON	OFF	OFF	ON	10	42
11	OFF	ON	OFF	ON	OFF	11	43
12	OFF	ON	OFF	ON	ON	12	44
13	OFF	ON	ON	OFF	OFF	13	45
14	OFF	ON	ON	OFF	ON	14	46
15	OFF	ON	ON	ON	OFF	15	47
16	OFF	ON	ON	ON	ON	16	48
17	ON	OFF	OFF	OFF	OFF	17	49
18	ON	OFF	OFF	OFF	ON	18	50
19	ON	OFF	OFF	ON	OFF	19	51
20	ON	OFF	OFF	ON	ON	20	52
21	ON	OFF	ON	OFF	OFF	21	53
22	ON	OFF	ON	OFF	ON	22	54
23	ON	OFF	ON	ON	OFF	23	55
24	ON	OFF	ON	ON	ON	24	56
25	ON	ON	OFF	OFF	OFF	25	57
26	ON	ON	OFF	OFF	ON	26	58
27	ON	ON	OFF	ON	OFF	27	59
28	ON	ON	OFF	ON	ON	28	60
29	ON	ON	ON	OFF	OFF	29	61
30	ON	ON	ON	OFF	ON	30	62
31	ON	ON	ON	ON	OFF	31	63
32	ON	ON	ON	ON	ON	32	64

V. RESULTS AND DISCUSSION

The proposed setting groups based protection scheme has been utilized to provide proper protection to a benchmark test system for NMG consisting of four MGs. Fig. 4 shows the NMG benchmark test system whose details are available in [6]. This test system has five PCCs to interconnect all four MGs. Additionally, this NMG system can be connected to the utility grid through MG1. Thus, it can be operated in 64 different topologies of which OFF-grid and ON-grid topologies are 32 each. Topological details are given in Table III.

There are 40 buses and 44 power cables in the system. Interconnecting cables (PCCs) make the overall power cable number to 49. For proper protection of this NMG system, a total of 98 (two for each cable) DOCRs are required. Additionally, there is a need for six more relays that are to be placed at the terminal of each SG and the two ends of the interconnecting cable of MG1 to the utility grid. These relays have been shown in Fig. 4. The number of primary-backup relay pairs in the system is 187, whose details are given in Table IV. It is to be noted that the direction of relays are set toward the line/cable being protected and the relays can correctly identify the fault direction in the system, as discussed in [8], [24]–[26]. Fault direction identification is out of scope of this article.

A. Various Current Calculations and CT Ratios

Maximum load current calculations have been performed using the Newton–Raphson load flow method. Short-circuit current calculations have been performed using the Z_{bus} matrix approach [17], [27], [28]. Maximum fault current calculations have been performed considering bolted three-phase fault, whereas

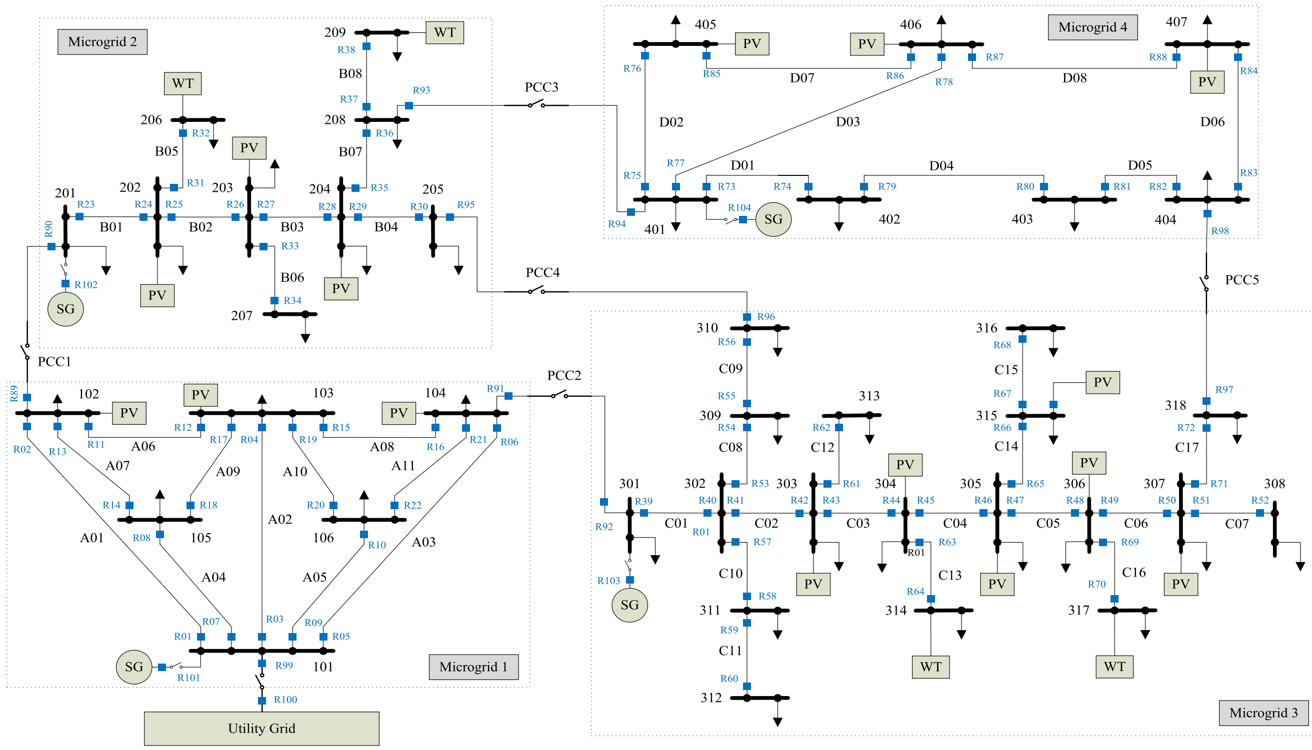

Fig. 4. Benchmark test system for NMGs [6].

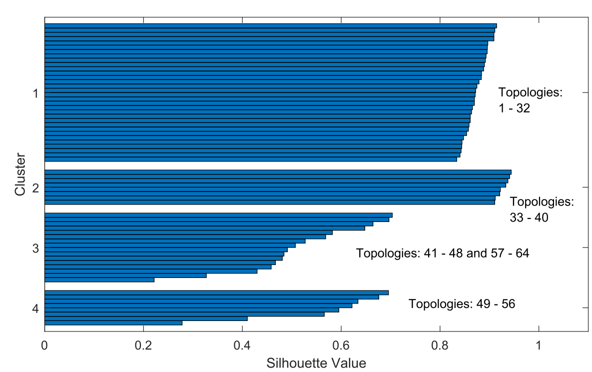

Fig. 5. Clusters of topologies of the benchmark test system.

the minimum fault current calculations have been performed using phase-phase fault considering only one SG in each MG. The short-circuit level of each SG is considered five times their maximum generation limit [17]. On the other hand, the short-circuit level of each WT and PV system is considered as 2 and 1.5 times, respectively, of their maximum generation limits [29], [30]. These sources have been incorporated in the Z_{bus} matrix as shunt elements connected to the associated node in such a way that these will contribute to the fault in the system by their mentioned short-circuit capacity [17], [28]. It is assumed that both PV and WT are working in grid-following mode at their peak power generation points. The considered WT is a type 4 doubly-fed induction generator. The detailed control strategy of these sources can be found in [6]. While calculating various load and fault currents, the intermittent nature of these sources has been ignored. The short-circuit strength of the utility grid is considered 300 MVA. Load flow and short-circuit current calculations have been performed for all the topologies of the NMG system.

Once various load and fault current details are obtained, the required CT can be calculated using (14). For this benchmark test system, CT details are given in Table V.

B. Optimum Setting Groups

The benchmark test system has 32 topologies without the utility grid and 32 topologies in the grid-connected mode of MG1. All these topologies are given in Table III. Topology indexing from 1–32 consists of all possible 32 topologies among the 5 PCCs without considering grid connection to MG1, whereas topology indexing from 33–64 consists of the same 32 topologies among the 5 PCCs with the integration of MG1 to the utility grid. All the 64 topologies have been categorized into four groups using *k*-means clustering discussed in Section III. Fig. 5 shows the silhouette plot of the clustered topologies for the considered benchmark test system of NMGs. Furthermore, Table VI gives details about these groups, topological information, and setting group names for each group of DOCRs in the system.

The larger silhouette value of topology, as shown in Fig. 5, indicates its closeness to the cluster. From Fig. 5 and Table VI, it is clear that the total number of topologies under clusters termed as Group 1, Group 2, Group 3, and Group 4 are 32, 8, 16, and 8, respectively, whose topology indices are given in the

TABLE IV
PRIMARY-BACKUP RELAY PAIRS IN THE BENCHMARK TEST SYSTEM

Fault zone	Primary relay	Backup relay	Fault zone	Primary relay	Backup relay
A01	1	4, 6, 8, 10, 100, 101	C04	45	43, 64
	2	12, 14, 90		46	48, 66
A02	3	2, 6, 8, 10, 100, 101	C05	47	45, 66
	4	11, 16, 18, 20		48	50, 70
A03	5	2, 4, 8, 10, 100, 101	C06	49	47, 70
	6	15, 22, 92		50	52, 72
A04	7	2, 4, 6, 10, 100, 101	C07	51	49, 72
	8	13, 17		52	–
A05	9	2, 4, 6, 8, 100, 101	C08	53	39, 42, 58
	10	19, 21		54	56
A06	11	1, 14, 90	C09	55	53
	12	3, 16, 18, 20		56	95
A07	13	1, 12, 90	C10	57	39, 42, 54
	14	7, 17		58	60
A08	15	3, 11, 18, 20	C11	59	57
	16	5, 22, 92		60	–
A09	17	3, 11, 16, 20	C12	61	41, 44
	18	7, 13		62	–
A10	19	3, 11, 16, 18	C13	63	43, 46
	20	9, 21		64	–
A11	21	5, 15, 92	C14	65	45, 48
	22	9, 19		66	68
B01	23	89, 102	C15	67	65
	24	26, 32		68	–
B02	25	23, 32	C16	69	47, 50
	26	28, 34		70	–
B03	27	25, 34	C17	71	49, 52
	28	30, 36		72	98
B04	29	27, 36	D01	73	76, 78, 93, 104
	30	96		74	80
B05	31	23, 26	D02	75	74, 78, 93, 104
	32	–		76	86
B06	33	25, 28	D03	77	74, 76, 93, 104
	34	–		78	85, 88
B07	35	27, 30	D04	79	73
	36	38, 94		80	82
B08	37	35, 94	D05	81	79
	38	–		82	84, 97
C01	39	91, 103	D06	83	81, 97
	40	42, 54, 58		84	87
C02	41	39, 54, 58	D07	85	75
	42	44, 62		86	77, 88
C03	43	41, 62	D08	87	77, 85
	44	46, 64		88	83

TABLE V
CT RATIOS OF DOCRS OF THE BENCHMARK TEST SYSTEM

CT Ratio	Relay No.
1200:1	1,3,5,7,9,89,91,99,100
1000:1	12,15,23
900:1	4,11,14,16,17,19,22,25,31,39,41,53,57
800:1	2,6,8,10,13,18,20,21,27,29,33,35,37,43,45,47,49,55,61,63,95,101
600:1	30,51,54,56,59,65,69,71,73,75,77,93,96,97
500:1	28
450:1	67,79,83,86,90,92,98
400:1	24,26,40,72,78,80,82,85,87,88,94,102,103
300:1	36,46,48,50,81,84
250:1	42,44,74,104
200:1	76
50:1	32,34,38,52,58,60,62,64,66,68,70

TABLE VI
SETTING GROUPS FOR THE BENCHMARK TEST SYSTEM

Setting Groups	NMG Topology	DOCRs settings
Group 1	1–32	MG1-SG1, MG2-SG1, MG3-SG1, MG4-SG1
Group 2	32–40	MG1-SG2, MG2-SG2, MG3-SG2, MG4-SG2
Group 3	41–48, 57–64	MG1-SG3, MG2-SG3, MG3-SG3, MG4-SG3
Group 4	49–56	MG1-SG4, MG2-SG4, MG3-SG4, MG4-SG4

second column of Table VI. The optimum settings of DOCRs for different setting groups are named in the last column of Table VI. Here, MG1-SG1, MG2-SG1, MG3-SG1, and MG4-SG1 are the setting group of DOCRs for all the topologies categorized in Group 1. Similarly, MG1-SG2, MG2-SG2, MG3-SG2, and MG4-SG2 are the setting group of DOCRs for all the topologies categorized in Group 2, etc.

The total number of primary-backup relay pairs in Group 1 is 5984 and in Group 3 is 2992, whereas that in Group 2 and Group 4 is 1496 each. These relay pairs are associated with the coordination constraints of their groups. Therefore, there is a large number of coordination constraints in each of these groups,

TABLE VII
OPTIMUM SETTINGS OF DOCRS FOR MG1

Relays	MG1-SG1		MG1-SG2		MG1-SG3		MG1-SG4	
	TMS	PCS	TMS	PCS	TMS	PCS	TMS	PCS
1	0.1309	0.4219	0.2334	0.25	0.2124	0.3587	0.1389	0.7945
2	0.1036	0.4912	0.1	0.25	0.1253	0.3827	0.1	0.25
3	0.1	0.25	0.1091	1.005	0.1122	1.0029	0.1142	1.005
4	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
5	0.1304	0.4156	0.2322	0.25	0.1941	0.4156	0.1275	1.1881
6	0.1309	0.3374	0.1	0.25	0.1	0.25	0.1553	0.2652
7	0.1	0.739	0.2803	0.25	0.1287	1.4411	0.1363	1.2685
8	0.1	0.5233	0.1	0.25	0.1	0.25	0.1	0.4889
9	0.1	0.7119	0.2783	0.25	0.129	1.4194	0.1272	1.5377
10	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
11	0.1177	0.5913	0.1	0.7831	0.1133	1.0713	0.1	1.0277
12	0.1292	0.5526	0.169	0.5651	0.1355	1.022	0.1362	0.9
13	0.1	1.0115	0.1263	1.005	0.1024	1.8509	0.1	1.4456
14	0.1	0.8492	0.1449	0.687	0.1277	1.2566	0.1344	1.005
15	0.1	0.771	0.1707	0.5473	0.1498	0.817	0.1097	1.5263
16	0.1106	0.64	0.1	0.7797	0.1063	1.0631	0.1532	0.6519
17	0.1	0.9213	0.1386	1.005	0.1124	1.8217	0.1255	1.5105
18	0.1	0.811	0.1866	0.498	0.1248	1.2728	0.1134	1.2742
19	0.1	0.9197	0.1386	1.005	0.1116	1.8261	0.1	1.9903
20	0.1	0.7326	0.1801	0.5387	0.121	1.2856	0.1464	1.005
21	0.1	0.968	0.1251	1.005	0.1	1.7225	0.1419	1.1943
22	0.1	0.8364	0.1447	0.6891	0.1242	1.2641	0.1098	1.7234

TABLE VIII
OPTIMUM SETTINGS OF DOCRS FOR MG2

Relays	MG2-SG1		MG2-SG2		MG2-SG3		MG2-SG4	
	TMS	PCS	TMS	PCS	TMS	PCS	TMS	PCS
23	0.2559	1.1	0.3536	0.4538	0.2444	2	0.2342	2
24	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
25	0.2094	1.15	0.2221	0.8484	0.1973	2	0.1884	2
26	0.132	1.2386	0.1	1.2027	0.1394	1.2708	0.1573	1.0856
27	0.1591	1.2483	0.2731	0.2844	0.1513	2	0.1432	2
28	0.2835	0.3875	0.2288	0.3973	0.2991	0.3875	0.3522	0.25
29	0.1	1.0156	0.1	0.25	0.1	0.25	0.1	1.0156
30	0.2289	1.0771	0.2664	0.431	0.266	1.0771	0.4514	0.25
31	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
32	0.1	0.675	0.1	0.675	0.1	0.675	0.1	0.675
33	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
34	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
35	0.1218	1.0063	0.1946	0.25	0.1806	0.4859	0.1	1.7318
36	0.3133	1.0458	0.4215	0.25	0.3101	1.0458	0.5307	0.25
37	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
38	0.1	0.375	0.1	0.375	0.1	0.375	0.1	0.375

which puts a huge burden on the solver while solving the formulated problem of protection coordination. The coordination constraint reduction strategy mentioned in [31] has been adopted in this article. This approach limits the number of coordination constraints within $4 \times N$ critical set of constraints, where N is the number of coordination constraints in one topology. Thus, the maximum number of coordination constraints in each setting group is limited to 748. These numbers further goes down by adopting (13). The optimum settings of DOCRs of all the four groups are given in the next section.

C. Discussion of Results

The optimum settings of DOCRs obtained for setting groups using the proposed approach for the NMG system are given in Tables VII–XI. While calculating the optimum settings of the DOCRs for each cluster, all primary-backup relay pairs of that cluster have been considered to ensure that all the primary-backup relay pairs are coordinating properly once the optimum solution is obtained. These tables give the optimum setting groups information of TMS and PCS of DOCRs for all four MGs. Furthermore, the operating times of primary-backup relay pairs for the critical values of fault currents and their corresponding CTI for each setting group are shown in Fig. 6.

The optimum values of TMS and PCS of DOCRs given in Table VII under different setting groups are adequate to protect MG1 under all possible interconnections to the outside network

TABLE IX
OPTIMUM SETTINGS OF DOCRS FOR MG3

Relays	MG3-SG1		MG3-SG2		MG3-SG3		MG3-SG4	
	TMS	PCS	TMS	PCS	TMS	PCS	TMS	PCS
39	0.3726	1.2028	0.4963	0.5556	0.3703	2	0.5885	0.5556
40	0.1	0.2594	0.1	0.2594	0.1	0.2594	0.1	0.2594
41	0.3501	0.9986	0.4986	0.3583	0.418	0.9986	0.3857	1.1072
42	0.3118	0.91	0.1	1.9498	0.4219	0.485	0.1299	2
43	0.2444	1.5508	0.4359	0.3328	0.3074	1.4538	0.2521	2
44	0.3748	1.04	0.1365	2	0.5605	0.405	0.1788	2
45	0.1665	2	0.281	0.5824	0.2074	2	0.1959	2
46	0.4391	0.9417	0.1554	2	0.7304	0.2542	0.2033	2
47	0.1286	2	0.1647	0.9658	0.1564	2	0.1435	2
48	0.4814	1.125	0.1958	2	0.8637	0.25	0.2507	2
49	0.1	1.8512	0.1234	0.7433	0.1098	2	0.1	1.8613
50	0.5635	1.0625	0.2359	2	0.9928	0.25	0.2997	2
51	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
52	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
53	0.1626	0.8597	0.1985	0.25	0.1796	0.8597	0.1715	0.5831
54	0.3878	1.1375	0.1237	1.5968	0.8531	0.25	0.1	1.1375
55	0.1	0.925	0.1	0.25	0.1	0.925	0.1	0.25
56	0.4318	1.1958	0.1237	1.8805	0.9704	0.25	0.1	1.1958
57	0.1	1.1794	0.188	0.25	0.2026	0.25	0.2042	0.25
58	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
59	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
60	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
61	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
62	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
63	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
64	0.1	0.45	0.1	0.45	0.1	0.45	0.1	0.45
65	0.1	1.5251	0.2	0.25	0.1561	0.6423	0.2118	0.25
66	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
67	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
68	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
69	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
70	0.1014	1.34	0.1	1.1	0.1456	1.1	0.1	1.1805
71	0.1	1.2167	0.1	0.25	0.1	1.2167	0.1	0.6
72	0.5852	0.9938	0.2502	1.8346	1.0512	0.25	0.303	2

TABLE X
OPTIMUM SETTINGS OF DOCRS FOR MG4

Relays	MG4-SG1		MG4-SG2		MG4-SG3		MG4-SG4	
	TMS	PCS	TMS	PCS	TMS	PCS	TMS	PCS
73	0.3575	1.0328	0.339	0.9858	0.403	2	0.4385	1.1631
74	0.3043	1.13	0.3331	1.2944	0.6469	1.13	0.3965	1.7554
75	0.2774	0.7604	0.5196	0.25	0.5065	0.9463	0.464	0.7196
76	0.2895	0.8536	0.2813	0.8068	0.8122	0.31	0.4016	1.005
77	0.1574	1.8533	0.3607	0.8479	0.3505	2	0.2607	2
78	0.2049	0.8773	0.2193	0.5949	0.4581	0.6185	0.3101	1.005
79	0.2424	2	0.2212	2	0.4005	2	0.3288	2
80	0.1933	2	0.2588	1.4187	0.4134	2	0.3253	2
81	0.2612	2	0.2446	1.8588	0.4363	2	0.3576	2
82	0.2974	1.3783	0.3646	1.056	0.7117	0.8281	0.741	0.3375
83	0.286	0.7806	0.2914	0.5529	0.4891	0.7806	0.5217	0.3889
84	0.237	2	0.3381	2	0.5864	2	0.4382	2
85	0.1583	2	0.2148	1.871	0.3732	2	0.3218	1.6666
86	0.131	2	0.1392	1.7241	0.268	2	0.221	1.9853
87	0.2429	2	0.3266	2	0.5578	2	0.4225	2
88	0.139	2	0.1635	1.1463	0.3487	1.3023	0.23	2

TABLE XI
OPTIMUM SETTINGS OF DOCRS OF TIE-CABLES AND SGS TERMINALS

Relays	Tie-SG1		Tie-SG2		Tie-SG3		Tie-SG4	
	TMS	PCS	TMS	PCS	TMS	PCS	TMS	PCS
89	0.2698	0.95	0.2338	1.005	0.2685	2	0.2676	1.8453
90	0.2812	0.25	0.1644	1.005	0.2695	0.25	0.1	0.25
91	0.3153	1.1117	0.441	0.6177	0.3584	2	0.4888	1.005
92	0.2772	0.25	0.2868	0.25	0.2437	0.25	0.2949	0.25
93	0.3551	1.2396	0.6167	0.25	0.5501	1.2012	0.4625	1.2396
94	0.3618	0.9438	0.4857	0.25	0.3463	0.9438	0.616	0.25
95	0.4721	0.9516	0.1294	1.6306	1.0064	0.25	0.1	0.9516
96	0.2774	1.1625	0.4163	0.25	0.3302	1.1625	0.5724	0.25
97	0.2956	1.1938	0.3492	0.6713	0.5651	1.1938	0.6271	0.575
98	0.648	0.9167	0.3578	1.1818	0.5529	2	0.333	2
99	0.1	0.25	0.1	0.25	0.1	0.25	0.1	0.25
100	0.1	0.25	0.1516	1.005	0.1301	1.4411	0.1269	1.5377
101	0.1	2	0.1	2	0.1	2	0.1	2
102	0.1451	2	0.1734	2	0.1265	2	0.1266	2
103	0.1993	2	0.2543	2	0.1751	2	0.2967	2
104	0.1628	2	0.1831	2	0.1954	2	0.1779	2

mentioned in the benchmark test system. Group 1 settings of DOCRs for MG1 are under column MG1-SG1 in this table. Group 2, Group 3, and Group 4 settings of DOCRs for MG1 are under columns MG1-SG2, MG1-SG3, and MG1-SG4, respectively, in the table. Similarly, Group 1, Group 2, Group 3, and Group 4 settings of DOCRs for MG2 are MG2-SG1, MG2-SG2, MG2-SG3, and MG2-SG4, respectively, whose optimum TMS

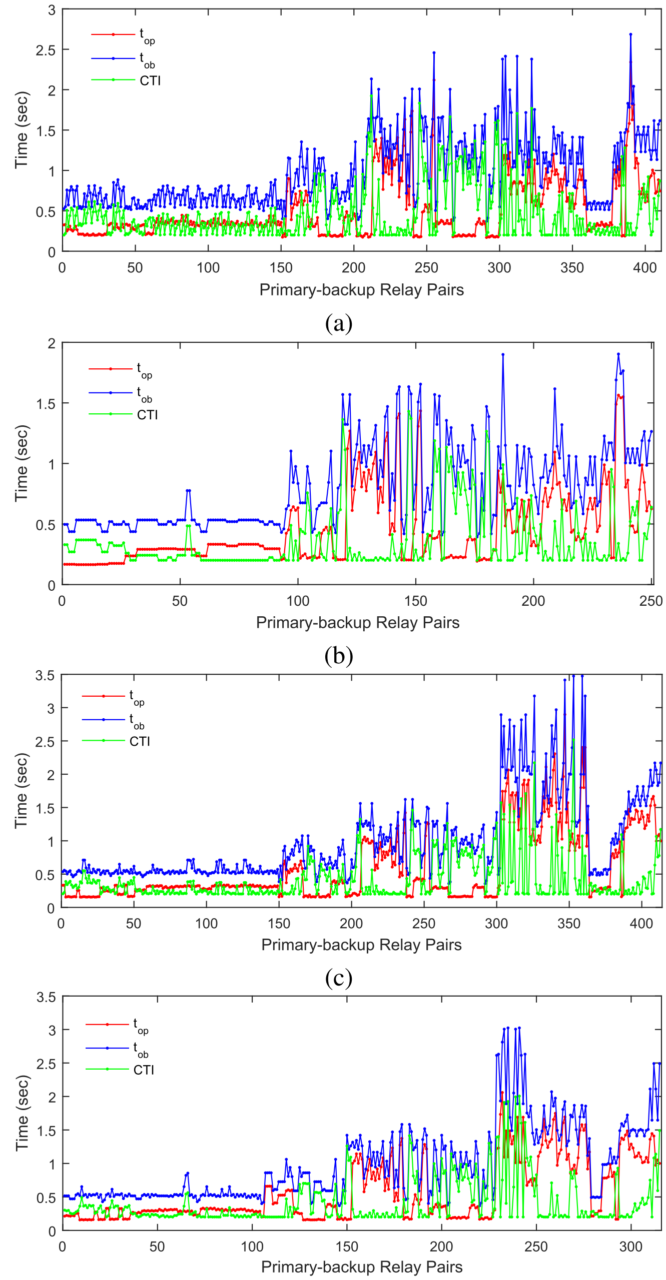

Fig. 6. Operating times of critical primary-backup relay pairs and their CTI for setting. (a) Group 1. (b) Group 2.(c) Group 3. (d) Group 4.

and PCS values are given in Table VIII. The optimum values TMS and PCS of DOCRs for MG3 and MG4 under various setting groups can be found in Tables IX and X, respectively. Similarly, the optimum values of TMS and PCS of DOCRs for tie-cables under all the four setting groups are given in Table XI. The different setting groups for tie-cables are designed as Tie-SG1, Tie-SG2, Tie-SG3, and Tie-SG4.

Thus, the optimum values of TMS and PCS of DOCRs suitable to protect the NMG system under various topology groups can be obtained from Tables VII–XI. The optimum settings of each group can coordinate adequately because primary-backup relay pairs satisfy the CTI requirements. This can be observed in Fig. 6. The time gaps between the operating times for all primary-backup relay pairs under all four groups of settings are more than 0.2 s, which is necessary for proper coordination among the pairs. Additionally, the operating times of most of the primary-backup relay pairs are quite low and suitable for the protection needs. However, the operating times of some of the primary-backup relay pairs in Fig. 6 are relatively large because they correspond to the lower possible values of fault currents under the concerned cluster. The actual number of such pairs is low and so the settings are acceptable.

The settings of DOCRs used for protecting the interconnecting tie-cables and SGs terminals of the NMG system are given in Table XI. These settings have been calculated along with the settings of each setting group of the NMG system. Whenever a tie-cable is in service, the optimum values of TMS and PCS of the relays associated with the tie-cable should be used.

The optimum settings of DOCRs categorized into four groups are adequate to protect the entire NMG benchmark test system of four MGs considering all possible interconnections among themselves. Based on the entire system operating conditions (topological information), suitable setting groups can be enabled by the NMG-EMS mentioned in Section IV.

D. Assessment of the Optimum Settings

To evaluate the suitability of the presented setting groups, it is necessary to check the coordination status of primary-backup relay pairs under different types of phase faults, such as three-phase (LLL), phase-phase (LL), and phase-phase-ground (LLG) faults and high impedance phase faults. The performance of relay pairs can be evaluated based on the values of CTIs for phase faults with the TCC plots of the optimum settings obtained under different setting groups. These performances can be summarized as follows.

1) Performance under different types of phase faults.
2) Performance under high impedance phase faults.

To validate these performances with the obtained settings, two relay pairs have been selected and the CTI requirement of these pairs for phase faults has been evaluated for a network topology of a setting group. The selected relay pairs are R59–R57 (from MG3) and R81–R79 (from MG4). A topology from setting Group 1 has been selected with PCC1, PCC2, and PCC3 as "ON," whereas PCC4 and PCC4 as "OFF" (topology index 29). The TCC plots of these relay pairs and the corresponding values of CTI for various phase faults are shown in Fig. 7.

It is clear from Fig. 7(a) that the minimum CTI requirement of 0.2 s is always maintained under LLL, LLG, LL faults for relay pairs R59–R57. The CTI value increases as the operating points of the pair move toward the left. For high impedance faults, the operating times of the pair will move toward the left of the operating points indicated for LL faults. Thus, the minimum CTI will always be maintained for high impedance faults until the minimum possible fault current of the pair, which is 1800 A. Similar observations can be made for relay pair R81–R79 from Fig. 7(b). The minimum CTI requirement of the pair is well

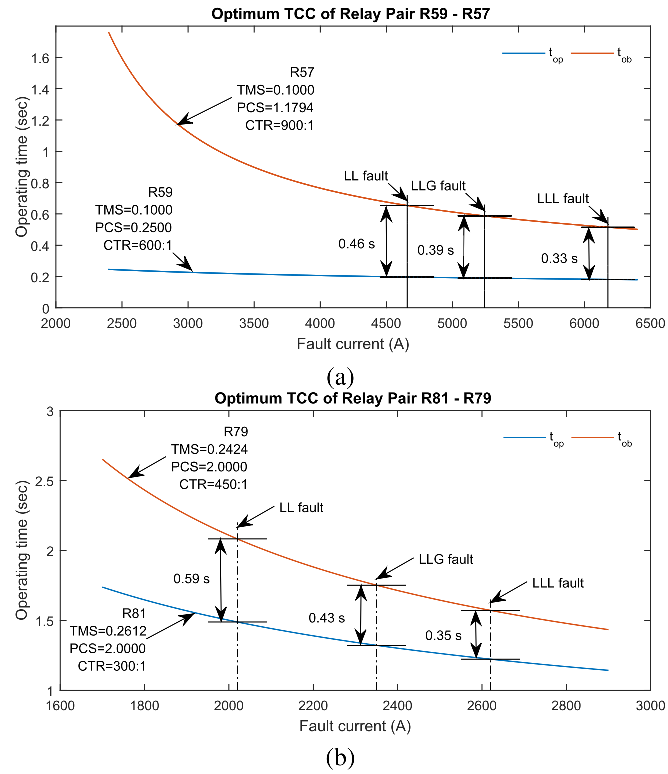

Fig. 7. TCC plots with the optimum settings of Group 1 and the CTI for different types of phase faults for relay pairs. (a) R81–R79. (b) R59–R57.

maintained for LLL, LLG, and LL faults along with a wide range for maintaining the CTI for high impedance faults.

Thus, the obtained settings of DOCRs under different setting groups coordinate adequately for the benchmark test system.

VI. Conclusion

In this article, setting groups based protection scheme of DOCRs was presented for the protection of NMGs. All the topologies of the considered test system was categorized into four groups and the optimum settings of the relays for each group were proposed. The following conclusions can be drawn based on the simulation study conducted on a benchmark test system for NMGs.

1) DOCRs with proposed setting groups have the potential to provide proper protection to NMG system.
2) Setting groups based protection scheme can coordinate properly under all topological interconnection among the MGs of the system.
3) Proposed optimum settings of relays for individual groups provide proper protection coordination for all the topologies of their group.
4) Fault current data based *k*-means clustering can be used for categorizing topologies of NMG systems among a suitable number of groups.

The obtained settings can be adopted for field applications as the numerical relays are usually well-equipped with the required functionality. In future, real-time testing will be performed to validate the adaptive protection scheme and the impact on relay coordination during a communication failure will be evaluated. Further extension of this work will focus on the development of a combined overcurrent, distance, and line differential relays based protection scheme by incorporating their best features for providing better protection coordination in NMGs.

References

[1] M. N. Alam, S. Chakrabarti, and A. Ghosh, "Networked microgrids: State-of-the-art and future perspectives," *IEEE Trans. Ind. Informat.*, vol. 15, no. 3, pp. 1238–1250, Mar. 2019.

[2] "Renewable 2019," International Energy Agency, Tech. Rep., 2019. [Online]. Available: https://www.iea.org/fuels-and-technologies/renewables

[3] F. Blaabjerg, Y. Yang, D. Yang, and X. Wang, "Distributed power-generation systems and protection," *Proc. IEEE*, vol. 105, no. 7, pp. 1311–1331, Jul. 2017.

[4] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked microgrids for enhancing the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1289–1310, Jul. 2017.

[5] M. M. Esfahani, A. Hariri, and O. A. Mohammed, "A multiagent-based game-theoretic and optimization approach for market operation of multimicrogrid systems," *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 280–292, Jan. 2019.

[6] M. N. Alam, S. Chakrabarti, and X. Liang, "A benchmark test system for networked microgrids," *IEEE Trans. Ind. Informat.*, vol. 16, no. 10, pp. 6217–6230, Oct. 2020.

[7] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018, 2018.

[8] A. Hooshyar and R. Iravani, "Microgrid protection," *Proc. IEEE*, vol. 105, no. 7, pp. 1332–1353, Jul. 2017.

[9] S. Beheshtaein, R. Cuzner, M. Savaghebi, and J. M. Guerrero, "Review on microgrids protection," *IET Gener. Transmiss. Distrib.*, vol. 13, no. 6, pp. 743–759, 2019.

[10] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Standard C37.113-2015 (Revision of IEEE Standard C37.113-1999), pp. 1–141, 2016.

[11] G. E. Alexander, J. G. Andrichak, and W. Z. Tyska, "Relaying short lines," GE Power Management, Anderson Avenue, Markham, ON, Canada, Tech. Rep. GER-3735, 2002, pp. 1–14. [Online]. Available: https://store.gegridsolutions.com/faq/documents/L90/

[12] S. M. Brahma, J. Trejo, and J. Stamp, "Insight into microgrid protection," in *Proc. IEEE PES Innov. Smart Grid Technol.*, 2014, pp. 1–6.

[13] R. Jain, D. L. Lubkeman, and S. M. Lukic, "Dynamic adaptive protection for distribution systems in grid-connected and islanded modes," *IEEE Trans. Power Del.*, vol. 34, no. 1, pp. 281–289, Feb. 2019.

[14] A. Sharma and B. K. Panigrahi, "Phase fault protection scheme for reliable operation of microgrids," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2646–2655, May/Jun. 2018.

[15] A. H. Etemadi and R. Iravani, "Overcurrent and overload protection of directly voltage-controlled distributed resources in a microgrid," *IEEE Trans. Ind. Electron.*, vol. 60, no. 12, pp. 5629–5638, Dec. 2013.

[16] M. H. Cintuglu, T. Ma, and O. A. Mohammed, "Protection of autonomous microgrids using agent-based distributed communication," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 351–360, Feb. 2017.

[17] W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, "Optimal protection coordination for microgrids with grid-connected and islanded capability," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1668–1677, Apr. 2013.

[18] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, "Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 143–151, Jan. 2018.

[19] M. N. Alam, R. Gokaraju, and S. Chakrabarti, "Protection coordination for networked microgrids using single and dual setting overcurrent relays," *IET Gener. Transmiss. Distrib.*, vol. 14, no. 14, pp. 2818–2828, Apr. 2020.

[20] M. Ojaghi and V. Mohammadi, "Use of clustering to reduce the number of different setting groups for adaptive coordination of overcurrent relays," *IEEE Trans. Power Del.*, vol. 33, no. 3, pp. 1204–1212, Jun. 2018.

[21] J. Gers and E. Holmes, *Protection of Electricity Distribution Networks* (IET Power and Energy Series), 3rd ed. London, U.K.: Inst. Eng. Technol., 2011.

[22] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 54–65, May/Jun. 2008.

[23] J. P. Singh and N. Bouguila, "Proportional data clustering using k-means algorithm: A comparison of different distances," in *Proc. IEEE Int. Conf. Ind. Technol.*, 2017, pp. 1048–1052.

[24] H. Muda and P. Jena, "Superimposed adaptive sequence current based microgrid protection: A new technique," *IEEE Trans. Power Del.*, vol. 32, no. 2, pp. 757–767, Apr. 2017.

[25] A. Hooshyar and R. Iravani, "A new directional element for microgrid protection," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6862–6876, Nov. 2018.

[26] P. Mishra, P. Singh, A. K. Pradhan, and P. Bajpai, "Protecting distribution systems with inverter-interfaced PV plants using Q-axis components," *IEEE Syst. J.*, to be published, doi: 10.1109/JSYST.2021.3071627

[27] S. Chaitusaney and A. Yokoyama, "Prevention of reliability degradation from recloser-fuse miscoordination due to distributed generation," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2545–2554, Oct. 2008.

[28] H. H. Zeineldin, Y. A. R. I. Mohamed, V. Khadkikar, and V. R. Pandi, "A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1523–1532, Sep. 2013.

[29] N. Nimpitiwan, G. T. Heydt, R. Ayyanar, and S. Suryanarayanan, "Fault current contribution from synchronous machine and inverter based distributed generators," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 634–641, Jan. 2007.

[30] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal coordination of directional overcurrent relays using a new time − current−voltage characteristic," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 537–544, Apr. 2015.

[31] M. N. Alam, B. Das, and V. Pant, "Protection coordination scheme for directional overcurrent relays considering change in network topology and OLTC tap position," *Elect. Power Syst. Res.*, vol. 185, pp. 1–10, Aug. 2020.

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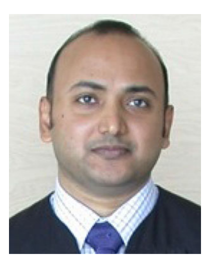

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