International Journal Of Industrial Electronics Control and Optimization
Print ISSN: 3517-2645
Online ISSN: 3568-2645
Homepage: https://ieco.usb.ac.ir/

Optimized Microgrid Protection Considering Different Topologies Based on N-1 Contingency by Dual Setting Directional Overcurrent Relays

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Article Info

Article type:
Research Article

Article History:
Received 2022-03-17
Received in revised form 2022-05-29
Accepted 2022-06-07
Published online: 2022-06-20

Keywords:
Different operating modes,
Overcurrent relays,
Microgrids,
N-1 contingency.

ABSTRACT

The deployment of microgrids (MGs) and smart grids to maximize the benefits from distributed generations (DGs) has increased. Although the MG framework and concept improve system flexibility and reliability, new challenges corresponding to the MG protection system appear compared to conventional passive distribution networks. The adaptive protection schemes, which have been reported to consider various topologies in MG protection, need communication infrastructure. Also, the failure of telecommunication systems and cyber-attacks has drawn attention to unrelated protection schemes using local measurements, taking into account different topologies and related selectivity constraints. The literature shows a research gap in the development of local measurement-based protection schemes considering different operating modes and network configurations due to the unavailability of upstream substations, DGs, and other MGs sub-systems such as lines. This research attempts to fill this research gap by proposing a new protection scheme using dual setting directional overcurrent relays (DS-DOCRs) based on N-1 contingency topologies. The introduced method is applied to the distribution portion of the IEEE 30-bus test system. The Genetic Algorithm (GA) has been selected as the optimization algorithm, which is implemented in MATLAB, and the power system analyses are done in DIgSILENT. The test results show the advantages of the proposed method compared to the existing designs, only considering the limited operation modes. The test results indicate that mis-coordination for the N-1 contingency-based topologies does not appear using the proposed method.

NOMENCLATURE

t_i	Tripping time of the *i*-th relay
TDS_i	Time dial setting (TDS) of the *i*-th relay
$I_{F,i}$	Short circuit current of the *i*-th relay
$I_{p,i}$	Pickup current setting (PCS) of the *i*-th relay
$I_{H,i}$	Breakpoint of the *i*-th relay's dual-setting curve
A_i, B_i	Standard relay curve coefficients of the *i*-th relay
TDS_i^f	TDS of the first level of the *i*-th relay
TDS_i^s	TDS of the second level of the i-th relay
$I_{p,i}^f$	PCS of the first level of the *i*-th dual-setting curve's relay
$I_{p,i}^s$	PCS of the second level of the *i*-th dual-setting curve's relay
$O.F$	Objective function
T_c	Total tripping time of primary and backup relays regarding various network topologies
N_c	Number of system topologies
$t_{c,i}^p$	Tripping time of the *i*-th primary relay in the *c*-th topology

DOI: 10.22111/IECO.2022.41721.1416

$t_{c,j}^{b}$	Operating time of the j-th backup relay under the c-th network topology
N_p	Number of primary relays
N_b	Number of backup relays
$I_{Load,i}^{\max}$	Maximum current of the i-th relay
$I_{SC,i}^{\min}$	Minimum fault current of the i-th relay
$TDS_{\min}$	Minimum limit of TDS
$TDS_{\max}$	Maximum limit of TDS

I. Introduction

Microgrids (MGs) and smart grids frameworks and concepts have been introduced to achieve the maximum benefits from distributed generations (DGs), besides distribution networks [1, 2]. However, the protection system of MGs and smart grids might be exposed to new challenges [3, 4]. Several research works have been done to improve the MGs' protection schemes and mitigate the new challenges compared to conventional distribution networks [5, 6].

If only the base grid-connected topology of the MG, while all upstream substations and DGs are connected, is concerned with the optimal protective scheme, several selectivity constraint violations in other topologies are expected [7]. On the other hand, the feasible area of the optimization problem to find the optimized settings for directional overcurrent relays (DOCRs), using conventional relay characteristics, due to increment of coordination constraints and limits decrease dramatically. Therefore, several approaches have been developed to meet the optimality and feasibility features of the optimization problem for the MG protection system, considering various system configurations.

The communication-aided adaptive protection methods [8, 9] and modified time-current curves for DOCRs [10] are some of the reported solutions to modify the MG protection system against changes in MG protection due to changes in system topologies. Since the adaptive scheme requires the hardware and software infrastructures to activate the suitable setting groups [11], a great deal of attention has also been paid to local measurement-based protection systems [12].

The literature shows that introducing new modified time-current curves for DOCRs is one of the effective solutions to respond to challenges due to changes in MG operating modes and topologies. In [13, 14], the double-inverse DOCRs (DI-DOCRs) were used to optimize the MG protection based on DGs' stability constraints. The main and auxiliary relays have been utilized in the introduced scheme of [14] to satisfy both selectivity and stability constraints simultaneously. Different network topologies have not been studied in [13, 14]. In [12], a new dual-setting time-current curve has been presented for relays, while the islanded mode has been considered beside the base configuration. The dual setting curves were reported according to a three-point coordination strategy in [15].

The literature review illustrates that the grid-connected mode, which consists of all sub-systems, has been studied in most of the references in the protection of MGs. In some papers, the islanded mode has been concerned in addition to the grid-connected mode. However, considering various system topologies due to the unavailability of DGs, upstream substations and lines in optimal protective schemes have received less attention. In [4], a novel scheme has been presented for smart grids/MGs' protective schemes based on all network topologies due to N-1 contingency. Although significant improvement in optimal protection of distribution networks has been achieved by applying [4], the speed of the protection system might be threatened due to the increased number of constraints.

In Table 1, a comparative summary of the literature on the protection of smart grids and MGs has been presented. The summarized literature review shows that a research gap exists in developing a new study for MG protection using the DS-DOCRs that takes into account N-1 contingency-based network topologies and corresponding selectivity constraints. This research aims to fill this gap. Indeed, using the DS-DOCRs, as a specified characteristic, would be useful to mitigate the challenges of the protection system's speed in [4].

TABLE 1
OVERVIEW OF THE LITERATURE REVIEW IN PROTECTION STUDIES OF MGs

Ref.	Year	Relay Model				N-1 contingency	Communication based
		OCR	DOCR	DI-DOCR	DS-DOCR		
[4]	2021	×	✓	×	×	✓	×
[11]	2018	×	×	✓	×	×	✓
[12]	2021	×	×	×	✓	×	×
[13]	2019	×	×	✓	×	×	×
[14]	2021	×	×	✓	×	×	×
[15]	2021	×	×	×	✓	×	×
[16]	2021	×	✓	×	×	×	✓
[17]	2017	×	✓	×	×	✓	×
[18]	2020	×	✓	×	×	×	✓
[19]	2021	×	✓	×	×	×	✓
[20]	2018	×	✓	×	×	×	×
[21]	2010	×	✓	×	×	✓	×
[22]	2009	×	✓	×	×	✓	×
[23]	2017	×	✓	×	×	×	×
[24]	2015	×	×	✓	×	×	×
Proposed method		×	×	×	✓	✓	×

The distribution network of the IEEE 30-bus test system, as a meshed distribution system, has been chosen to investigate the proposed study advantages. The proposed protective scheme using the DS-DOCRs is simulated by linking the DIgSILENT and MATLAB. The load flow and short circuit simulations are performed in DIgSILENT, and the introduced optimization problem is solved in the MATLAB environment by the genetic algorithm (GA). The obtained optimum settings and tripping time of DOCRs are compared to available approaches. The novelties and effectiveness of this study are emphasized based on the speed of the MG protection system and satisfaction of all selectivity constraints in various N-1 contingency-based configurations. The relaying studies also are simulated in DIgSILENT according to obtained optimum settings to validate the proposed method.

In the rest of this article, the introduced methodology and modeling will be given in Section II. Section III presents optimization results and discussions. Finally, the conclusion is drawn in Section IV.

II. Methodology

A. DS-DOCR Characteristics

In (1), the formula for standard relay tripping time is shown. As seen, the tripping time of DOCRs is a function of the short-circuit current that passes the relays. In addition, the coefficients for standard characteristics are given in Table 2 [4, 12].

$$t_i = TDS_i \frac{A_i}{\left(\frac{I_{F,i}}{I_{p,i}}\right)^{B_i} - 1} \tag{1}$$

In this research, to modify the MGs' protective scheme, considering N-1 contingency, the DS-DOCRs are selected. The tripping curve of DS-DOCRs is shown in Fig. 1 [12]. As depicted, the relay curve is divided into two levels. Separate current and time settings can be assigned for the first and second parts according to the breakpoint (the H points shown in Fig. 1). The formula of the operating time for DS-DOCRs is described in (2). The DS-DOCR operates according to the normal inverse curve in the first part. Indeed, the DS-DOCR slowly operates if the small short circuit currents pass through the relay. Otherwise, the very inverse curve is assigned for the second part regarding the severe short circuits and fast operating. Therefore, sufficient time intervals appear between the operating time of the main and backup DS-DOCRs.

A. Proposed Protection Scheme Using DS-DOCRs Considering N-1 Contingency

The objective function of this study has been defined according to the summation of operating times of main and backup DS-DOCRs in different N-1 contingency-based topologies, which is shown in (3). To calculate the operating time of DS-DOCRs, (2) should be used.

TABLE 2
DOCRS' IEC STANDARD CURVES [25]

Item	Time-current curve	A	B
1	Normally inverse (NI)	0.14	0.02
2	Very inverse (VI)	13.5	1
3	Extermely inverse (EI)	80	2

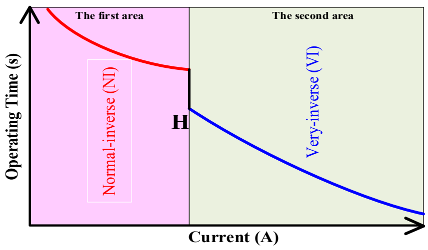


Fig. 1. Time-current curve of DS-DOCRs [12].

$$t_i = \begin{cases} TDS_i^f \dfrac{A_i}{\left(\dfrac{I_{F,i}}{I_{p,i}^f}\right)^{B_i} - 1} & I_{p,i} < I_{F,i} < I_{H,i} \\[2ex] TDS_i^s \dfrac{A_i}{\left(\dfrac{I_{F,i}}{I_{p,i}^s}\right)^{B_i} - 1} & I_{F,i} \geq I_{H,i} \end{cases} \tag{2}$$

$$O.F = \sum_{c=1}^{N_c} T_c\left(I_{p,i}^f, TDS_i^f, I_{p,i}^s, TDS_i^s\right) = \sum_{c=1}^{N_c}\left(\sum_{i=1}^{N_p} t_{c,i} + \sum_{j=1}^{N_b} t_{c,j}\right) \tag{3}$$

The base network operation mode (all lines and generation sources are in-service) and other topologies due to the unavailability of any sub-system are studied to distinguish the OF.

To find the optimum DS-DOCRs' settings, the coordination constraints should be met, as given in (4) [26]. The minimum allowed coordination time interval (CTI) is commonly considered to be between 0.2 to 0.5 s [17, 18]. Hence, in this study, 0.2 s has been selected for the minimum allowed CTI.

$$t_{c,j}^b - t_{c,i}^p \geq CTI \tag{4}$$

As expressed in (5-6), the DS-DOCR's current setting must be greater than the maximum load current. Also, the current setting must be less than the minimum short circuit current to ensure that the DS-DOCR acts against all the downstream faults [4, 12, 18].

$$1.2 I_{Load,i}^{\max} \leq I_{p,i}^f \leq I_{F,i}^{\min} \tag{5}$$

$$1.2 I_{Load,i}^{\max} \leq I_{p,i}^s \leq I_{F,i}^{\min} \tag{6}$$

The maximum and minimum allowed TDS of the DS-DOCRs' levels should be considered in the proposed optimization problem using (7-8) [12, 18, 22]. The time dial settings are assumed to be between 0.05 and 1s in this study [4, 27].

$$TDS_{\min} \leq TDS_i^f \leq TDS_{\max} \tag{7}$$

$$TDS_{\min} \leq TDS_i^s \leq TDS_{\max} \tag{8}$$

In Fig. 2, it has been shown how the introduced method can be implemented. The DIgSILENT and MATLAB are linked to implementing this study, and other step-by-step procedures are shown in Fig. 2.

Different optimization algorithms can be used to solve the proposed optimization problem. The GA has been selected in this study because it has been reported in the literature that the

GA has a good performance from the viewpoint of convergence speed, finding the global optima. Also, implementing the GA or using the MATLAB toolbox optimization's GA is easy. However, other meta-heuristic algorithms, such as particle swarm optimization (PSO), learning-based optimization algorithm (TLBO), and shuffled frog mutation algorithm (SFLA), can be used.

III. TEST RESULTS

This research is investigated by applying the introduced DS-DOCR-based protection system to the distribution network of the IEEE 30-Bus test system. The single line diagram (SLD) of the selected system is depicted in Fig. 3 [12]. This modified test system consists of 3 coupling points to external grids through three 132/33 kV substations, which their capacities are 50 MVA. The distribution network of the IEEE 30-bus test system consists of 11 DGs (interconnecting with 6.6/33 kV step-up transformers). There are 14 buses and 16 feeders in the understudy test system, while it consists of 29 DOCRs and 61 pairs of relays. Also, the current transformer (CT) ratios for this test system have been presented in Table 3. It should be noted that this article is an extension of [28], and a larger test system has been selected to emphasize the advantages of the proposed method for more probable topologies of a distribution system.

The developed method will be investigated in three cases as follows:

Case 1: The base network mode (availability of all DGs and network lines) is considered.

Case 2: The base topology and those that occur due to DGs and the upstream substation disconnecting, like [12], are studied.

Case 3: All network configurations and operational modes, including the base topology, unavailability of external grids (islanded mode), and the DGs and lines' outage, are considered.

TABLE 3
DOCRs CT INFORMATION

Relay No.	CT	Relay No.	CT	Relay No.	CT
1	1000:1	11	500:1	21	800:1
2	800:1	12	600:1	22	500:1
3	800:1	13	800:1	23	1200:1
4	1000:1	14	800:1	24	1200:1
5	800:1	15	1000:1	25	1200:1
6	800:1	16	500:1	26	600:1
7	600:1	17	800:1	27	600:1
8	500:1	18	800:1	28	1000:1
9	500:1	19	800:1	29	1000:1
10	500:1	20	800:1		

The understudy distribution system can operate in 33 different network topologies/operating modes. The first to third configurations are the base grid-connected, islanded, and outage of all DGs, respectively. The fourth to fourteenth configurations occur due to the outage of DG_2 to DG_{10}, DG_{12}, and DG_{14}. The other network configurations appear due to the outage of any line (configurations fifteenth to thirty-third).

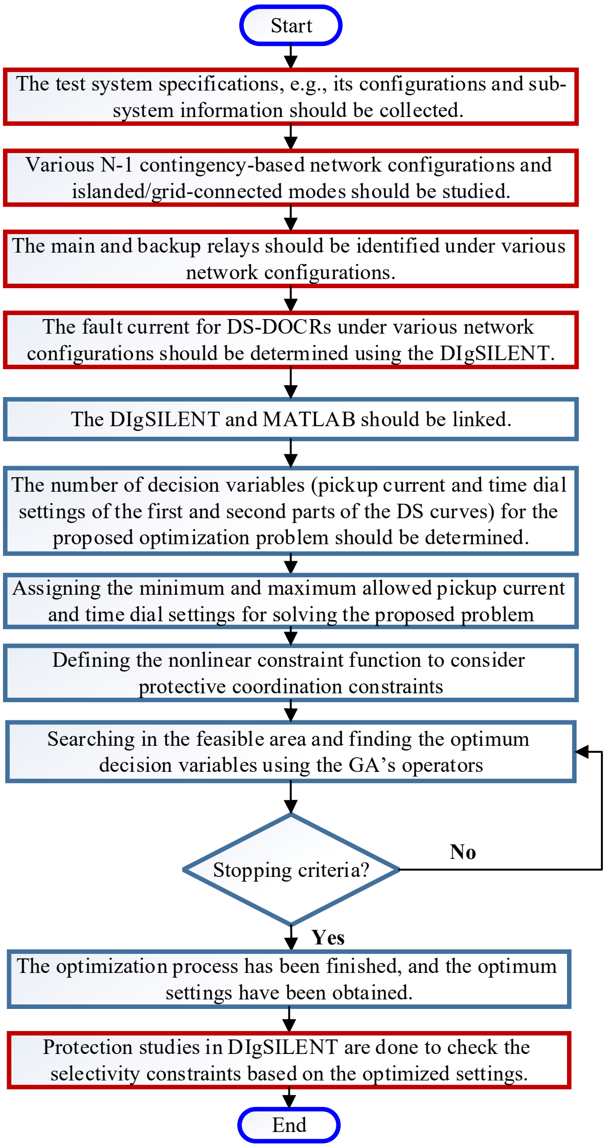


Fig. 2. Flowchart of the presnted method based on N-1 contingency-based configurations by DS-DOCRs.

Table 4 presents the number of network topologies in any case and corresponding constraints.

A comparison of Case 3 with Case 2 (the unavailability of DGs has been studied, besides the base and islanded modes) shows that the tripping time of the proposed scheme using DS-DOCRs in Case 3 has increased 536.8646s (27.02%). Moreover, comparing Case 3 with Case 1 implies that the total operating time of DOCRs has increased by 759.5888s (38.23%) because of N-1 contingency considerations, such as line outages. As seen in Table 5, in addition to reducing the total operating time of network operation modes in Case 2 compared to Case 1, the number of violations of selectivity constraints has decreased (according to Table 6).

TABLE 4
NUMBER OF CONFIGURATIONS AND COORDINATION CONSTRAINTS IN DIFFERENT CASES

Item	Case No.		
	1	2	3
Number of network configurations	1	14	33
Number of selectivity constraints	61	854	2013

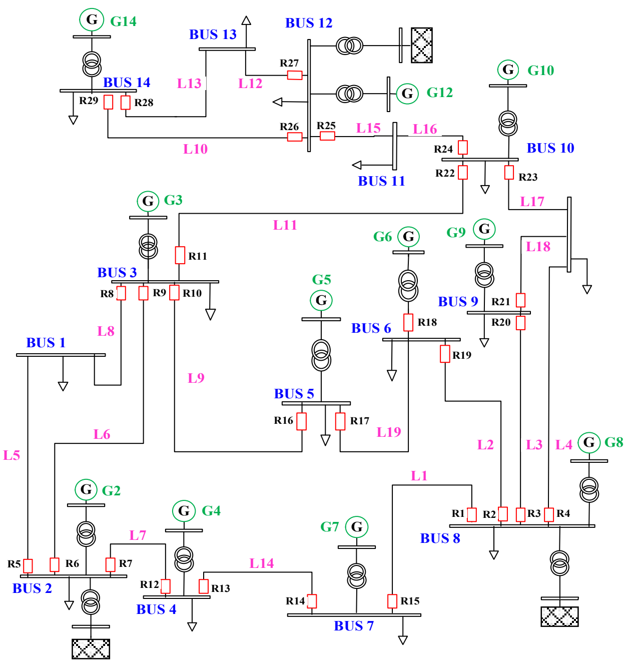


Fig. 3. The distribution network of the IEEE 30-bus test system [12].

Table VI presents the number of selectivity constraint violations for different topologies in discussed cases. The advantages of the introduced study, focusing on different topologies and corresponding constraints, have been highlighted in Table VI. Comparing the obtained results based on the proposed study (Case 3) with others (Cases 1 and 2 according to the methods of existing references like [12]) emphasizes that although the speed of MG protection system has reduced, no selectivity constraint violation appears. As can be concluded from Table VI, the number of mis-coordinations in Case 2 (like [12]) has decreased considerably compared to Case 1. However, some selectivity constraint violations in Case 2 exist, which is not satisfying. In the third case, no mis-coordination occurs, and the selectivity constraints are met in different N-1 contingency-based topologies. Test results emphasize the advantages of the proposed method.

Tables 7 presents the optimized settings based on Case 3. The optimum TDS and PCS values for DS-DOCRs have been demonstrated. As given in the methodology, the NI characteristic is applied to the first part of DS-DOCRs, and the VI characteristic will be assigned to the second part.

In Case 1, based on the base mode, including all DGs, lines, and upstream substations, 160 coordination violations appear. The mis-coordinations can be decreased by applying the results of Case 2, 38 mis-coordination remain. However, no coordination constraint violation appears by applying the settings of Case 3.

TABLE 5
OPTIMUM RESULTS FOR DIFFERENT TOPOLOGIES

Topology	DOCRs' tripping time (s)		
	Case 1	Case 2	Case 3
Grid-connected	35.6661	38.0228	47.3028
Islanded	87.3669	66.5543	106.8834
Exit all DGs	54.6365	47.6546	59.2855
Exit DG_2	40.2825	34.4974	47.9451
Exit DG_3	46.9097	35.6888	48.8687
Exit DG_4	41.6646	34.6876	48.0971
Exit DG_5	46.6955	35.3990	48.7228
Exit DG_6	43.0298	34.9790	48.3789
Exit DG_7	42.0218	34.6704	48.0975
Exit DG_8	41.7143	34.4191	47.8545
Exit DG_9	40.8995	33.3631	46.3972
Exit DG_{10}	47.3513	35.7051	52.7710
Exit DG_{12}	40.5097	34.2112	47.7317
Exit DG_{14}	40.1523	33.8903	41.4823
Exit $Line_1$	60.8710	59.7195	73.1989
Exit $Line_2$	75.2967	57.2918	72.7635
Exit $Line_3$	38.4685	31.5751	48.9362
Exit $Line_4$	37.5242	31.2808	43.0855
Exit $Line_5$	34.1320	36.0384	47.7811
Exit $Line_6$	33.6143	35.1720	63.8185
Exit $Line_7$	59.6790	70.1830	74.0355
Exit $Line_8$	34.0945	35.8092	47.1004
Exit $Line_9$	80.7778	58.5541	110.7919
Exit $Line_{10}$	39.4504	32.5177	40.8556
Exit $Line_{11}$	33.7678	40.8413	48.8529
Exit $Line_{12}$	39.3735	32.5571	41.9806
Exit $Line_{13}$	39.5905	33.7479	43.3018
Exit $Line_{14}$	80.7132	85.8320	93.5651
Exit $Line_{15}$	31.3068	41.3466	58.6840
Exit $Line_{16}$	30.6391	41.0973	60.4675
Exit $Line_{17}$	41.4797	40.1324	100.7326
Exit $Line_{18}$	45.4551	39.9557	49.8410
Exit $Line_{19}$	98.7521	112.6143	127.2624
All modes	1227.2847	1450.0089	1986.8735

For example, R_1 and R_{19} in the test system, while the system operates in islanded mode, are selected to show the effectiveness of Cases 2 and 3 compared to Case 1. The protection simulations in DIgSILENT for R_1 and R_{19} in the discussed network configuration are shown in Fig. 5. Moreover, R1 and R19, while line 5 is out-of-service, are chosen to emphasize the effectiveness of this research in Case 3 compared to others. In Fig. 6, the DIgSILENT protection simulations for R_{19} and R_1 in the network configuration due to the outage of line 3 are shown.

Finally, the selectivity constraints satisfaction is investigated in DIgSILENT. The typical results of protection studies in DigSILENT based on optimum settings under various cases are shown.

As it can be concluded from Fig. 5(a), the tripping time of R_1 in Case 1 is not sufficiently greater than R_{19}. Therefore, the selectivity constraint regarding these relays has not been met in Case 1. Fig. 5(b) shows that the coordination between the main and backup relays in Case 2 can be satisfied. It is expected because DGs unavailability and various arrangements of generation units are considered in Case 2 (like the method of [12]). Moreover, these relays (R_1 and R_{19}) are coordinated in Case 3, as depicted in Fig. 5(c). Simulation results and investigations have emphasized the advantages of Cases 2 and 3 to satisfy the selectivity constraints of various operational modes, such as unavailability of DGs and islanded mode. The DIgSILENT results imply that programming and evaluations in MATLAB are valid and accurate.

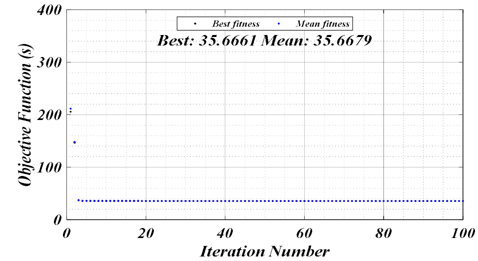
Comparing the relays' tripping time in DIgSILENT simulations and MATLAB by the presented method shows that the calculations are adequately precise.

TABLE 6
MIS-COORDINATIONS IN DIFFERENT SYSTEM TOPOLOGIES

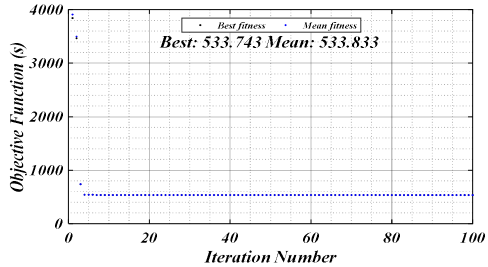
Topology	Number of mis-coordinations		
	Case 1	Case 2 (like [12])	Case 3
Grid-connected	0	0	0
Islanded	4	0	0
Exit all DGs	6	0	0
Exit DG2	2	0	0
Exit DG3	4	0	0
Exit DG4	1	0	0
Exit DG5	5	0	0
Exit DG6	4	0	0
Exit DG7	2	0	0
Exit DG8	4	0	0
Exit DG_9	3	0	0
Exit DG_{10}	3	0	0
Exit DG_{12}	3	0	0
Exit DG_{14}	3	0	0
Exit $Line_1$	2	0	0
Exit $Line_2$	6	2	0
Exit $Line_3$	8	2	0
Exit $Line_4$	9	4	0
Exit $Line_5$	8	5	0
Exit $Line_6$	4	3	0
Exit $Line_7$	6	0	0
Exit $Line_8$	8	5	0
Exit $Line_9$	7	3	0
Exit $Line_{10}$	5	3	0
Exit $Line_{11}$	8	3	0
Exit $Line_{12}$	4	1	0
Exit $Line_{13}$	4	1	0
Exit $Line_{14}$	5	0	0
Exit $Line_{15}$	5	0	0
Exit $Line_{16}$	6	1	0
Exit $Line_{17}$	8	1	0
Exit $Line_{18}$	7	1	0
Exit $Line_{19}$	6	3	0
All modes	160	38	0

In addition, it has been examined that the global optima have been achieved according to convergence analyses and other supplementary statistical studies. Also, the protection system's speed for different topologies shows that the DS-DOCRs can be an appropriate strategy to mitigate the protection challenges of MGs.

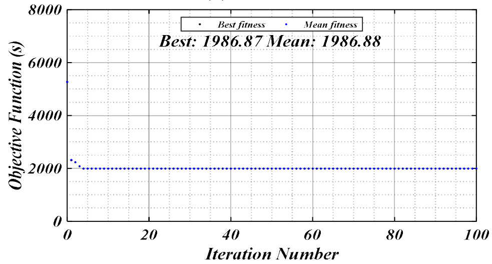
In Fig. 6, the coordination of R_1 and R_{19}, while a distribution line has experienced a failure (L_5 is out-of-service), is examined. The obtained results illustrate that these two relays are not coordinated in Cases 1 and 2. It is concluded that neglecting some operational modes and topologies might lead to some mis-coordinations.



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 4. Convergence of the GA to solve the introduced protection problem in various cases.

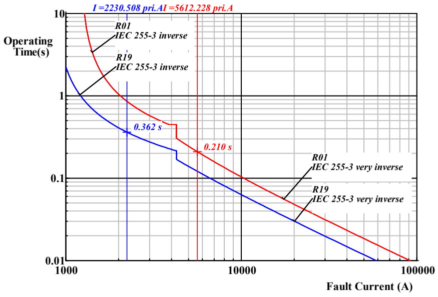
TABLE 7
OPTIMUM RELAY SETTINGS IN CASE 3

Relay	TDS^f (s)	TDS^s (s)	I_p^f (A)	I_p^s (A)
1	0.0777	0.0500	1211.0000	1332.1001
2	0.0748	0.0500	1347.0000	1481.7000
3	0.0501	0.0500	4679.4065	1087.9000
4	0.0683	0.0500	926.0000	1018.6000
5	0.0801	0.0500	653.1678	718.3000
6	0.0501	0.0500	1110.0463	540.1000
7	0.0856	0.0943	873.0259	960.3001
8	0.0501	0.0500	2277.8980	651.2000
9	0.1117	0.0500	491.0000	540.1000
10	0.0726	0.0500	1060.0000	1166.0000
11	0.0929	0.0500	1163.4911	1279.3001
12	0.0500	0.0500	823.3305	854.7000
13	0.0927	0.0500	777.0000	854.7000
14	0.0915	0.0500	777.2300	854.7001
15	0.0622	0.0500	777.0000	854.7001
16	0.0740	0.0500	777.0000	854.8013
17	0.0874	0.0500	846.7400	854.7000
18	0.0923	0.0500	777.0000	854.7000
19	0.0625	0.0500	777.0000	854.7000
20	0.0610	0.0501	666.0000	732.6000
21	0.0754	0.0501	888.0000	976.8000
22	0.0500	0.0500	2089.7311	1279.3862
23	0.0500	0.0500	1466.0000	1612.6000
24	0.0500	0.0500	1055.0000	1160.5228
25	0.0998	0.0500	1055.0000	1160.5000
26	0.2035	0.0500	98.0000	107.8000
27	0.1873	0.0500	64.0000	70.4000
28	0.1743	0.0500	96.9965	104.5000
29	0.4432	0.1224	98.9917	107.8000

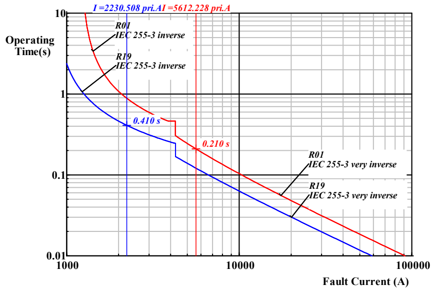
Fig. 6 emphasizes the benefits of the introduced method in

Case 3. The coordination analyses in DIgSILENT approve that it is essential to use the reported method in this article to mitigate selectivity constraint violations.

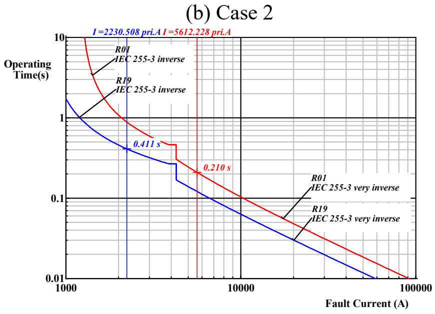
According to the results, although considering all topologies and network operation modes (the base topology, the unavailability of the all external grids (islanded mode), and the unavailability of DGs and distribution lines) slightly increases the speed of the presented scheme, it ensures that the violation of the coordination constraint for the N-1 contingency does not appear using the proposed method. So, the prominence of the proposed method is determined.



(a) Case 1



(b) Case 2

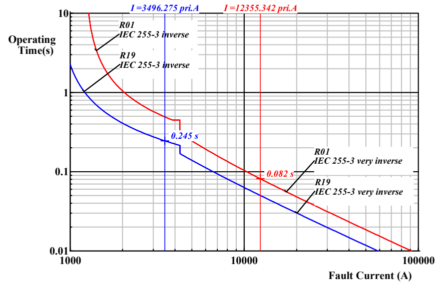


(c) Case 3

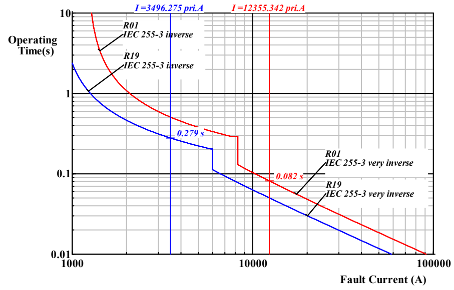
Fig. 5. DIgSILENT coordination diagram of R1 and R19 for islanded mode in Cases 1-3

IV. Conclusions

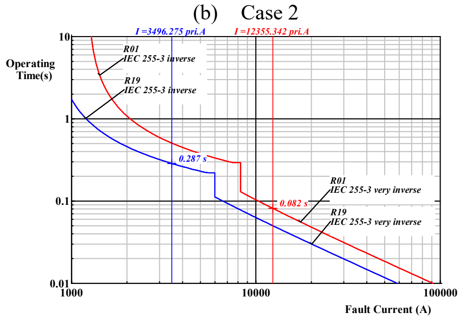
The literature review shows that MG's protection optimization according to N-1 contingency-based topologies, e.g., distribution lines unavailability, has received less attention. This research aimed to fill the addressed knowledge gap. A modified optimized protection system by the DS-DOCRs has been reported based on N-1 contingency topologies. The introduced method has been investigated on the distribution portion of the IEEE 30-bus test system. Comparing the introduced study with available references illustrated the importance of considering the N-1 contingency-based topologies. The test results of the comparison analyses emphasized the effectiveness of the presented method. Test results implied that the developed protective scheme is fast, while no mis-coordination occurs for different network topologies, even those regarding the distribution lines' unavailability. Studying the CT saturation, besides the proposed optimal protection using the DS-DOCRs based on N-1contingency topologies, can be an interesting future research work. Furthermore, the proposed method can be extended in future research works through new objectives and other multi-objective functions, such as load and capacitor switching.



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 6. DIgSILENT coordination curve of relays 1 and 19 of the test system for outage L_5 under various cases

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