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Comparative Study of Relay Coordination in a Microgrid with the Determination of Common Optimal Settings Based on Different Objective Functions

Priyanshul Niranjan*, Ravindra Kumar Singh, Niraj Kumar Choudhary

Department of Electrical Engineering, Motilal National Institute of Technology Allahabad, Prayagraj, India

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Abstract

This study aims to analyze the optimal settings of directional overcurrent relays (DOCRs) for the protection of an alternating current (AC) microgrid in both islanded and grid-connected operation modes. In this context, two different types of objective functions are used for comparing the total operating time of all primary DOCRs. The optimal settings obtained in either mode of the microgrid are different due to the variable magnitude of fault currents. The proposed protection coordination scheme is formulated as a mixed-integer non-linear programming problem, and the settings are obtained using various optimization techniques such as firefly algorithm, simulated annealing algorithm, and genetic algorithm. The results show that the settings obtained in common operation modes are robust as no miscoordination of relays occurs in any of the operation modes.

Keywords: protection coordination, DOCRs, mixed-integer non-linear programming, coordination time interval

1. Introduction

A microgrid is a group of interconnected loads along with distributed energy resources (DERs) within the well-defined electrical boundaries, which acts as a single controllable entity to the electrical grid [1-5]. The microgrid can be operated in the grid-connected mode (GCM) and islanded mode (ISM) when connected and disconnected from the utility grid respectively [6-8]. The alternating current (AC) microgrid is widely used because of its advantageous characteristics, i.e., easy modeling, simple design, and efficient output [9-10]. However, there are several significant problems in the microgrid, such as bidirectional power flow, topology-dependent load flow, short circuit current, relay coordination, etc. [11-13]. Among them, the most demanding issue is the design of the control and protection system for switching the microgrid from one mode to another mode of operation.

In modern power systems, numerical relays have microprocessors to analyze power system voltages, currents, or other quantities for detecting faults in an electric power system or industrial system. Such relays may have an extensive collection of settings that can be transferred to the relays through an interface with a personal computer (PC), and the same PC interface may be used to collect event reports from the relays. The obtained settings with the proposed techniques can be fed to the memory of numerical relays.

For the proper protection coordination of distribution systems, directional overcurrent relays (DOCRs) are convenient economical devices as compared to conventional relays [14]. The coordination of DOCRs is a challenging task in distribution networks because of the nonlinear characteristic of the relays and the presence of different constraints in the optimization problem. Therefore, in general, the conventional methods do not give the best solution [10].

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* Corresponding author. E-mail address: priyanshul.2018ree04@mnnit.ac.in

Tel.: +917459935284

For the protection of any distribution system, primary and backup DOCRs are considered to remove the faulty section as quickly as possible [14-16]. Firstly, the primary relay has to be operated; however, if the faulty section is not isolated, then the corresponding backup relay should operate. The operating times of both relays should maintain the least time between them which is known as the coordination time interval (CTI) [17]. Thus, the proper coordination of DOCRs is necessary to remove the faulty section as quickly as possible. In literature, many researchers performed the study of relay coordination by considering the total operating time of the primary relays only. However, few others have also considered the total operating time of both primary and backup relays. In both cases, the values of plug setting (PS) and time dial setting (TDS) are obtained for all the primary and backup DOCRs to make the relays coordinate properly [18-19].

In the literature, depending upon the number of variables (TDS and PS), the relay coordination problem is formulated as linear programming (LP), non-linear programming (NLP), and mixed-integer non-linear programming (MINLP) problems. In the case of LP, only TDS is taken as a variable, and PS is kept constant. Using LP, the optimal values of TDS are obtained by simplex method [20], improved firefly algorithm (FA) [21], genetic algorithm (GA) [22-24], etc. In the case of NLP, TDS and PS are both treated as continuous variables. In the case of MINLP, TDS and PS are both considered decision variables where TDS is considered a continuous variable and PS is considered a discrete variable. In the MINLP, the optimal values of TDS and PS are obtained by particle swarm optimization [25], random search technique [26], differential algorithm [27], and teaching-learning optimization [28] to solve the relay coordination problem.

This study presents two different objective functions for comparing the total operating time of primary relays (OTPR) for proper protection coordination in each operation mode of a microgrid. Furthermore, common optimal settings are obtained to remain valid for both the operating modes (i.e., GCM and ISM). The relay coordination problem is formulated as a constrained MINLP problem, which is solved using FA, simulated annealing algorithm (SA), and GA. The proposed approach is tested on a 7-bus test system which is the low voltage part of an IEEE-14 bus system. The rest of the study is organized as follows. Section 2 presents the formulation of the relay coordination problem. Section 3 describes the information of the 7-bus system and also the simulation setup. Section 4 and section 5 present the details of the results obtained and the conclusions of this study, respectively.

2. Formulation of the Relay Coordination Problem

The operating time of DOCRs is the inverse function of the fault current flowing through it. In this study, the operating time of DOCRs is determined using the normal inverse (NI) characteristics according to IEC-60255.

$$t_{op,i} = \frac{TDS_i \times A_N}{\left(\dfrac{I_{f,i}}{CTR_i \times PS_i}\right)^{B_N} - 1} \tag{1}$$

In Eq. (1), $t_{op,i}$ represents the operating time of the i_{th} relay. A_N and B_N are the NI curve coefficients of the relay, which are 0.14 and 0.02 respectively. $I_{f,i}$ is the measured fault current through the relay coil. CTR_i, PS_i, and TDS_i are the current transformer ratio (CTR), plug setting (PS), and time dial setting (TDS) respectively of the i_{th} relay. To perform the relay coordination study, the objective function has been formulated with or without considering the operating time of the backup relays. The OTPR is determined for the two types of objective functions. The main objective of the relay coordination study is to obtain the optimal values of TDS and PS for all the DOCRs such that the OTPR is minimum.

2.1. Problem formulation by considering the primary DOCRs only

The objective function formed by considering the total operating time of the primary relays for different fault locations is represented by OBJ_1, as shown in Eq. (2). The relay coordination study aims to minimize OBJ_1 subjected to the validation of constraints mentioned from Eqs. (3)-(6).

$$OBJ_1 = \min_{TDS,PS} \sum_{i=1}^{n} \sum_{j=1}^{m} t_{op,ij}^{p} \tag{2}$$

$$t_{op,ij}^{p} - t_{op,ij}^{b} \geq LCT \tag{3}$$

$$TDS_{\min,i} \leq TDS_i \leq TDS_{\max,i} \tag{4}$$

$$PS_{\min,i} \leq PS_i \leq PS_{\max,i} \tag{5}$$

$$t_{\min,i}^{p} \leq t_{op,i}^{p} \leq t_{\max,i}^{p} \tag{6}$$

In Eq. (2), $t_{op,ij}^{p}$ is the operating time of the i_{th} primary relay. The total number of relays, the fault location identifier, and the total number of fault locations are n, j, and m respectively. In Eq. (3), $t_{op,ij}^{b}$ is the operating time of the i_{th} backup relay, and LCT represents the least coordination time (LCT). The superscripts p and b refer to primary relays and backup relays respectively. In Eq. (4), $TDS_{\max,i}$ and $TDS_{\min,i}$ are the maximum and minimum TDS limits respectively, whilst in Eq. (5), $PS_{\max,i}$ and $PS_{\min,i}$ are the maximum and minimum PS limits respectively. In Eq. (6), $t_{\max,i}^{p}$ and $t_{\min,i}^{p}$ are the maximum and minimum operating times of the primary relays respectively.

2.2. Problem formulation by considering both primary and backup DOCRs

The objective function formed by considering the total operating time of primary and backup relays for different fault locations is represented by OBJ_2, as shown in Eq. (7). The relay coordination study aims to minimize OBJ_2, such that the constraints mentioned by Eqs. (8)-(11) are satisfied.

$$OBJ_2 = \min_{TDS,PS} \sum_{i=1}^{n} \sum_{j=1}^{m} (t_{op,ij}^{p} + \sum_{k=1}^{K} t_{op,ij}^{b_k}) \tag{7}$$

$$t_{op,i}^{p} - t_{op,j}^{b} \geq LCT \tag{8}$$

$$TDS_{\min,i} \leq TDS_i \leq TDS_{\max,i} \tag{9}$$

$$PS_{\min,i} \leq PS_i \leq PS_{\max,i} \tag{10}$$

$$t_{\min,i}^{p} \leq t_{op,i}^{p} \leq t_{\max,i}^{p} \tag{11}$$

In this study, the minimum and maximum values of TDS and PS are considered in the range of [0.1, 1.1] and [0.5, 2.0], respectively [18]. The LCT value for different types of relays lies between 0.2 and 0.5 s [18]. The minimum LCT value considered is 0.2 s. Based on the range of TDS, PS, and LCT, the minimum and maximum operating times of relays are calculated to lie between 0.1 and 4.0 s.

After the formulation of the relay coordination problem, the optimal settings, operating time of relays, and OTPR are determined by GA, SA, and FA. The various parameters considered for solving the optimal relay coordination problem are shown in Table 1.

The algorithms have been executed several times with different values of the parameters and it has been found that with the parameters mentioned in Table 1, the minimum OTPR is obtained in the less iteration. The steps involved in the relay coordination problem by considering OBJ_1 and OBJ_2 are shown in Fig. 1.

Table 1 Algorithm parameters

Optimization technique	Parameters
FA	Iteration: 200 Population size: 50 Alpha: 0.25 Beta: 0.20 Gamma: 1
SA	Iteration: 200 Population size: 50 Boltzmann constant (k): 1 Energy norm: 1e-1 Alpha: 0.95
GA	Iteration: 200 Population size: 50

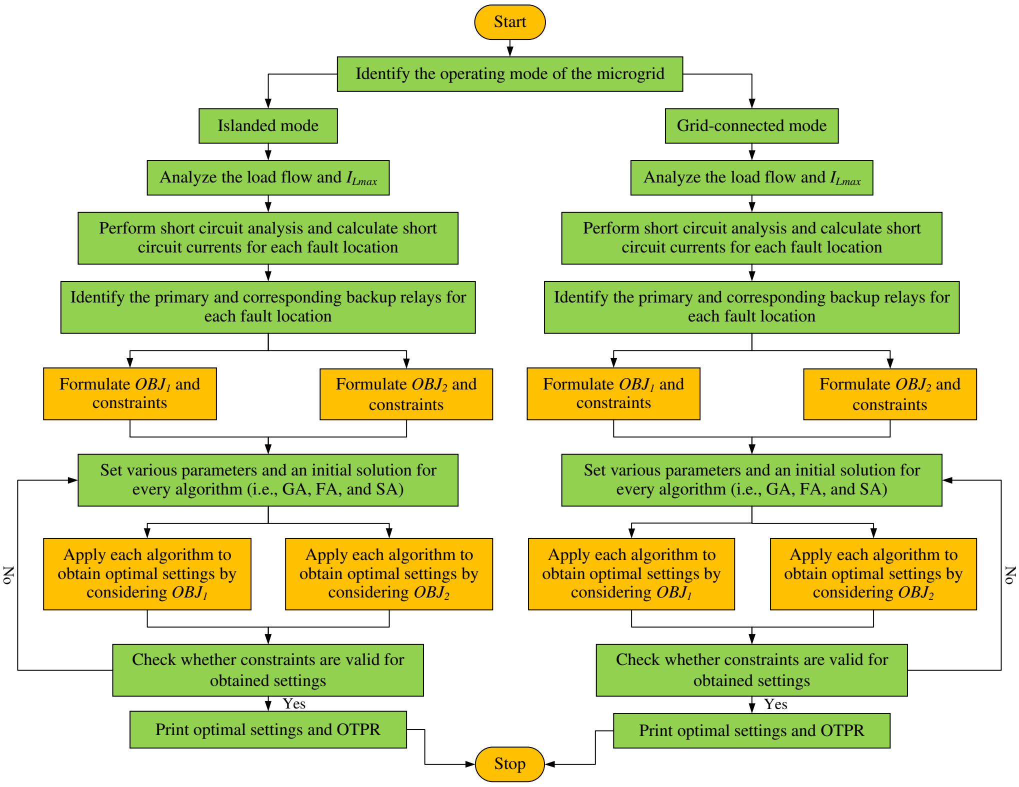

Fig. 1 Proposed methodology to obtain the optimal settings and OTPR in each operation mode of a microgrid

3. System Details and Simulation Setup

The performance of the proposed relay coordination scheme is tested on the 7-bus test system which is shown in Fig. 2. The system consists of a synchronous generator (SG) and two inverter-based distributed generators (IBDGs) with the highest generation limit of 50 MVA and 20 MVA, respectively. The SG and IBDGs are connected at bus B1, B2, and B7 respectively. In GCM, the microgrid has the highest generation limit of 60 MVA through B3 and B6. The maximum short-circuit level of the generators at B1, B2, B3, B6, and B7 are 250 MVA, 80 MVA, 300 MVA, 300 MVA, and 80 MVA, respectively [18]. The other parameters of the 7-bus test system are shown in the Appendix (Tables A-C).

For complete protection of the microgrid, it is required to have 16 DOCRs (two relays on each line). Among the 16 DOCRs, more than one backup relays are possible for some of the primary relays. For the considered fault locations, 22 primary-backup relay pairs are identified where each relay must operate for both near- and far-end faults within its division. In the microgrid, 3-phase faults are considered at eight locations (L1-L8). The fault currents in each operating mode of the microgrid along with the details of 22 primary-backup relay pairs are shown in Table 2. The primary-backup relay pairs are formed by considering different fault locations. As an example, for a fault at L1, R1 and R2 are the primary relays. In the conventional relay coordination scheme, the backup for R1 is R4 and R6 while R8 is the backup for relay R2.

The CTR for the DOCRs is calculated by Eq. (12) [29]. $I_{L\max,\,i}$ and $I_{f\max,\,i}$ is the maximum value of load currents and fault currents respectively for the i_{th} relay. The obtained CTR for each DOCR is shown in Table 3. The CTR is kept fixed in both operating modes of the microgrid.

$$CTR_i = MAXIMUM\,(I_{L\max,i}, \frac{I_{f\max,i}}{20}) \tag{12}$$

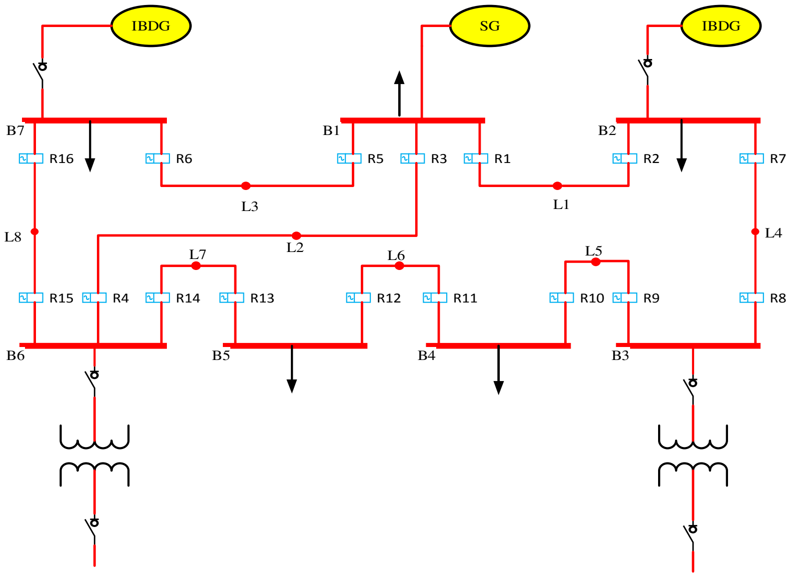

Fig. 2 The 7-bus test system (the low voltage part of IEEE-14 bus system)

Table 2 Fault currents in GCM and ISM for primary-backup relay pairs

Fault location	Serial number	Primary relay	Backup relay	GCM		ISM	
				I_{fp} (A)	I_{fb} (A)	I_{fp} (A)	I_{fb} (A)
L1	1	1	4	4830	1914	3612	384
	2	1	6	4830	812	3612	564
	3	2	8	3435	2069	2305	726
L2	4	3	2	5737	1641	4844	959
	5	3	6	5737	694	4844	333
	6	4	13	6430	1587	2140	954
	7	4	16	6430	543	2140	1057
L3	8	5	2	5503	1308	3968	928
	9	5	4	5503	1600	3968	323
	10	6	15	3357	1980	2345	835
L4	11	7	1	3519	1988	3087	1469
	12	8	10	5374	1170	1963	1403
L5	13	9	7	8019	1948	2678	2087
	14	10	12	2792	2607	2076	1886
L6	15	11	9	4777	4648	2197	2008
	16	12	14	3590	3544	2470	2419
L7	17	13	11	2926	2879	1548	1486
	18	14	3	6626	2206	3862	2548
	19	14	16	6626	964	3862	1173
L8	20	15	3	5673	1219	3048	2091
	21	15	13	5673	1245	3048	861
	22	16	5	3115	1829	2606	1233

Table 3 CTR of each DOCR

DOCR	CTR	DOCR	CTR
1	2000/5	9	2500/5
2	1000/5	10	1200/5
3	3000/5	11	1200/5
4	2000/5	12	2500/5
5	1600/5	13	800/5
6	1000/5	14	3000/5
7	2500/5	15	1600/5
8	1600/5	16	1600/5

4. Results and Analysis

This section presents an analysis of obtained results in the ISM, GCM, and common operating mode of the microgrid. Further, the comparison of OTPR is done by considering OBJ_1 and OBJ_2 as mentioned in sections 2.1. and 2.2., respectively. The results obtained in each mode are discussed in the subsequent sections.

4.1. Optimal settings of DOCRs for ISM of the microgrid

The optimal values of TDS and PS for DOCRs obtained by GA are shown in Table 4. The OTPR for OBJ_1 and OBJ_2 is found to be 10.4605 s and 8.7238 s, respectively. Table 5 shows the optimal values of TDS and PS for DOCRs along with the OTPRs obtained by FA. The OTPR is found to be 12.8877 s and 12.2794 s by considering OBJ_1 and OBJ_2, respectively. The optimal values of TDS and PS along with the OTPR calculated by SA are shown in Table 6. The OTPR in the two different cases is found to be 10.5005 s and 9.3621 s.

From the results, it is observed that the OTPR obtained by GA (considering OBJ_2) is the least compared to FA and SA. With the obtained settings for DOCRs, the operating time of each relay is calculated and the validity of constraints is checked. It is found that the backup relays for each fault location operate after the primary relays, which ensures the proper coordination among the relay pairs. The operating time of each relay is calculated, as shown in Figs. 3-5.

Table 4 DOCRs' optimal settings for ISM of the microgrid by GA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.3319	0.5925	0.2580	0.5057
2	0.2330	1.0582	0.2245	0.8020
3	0.3038	0.7264	0.2605	0.5554
4	0.1123	0.5467	0.1000	0.5000
5	0.1582	1.3321	0.2237	0.6234
6	0.2056	0.7581	0.2175	0.5000
7	0.3552	0.5415	0.2544	0.5000
8	0.1616	0.6837	0.1656	0.5218
9	0.2355	0.6097	0.2154	0.5000
10	0.2611	0.5305	0.2221	0.5842
11	0.2587	0.5078	0.1787	0.8300
12	0.2375	0.5470	0.2156	0.5401
13	0.2098	0.5529	0.1143	1.4239
14	0.3042	0.5306	0.2098	0.7637
15	0.1817	0.5135	0.1626	0.5386
16	0.3171	0.5239	0.2615	0.5000
OBJ_1	10.4605 s		8.7238 s	

Table 5 DOCRs' optimal settings for ISM of the microgrid by FA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.1848	0.5925	0.3883	0.5006
2	0.4278	1.0582	0.3333	1.1320
3	0.3286	0.7264	0.1278	1.7210
4	0.1000	0.5467	0.1062	0.5102
5	0.3211	1.3321	0.6611	0.5184
6	0.1542	0.7581	0.1431	1.1570
7	0.4348	0.5415	0.2230	1.1530
8	0.1000	0.6837	0.1001	1.3430
9	0.2003	0.6097	0.2246	1.1340
10	0.2475	0.5305	0.1435	1.2910
11	0.1300	0.5078	0.4338	0.5184
12	0.1726	0.5470	0.2133	0.5469
13	0.1809	0.5529	0.2623	1.0630
14	0.1338	0.5306	0.1890	0.8992
15	0.1000	0.5135	0.3919	0.5000
16	0.7338	0.5239	0.2153	1.0470
OBJ_1	12.8877 s		12.2794 s	

Table 6 DOCRs' optimal settings for ISM of the microgrid by SA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.3051	0.6772	0.2798	0.9400
2	0.1930	1.4575	0.1905	0.9016
3	0.3023	0.6585	0.1379	1.2968
4	0.1000	0.7346	0.1000	0.5000
5	0.3419	0.8322	0.2171	0.5078
6	0.3310	1.1063	0.2259	0.7389
7	0.2117	0.9168	0.2356	1.1253
8	0.1292	0.8771	0.1000	1.2937
9	0.1000	1.7884	0.3128	0.5822
10	0.2071	0.7078	0.1596	1.2188
11	0.2518	0.6454	0.2547	1.0700
12	0.1264	1.2345	0.1000	1.6294
13	0.2153	0.5030	0.1145	1.8884
14	0.1502	1.1870	0.1169	1.6186
15	0.1000	1.8054	0.1000	1.0525
16	0.2741	0.9114	0.1218	1.2567
OBJ_1	10.5005 s		9.3621 s	

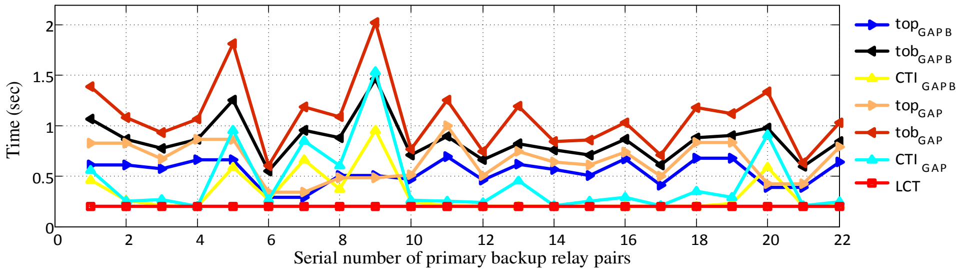

Fig. 3 The operating time of primary and backup relays along with the actual CTI for ISM of the microgrid using GA

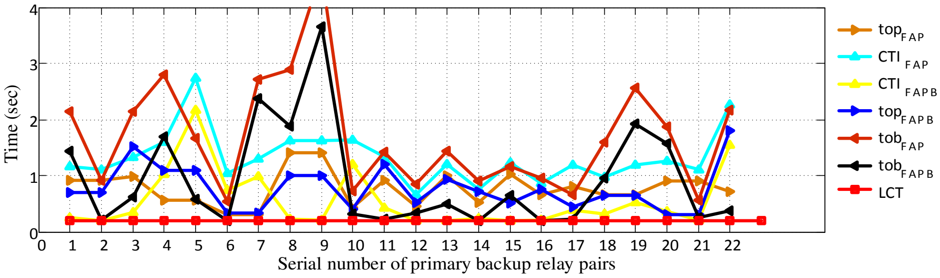

Fig. 4 The operating time of primary and backup relays along with the actual CTI for ISM of the microgrid using FA

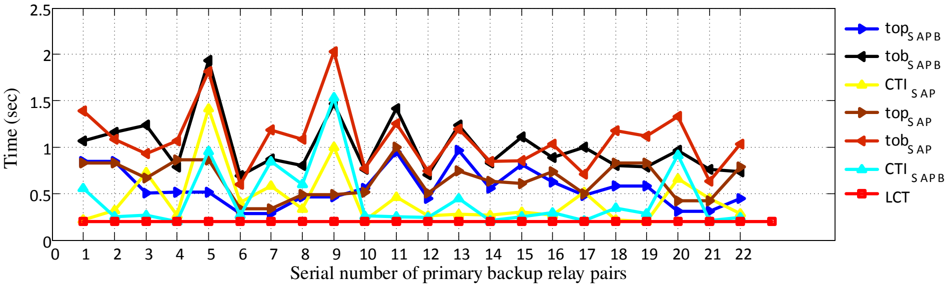

Fig. 5 The operating time of primary and backup relays along with the actual CTI for ISM of the microgrid using SA

The operating time of relay pairs along with the actual CTI obtained using GA, FA, and SA are shown in Figs. 3-5, respectively. In all the cases, the operating time of DOCRs is minimum when the objective function is formulated as OBJ_2. The operating time of DOCRs is the least when GA is used as an optimization tool. This is due to the higher values of operating time of backup relays for the obtained settings in the case of FA and SA. It is also observed that CTI is greater than the predefined LCT in all the cases.

4.2. Optimal settings of DOCRs for GCM of the microgrid

The optimal values of TDS and PS for the DOCRs determined by GA are shown in Table 7. The OTPR for OBJ_1 and OBJ_2 is found to be 8.5369 s and 7.0968 s, respectively. The optimal values of TDS and PS for the DOCRs along with the OTPR obtained by FA for OBJ_1 and OBJ_2 are shown in Table 8. The OTPR for both cases is 9.6819 s and 8.5967 s. The optimal values of TDS and PS for the DOCRs obtained by SA are shown in Table 9. The OTPR by considering OBJ_1 and OBJ_2 is calculated as 9.2857 s and 8.1609 s, respectively.

Thus, in the GCM, it is observed that the OTPR obtained by GA (considering OBJ_2) is the least compared to FA and SA. The operating time of primary and corresponding backup relays along with the actual CTI for each relay pair (considering OBJ_1 and OBJ_2) using GA, FA, and SA is shown in Figs. 6-8, respectively.

From Figs. 6-8, it is observed that the operating time of DOCRs (considering OBJ_2) obtained by GA is minimum as compared to FA and SA. This is due to the higher values of the operating time of backup relays with the settings obtained in FA and SA. It can also be concluded that the CTI is greater than the predefined LCT.

Table 7 DOCRs' optimal settings for GCM of the microgrid by GA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.1381	1.5540	0.2024	0.9400
2	0.2506	0.5005	0.1423	1.4120
3	0.1000	1.6393	0.1009	1.3613
4	0.2178	0.5235	0.1676	1.0090
5	0.2433	0.5000	0.1392	1.2205
6	0.1669	0.7148	0.1455	1.0459
7	0.2022	0.7598	0.2448	0.5104
8	0.3345	0.5066	0.1049	1.8942
9	0.2452	1.2279	0.3209	0.5000
10	0.2903	0.5018	0.1087	1.1828
11	0.2787	0.9893	0.1835	2.0000
12	0.2818	0.5166	0.1268	0.9921
13	0.2885	0.5188	0.2673	0.5111
14	0.1794	1.5935	0.2230	0.5471
15	0.2169	0.5086	0.1511	0.9596
16	0.1625	0.8359	0.1840	0.5000
OBJ_1	8.5369 s		7.0968 s	

Table 8 DOCRs' optimal settings for GCM of the microgrid by FA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.3773	0.5778	0.2114	0.9494
2	0.1324	1.8590	0.2480	1.102
3	0.1353	1.0250	0.2456	0.5000
4	0.2143	1.1590	0.1599	1.2180
5	0.1018	1.6000	0.3769	0.5251
6	0.3170	0.6548	0.1000	1.6940
7	0.1291	1.8310	0.2009	0.8523
8	0.1398	1.7350	0.1708	1.5620
9	0.3670	1.2700	0.2569	1.3600
10	0.1000	1.6880	0.1753	0.8533
11	0.5005	0.8227	0.2948	1.2130
12	0.1516	0.8005	0.1079	1.6760
13	0.3535	1.7510	0.2241	0.8557
14	0.2390	0.5225	0.2370	0.8545
15	0.3076	0.6464	0.1000	1.5870
16	0.1164	1.0020	0.1669	0.7540
OBJ_1	9.6819 s		8.5967 s	

Table 9 DOCRs' optimal settings for GCM of the microgrid by SA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.1372	1.6910	0.1248	1.8540
2	0.3344	0.8360	0.2483	0.8041
3	0.2510	0.7837	0.2228	0.5256
4	0.1284	1.4290	0.1000	1.7790
5	0.1814	0.9144	0.3127	0.5293
6	0.2356	0.5926	0.1735	0.7872
7	0.1336	1.3780	0.1990	0.9265
8	0.3510	0.5218	0.1379	1.9280
9	0.2403	1.3320	0.2501	1.4250
10	0.2487	0.7849	0.1215	1.3120
11	0.3255	0.5463	0.2297	1.8250
12	0.3020	0.5812	0.2101	0.5260
13	0.1602	1.7430	0.1997	1.6400
14	0.3722	0.5975	0.1261	1.8830
15	0.1165	1.9190	0.1798	0.8782
16	0.1180	1.6190	0.1893	0.6033
OBJ_1	9.2857 s		8.1609 s	

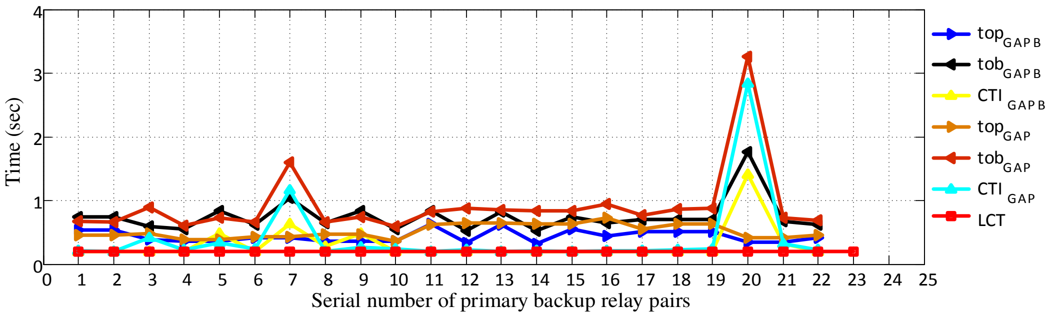

Fig. 6 The operating time of primary and backup relays along with the actual CTI for GCM of the microgrid using GA

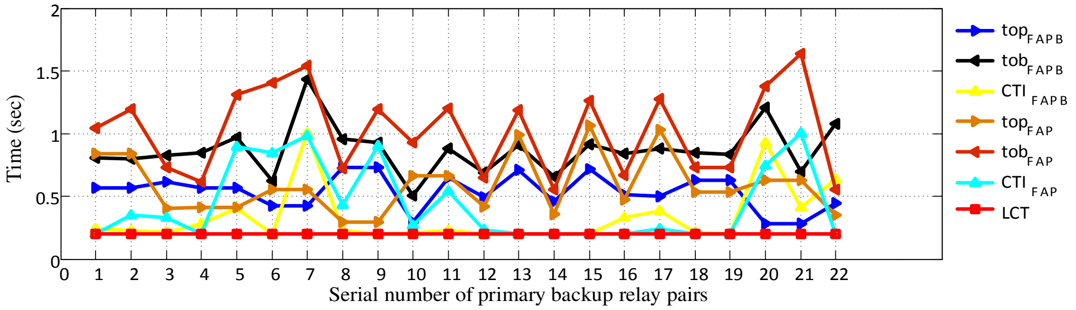

Fig. 7 The operating time of primary and backup relays along with the actual CTI for GCM of the microgrid using FA

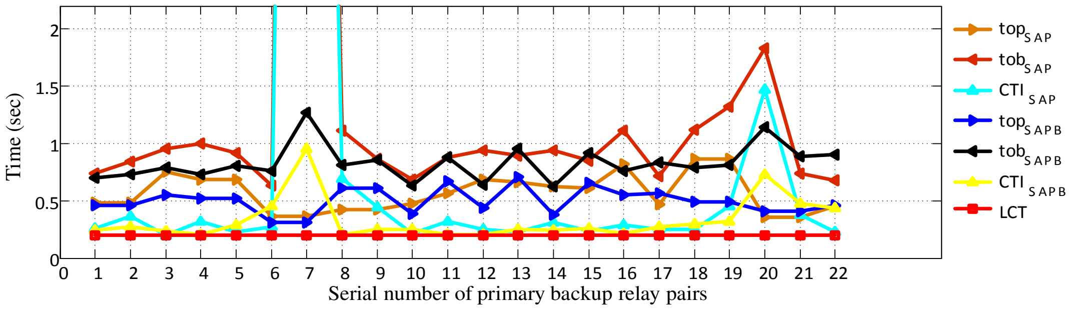

Fig. 8 The operating time of primary and backup relays along with the actual CTI for GCM of the microgrid using SA

4.3. Common optimal setting of DOCRs for both GCM and ISM of the microgrid

The optimal settings of DOCRs obtained in the ISM may miscoordinate the relay pairs when used for protecting the microgrid in the GCM and vice versa. Therefore, depending upon the operation mode of the microgrid, two sets of optimal settings of DOCRs are required to prevent any miscoordination. Thus, it is required to determine common optimal settings that remain valid in both the operating modes. To achieve this, the constraints of both modes are combined simultaneously. The number of DOCRs remains the same, but the primary-backup relay pairs become double, i.e., (44), compared to the relay pairs when each mode is considered separately. The steps involved in the relay coordination study for determining the common optimal settings are shown in Fig. 9.

The common optimal settings of DOCRs for the 7-bus test system obtained using GA, FA, and SA are shown in Tables 10-12 respectively. The optimal values of TDS and PS determined by GA are shown in Table 10. The OTPR for OBJ_1 and OBJ_2 is found to be 13.1740 s and 11.4691 s, respectively. Table 11 shows the common optimal settings of the DOCRs along with the OTPR obtained by FA. The OTPR for OBJ_1 and OBJ_2 is found as 20.5662 s and 17.2724 s, respectively. Table 12 shows the OTPR along with the common optimal values of TDS and PS for the DOCRs obtained by SA. The OTPR for OBJ_1 and OBJ_2 is found to be 15.1859 s and 14.0270 s, respectively.

From the results, it is observed that the OTPR obtained by GA (considering OBJ_2) is the least compared to FA and SA. The optimal settings obtained in all the cases are valid in both GCM and ISM. The operating time of the primary relays and the corresponding backup relays along with the actual CTI for each relay pair (for OBJ_1 and OBJ_2) using GA, FA, and SA are shown in Figs. 10-12, respectively. In the figures, the first 22 relay pairs are for the ISM and the last 22 relay pairs are for the GCM of the microgrid. Thus, from Figs. 10-12, it is observed that the operating time of the relays (considering OBJ_2) obtained by GA is the least compared to FA and SA. This is due to the higher values of operating time of the backup relays with the settings obtained in FA and SA. It can also be concluded that the CTI is greater than the predefined LCT.

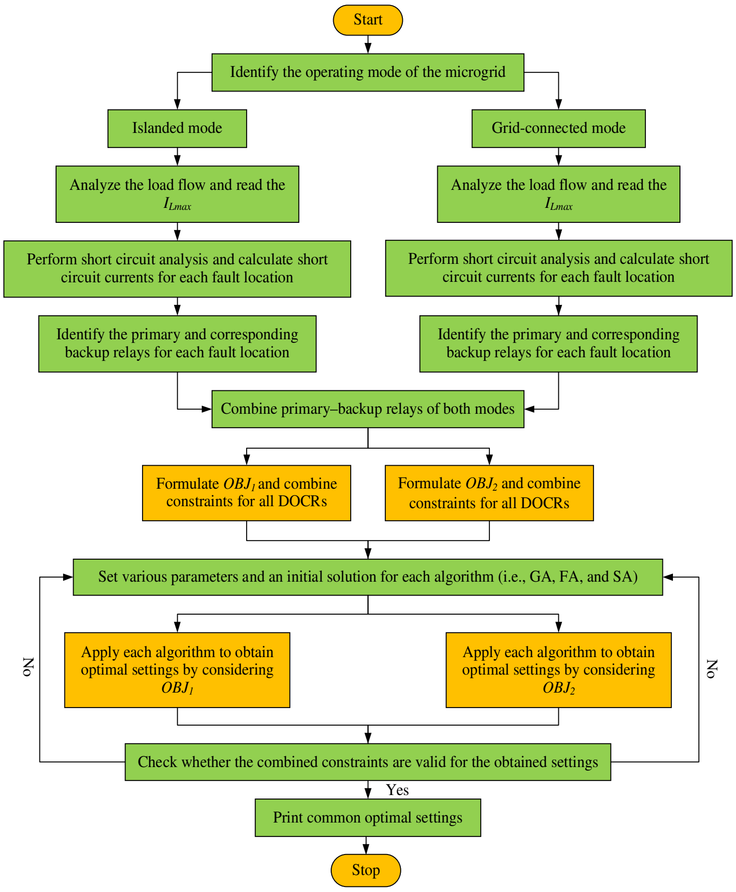

Fig. 9 Proposed methodology for common optimal settings for both operating modes

Table 10 DOCRs' common optimal settings for both operating modes by GA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.2395	0.9261	0.2773	1.2188
2	0.4935	0.5750	0.3652	0.5008
3	0.4352	0.5832	0.1758	1.6308
4	0.2777	0.5773	0.3384	0.5032
5	0.4043	0.5218	0.2437	0.7850
6	0.3462	0.5361	0.2695	0.6753
7	0.1446	1.9531	0.4371	0.5070
8	0.3296	0.9623	0.3547	0.5014
9	0.3886	0.5002	0.3367	0.7157
10	0.5141	0.5016	0.2619	1.2571
11	0.3311	0.7968	0.2695	1.4142
12	0.3610	0.7868	0.3605	0.5067
13	0.2290	1.4882	0.2361	1.5156
14	0.4716	0.5149	0.2400	1.3607
15	0.3239	0.5035	0.1715	1.3918
16	0.3762	0.6419	0.1757	1.4150
OBJ_1	13.1740 s		11.4691 s	

Table 11 DOCRs' common optimal settings for both operating modes by FA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.3696	1.7870	0.2813	1.9580
2	0.6500	0.5403	0.3333	1.5860
3	0.2605	1.5450	0.3497	0.9366
4	0.5794	0.5004	0.4524	0.5355
5	0.2064	1.7020	0.4055	0.7996
6	0.7277	0.6939	0.1857	1.4620
7	0.5763	1.1850	0.4658	1.2950
8	0.3212	1.4340	0.2906	1.2320
9	0.5673	1.4090	0.7348	0.7430
10	0.4005	1.1950	0.4330	0.7894
11	0.8426	0.6754	0.6839	1.4180
12	0.2225	1.7400	0.3231	0.9496
13	0.6453	1.2270	0.3717	1.2830
14	0.3640	1.1010	0.5098	0.5261
15	0.6000	0.8903	0.2072	1.4580
16	0.3056	1.0670	0.4000	0.6699
OBJ_1	20.5662 s		17.2724 s	

Table 12 DOCRs' common optimal settings for both operating modes by SA

Relay	OBJ_1		OBJ_2	
	TDS	PS	TDS	PS
1	0.5081	0.6798	0.4187	0.7925
2	0.2938	1.4130	0.3067	1.1250
3	0.2138	1.8700	0.1397	2.0000
4	0.4589	0.6024	0.4077	0.5434
5	0.5598	0.5000	0.4294	0.6263
6	0.2123	1.5800	0.3149	1.0720
7	0.4467	0.9054	0.3232	1.3540
8	0.2590	1.1290	0.2524	1.0770
9	0.4505	0.9481	0.5455	0.6160
10	0.4503	0.6394	0.2351	1.5680
11	0.4452	1.2960	0.5735	0.5599
12	0.4388	0.5228	0.1623	1.7980
13	0.2738	1.9380	0.2956	1.6220
14	0.4253	0.7048	0.2892	1.0040
15	0.1495	1.8910	0.4036	0.6124
16	0.2221	1.3360	0.3358	0.6586
OBJ_1	15.1859 s		14.0270 s	

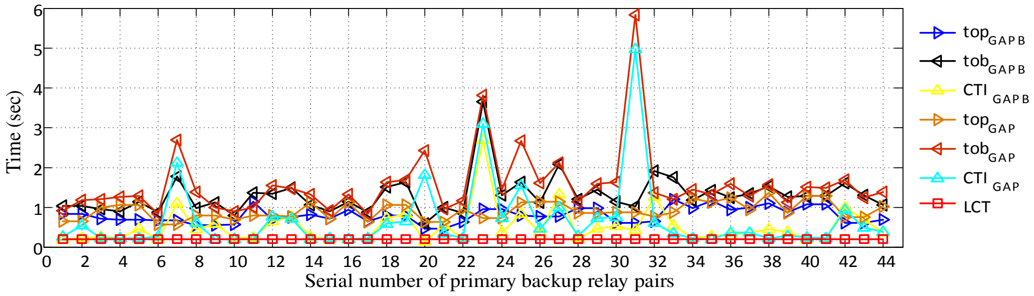

Fig. 10 The operating time of primary and backup relays along with the actual CTI for the relay pairs in both operating modes by using GA

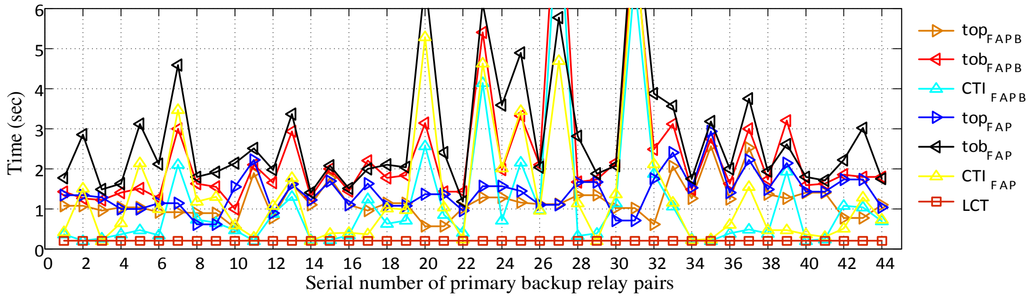

Fig. 11 The operating time of primary and backup relays along with the actual CTI for the relay pairs in both operating modes by using FA

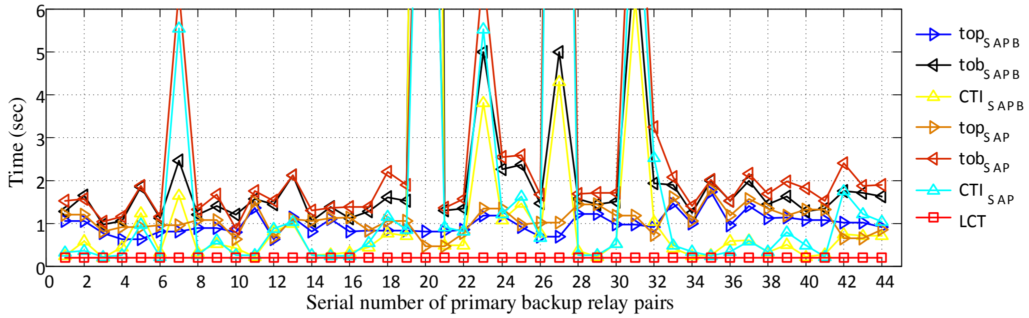

Fig. 12 The operating time of primary and backup relays along with the actual CTI for the relay pairs in both operating modes by using SA

4.4. Comparison of the convergence characteristics of the objective functions in various operating modes

The performance of the three optimization techniques in each operating mode is shown in Table 13. From the convergence characteristics, it is found that the performance of GA is better compared to FA and SA in each operating mode of the microgrid for OBJ_1 and OBJ_2. The iterations required for the convergence of OBJ_1 and OBJ_2 in three algorithms are shown in Table 13. It can be seen that the minimum iteration is required in each operating mode when the relay coordination problem is solved using GA.

Table 13 Comparison of different optimization techniques in terms of iterations

Operating modes	Algorithms	No. of iteration	
		OBJ_1	OBJ_2
ISM	GA	1050	300
	FA	1100	450
	SA	1070	900
GCM	GA	700	300
	FA	900	450
	SA	750	900
Both	GA	625	500
	FA	1050	600
	SA	700	690

4.5. Violation of coordination constraints

The number of coordination constraint violations for OBJ_1 and OBJ_2 is calculated by applying the obtained settings from one to another operating mode of the microgrid. The coordination constraint is said to be violated if any of the following conditions are observed:

(1) The backup relay operates before the primary relay.

(2) The fixed LCT becomes greater than the CTI, for any primary backup relay pair.

The number of coordination constraint violations in each operating mode is shown in Table 14. When the optimal settings of DOCRs determined in the ISM are applied to the DOCRs in GCM, many constraint violations occur. Similarly, many violations of coordination constraints are observed when the optimal settings of DOCRs determined in GCM of the microgrid are applied to the DOCRs in the ISM of the microgrid. Further, the common optimal settings of DOCRs obtained are found to be valid in either of the operating modes, i.e., no violation of coordination constraint occurs.

Table 14 Violations of coordination constraints in each operating mode of the microgrid

Settings calculated	Algorithms	Number of violations of coordination constraint (relay number)			
		ISM		GCM	
		OBJ_1	OBJ_2	OBJ_1	OBJ_2
ISM	GA	0	0	12, 13, 18, 19	1, 7, 9, 12, 13, 18
	FA	0	0	1, 7, 9, 12, 13, 19, 20	1, 5, 9, 12, 13, 18, 19
	SA	0	0	1, 9, 12, 13	1, 9, 12, 13, 18, 19
GCM	GA	1, 3, 4, 9	1, 3, 9	0	0
	FA	1, 3, 5, 9, 11, 22	1, 2, 3, 9, 15	0	0
	SA	1, 3, 4, 9, 10, 15	1, 3, 9, 10	0	0
Common optimal settings	GA	0	0	0	0
	FA	0	0	0	0
	SA	0	0	0	0

4.6. Comparison of the results obtained

To summarize the performance of GA, FA, and SA, a comparative analysis of the OTPR for OBJ_1 and OBJ_2 is done as shown in Table 15. In Table 15, it can be seen that the OTPR determined using GA is better than FA and SA in each operating mode. It can be analyzed that the obtained OTPR considering OBJ_2 is less compared to OBJ_1. This study demonstrates that GA is superior for solving the relay coordination problem.

Table 15 OTPR by considering two objective functions in each operating mode

Operating modes	Algorithms	OTPR	
		OBJ_1	OBJ_2
ISM	GA	10.4605 s	8.7238 s
	FA	12.8877 s	12.2794 s
	SA	10.5005 s	9.3621 s
GCM	GA	8.5369 s	7.0968 s
	FA	9.6819 s	8.5967 s
	SA	9.2857 s	8.1609 s
Both	GA	13.1740 s	11.4691 s
	FA	20.5662 s	17.2724 s
	SA	15.1859 s	14.0270 s

5. Conclusions

An analysis of optimal settings of DOCRs considering NI characteristics for the operating modes of an AC microgrid has been presented in this study. It can be concluded that the determined optimal settings obtained in GCM are not sufficient to properly coordinate the relays in the ISM of the microgrid and vice-versa. To tackle the problem of multiple settings for the different operating modes and to solve the miscoordination problem, the common optimal settings have been determined to be valid in both GCM and ISM of the microgrid. Three different types of algorithms, namely GA, FA, and SA, have been considered for solving the relay coordination problem.

From the obtained results in different cases, it has been concluded that GA is better than FA and SA in terms of the OTPR and iterations required. Further, it has been observed that the performance of the algorithms is better when both primary and backup relays are considered in the formulation of the objective functions. The optimal settings obtained in common operating modes are robust as no miscoordination of relays occurs in any of the operating modes of the microgrid. The proposed relay coordination scheme may apply to all the industrial microgrid systems (both mesh and radial distributed generation-based systems) operating at low and medium voltage levels. Therefore, with the obtained optimal settings in either of the operating modes, the protection coordination requirements in such industries can be fulfilled. The proposed work can be extended for estimating the performance of relay coordination problems with different standard and user-defined relay characteristics.

Nomenclature

TDS	Time dial setting	OTPR	Total operating time of primary relays
PS	Plug setting	FA	Firefly algorithm
CTR	Current transformer ratio	SA	Simulated annealing algorithm
ISM	Islanded mode	GA	Genetic algorithm
GCM	Grid-connected mode	LCT	Least coordination time
t_{op}	Operating time of relay	SG	Synchronous generator
DOCR	Directional overcurrent relay	IBDG	Inverter-based distributed generator
DER	Distributed energy resource	NI	Normal inverse
LP	Linear programming	OBJ_1	The objective function formed by considering the total operating time of primary relays
NLP	Nonlinear programming	OBJ_2	The objective function formed by considering the total operating time of primary and backup relays
MINLP	Mixed-integer nonlinear programming		

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Table A Fault level, power source, and power transformer details of the 7-bus test system

Fault level details (MVA)					Power source details						Power transformer details	
Generator		SG	IBDG		Generator (MVA)		SG (MVA)	IBDG (MVA)		Base voltage	Tap setting value (p.u.)	
B3	B6	B1	B2	B7	B3	B6	B1	B2	B7	11 kV	B3	B6
300	300	250	80	80	60	60	50	20	20		0.932	0.969

Table B Line details of the 7-bus test system

Transmission line details						
Line no.	From bus	To bus	Line impedance (p.u.)		Half-line charging susceptance (p.u.)	MVA rating
			Resistance	Reactance		
1	1	2	0.17093	0.34802	0	12
2	1	6	0.06615	0.13027	0	32
3	1	7	0.22092	0.19988	0	12
4	2	3	0.12711	0.27038	0	32
5	3	4	0.03181	0.08450	0	32
6	4	5	0.08205	0.19207	0	12
7	5	6	0.09498	0.19890	0	18
8	6	7	0.12291	0.25581	0	32

Table C DOCR details and fault type in the 7-bus test system

DOCR details	Fault type
• Standard IDMT characteristics of IEC-60255-3 • Normal inverse characteristic curve	Mid-point fault (3-phase fault)