Optimal Coordination of Dual-Setting Directional Overcurrent Relays in Microgrids

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***Abstract*— Microgrids are gaining popularity due to their improved reliability and resilience. However, their protection is challenging due to bidirectional current flow and varying fault current levels in different operating modes. This paper proposes the use of dual-setting directional overcurrent relays for microgrid protection. To demonstrate their effectiveness, a comparative analysis of dual-setting relays and conventional relays is conducted. The relay coordination problem is formulated as a nonlinear programming problem, and the settings of relays are optimally determined using genetic algorithm and an efficient hybrid optimization algorithm that combines the modified firefly algorithm and genetic algorithm to minimize the overall relay operating time for primary relays. The proposed scheme is implemented on the distribution section of the IEEE-14 bus system, demonstrating a reduction in total system operating time with dual-setting directional overcurrent relays.**

Keywords—Microgrid protection, Dual-setting directional overcurrent relays, Firefly algorithm, Optimization.

I. Introduction

Microgrids are electrical systems that combine renewable energy sources, energy storage, and loads [1]. They can operate in grid-connected or islanded mode, offering many benefits, including high reliability and efficiency, lower carbon emissions, and reduced technical losses [2]. AC microgrids are popular due to their simple design, efficient performance, and ease of modeling [3]. However, their control and protection are two key challenges that must be addressed for proper operation [4]. AC microgrid protection is challenging task due to the bidirectional flow of current and varying fault current levels in different operating modes [5].

Directional overcurrent relays (DOCRs) are one of the main AC microgrid protection elements [6]. They monitor current flow to identify abnormal conditions, such as short circuits and overcurrents. When a fault is detected, the DOCR sends a trip signal to the circuit breaker, which opens the circuit and isolates the faulted section of the electric network [7].

Relay coordination ensures that protective relays operate in the correct order when a fault occurs. Primary and backup relay pairs are identified based on the fault location in the network. For proper relay coordination, the primary relay must operate before the backup relay, with a time gap known as the coordination time interval (CTI) [8]. Proper coordination among DOCRs is necessary to prevent unwanted power outages. This can be achieved by optimizing the settings and curve selections of the DOCRs [3].

DOCRs are configured with two settings, the time multiplier setting (TMS) and the plug setting (PS). The coordination scheme for DOCRs can be formulated as a linear, nonlinear, or mixed integer nonlinear programming problem, depending on the two relay settings. In linear programming, only the TMS is treated as a decision variable, while the PS is fixed. In nonlinear programming, both TMS and PS are treated as continuous decision variables. In mixed-integer nonlinear programming, TMS is continuous, while PS is discrete [8], [9]. The DOCR coordination problem can be formulated as an optimization problem to minimize the total operating time of the DOCRs, subject to various constraints and boundary limits, such as relay settings and selectivity constraints [7].

Once the coordination problem has been formulated as an optimization problem, it can be solved using a variety of optimization algorithms, including conventional optimization methods [10], [11] like linear programming [10], and sequential quadratic programming [11]. Additionally, metaheuristic algorithms [9], [12]–[15] such as genetic algorithm [12], particle swarm algorithm [13], firefly algorithm [9], cuckoo search algorithm [14], and grey wolf optimizer [15]. Moreover, hybrid approaches [16]–[18] such as combining particle swarm algorithm with differential evolution [16], utilizing artificial bee colony algorithm with linear programming [17], and biogeography-based optimization-linear programming technique [18]. All of these optimization algorithms are used with conventional DOCRs scheme, which has a single relay setting that can be utilized for both primary and backup relay operation. Dual-setting DOCRs have two different relay settings (PS_{FWD}, TMS_{FWD}, and PS_{REV}, TMS_{REV}) that depend on the direction of fault current. When the fault current flows in the forward direction, the relay acts as the primary relay, while when the fault current flows in the reverse direction, the same relay acts as the backup protection in both operating modes of the microgrid [19]. The main advantage of dual-setting relays is that one relay can be used in place of two relays, which can significantly reduce the total operating time of the relays [20].

This article presents a comparative analysis of conventional and dual-setting DOCRs having different standard relay characteristics for the protection of the 7-bus AC microgrid test system. The coordination problem is expressed as a nonlinear programming problem and solved using a genetic algorithm and an efficient hybrid algorithm that combines modified firefly algorithm and genetic algorithm proposed in [7]. The main contributions of this study can be summarized as follows:

- Compare the performance of conventional and dual-setting DOCRs for the protection of the 7-bus AC microgrid test system.
- Analyze the impact of different relay settings on the performance of the protection system, highlighting the influence of standard relay characteristics on the overall performance.

- Evaluate the performance of the genetic algorithm and the hybrid firefly genetic algorithm on the formulated relay coordination problem.

The remaining sections of this paper are structured as follows. Section II presents the coordination problem formulation. In Section III, an introduction to the proposed algorithms designed to solve the coordination problem is provided. Section IV describes the system that was tested. Section V provides the optimization results, along with discussions and a comparative analysis between dual-setting and conventional relays. Finally, Section VI concludes the paper.

II. Problem Formulation

Conventional DOCRs have two settings that determine the shape of the relay characteristic curve. These settings are optimized to minimize the total relay operating time while satisfying selectivity constraints and relay settings. The relay acts as the primary or backup relay depending on the direction of fault current. In contrast, each dual-setting DOCR has two independent sets of relay settings for the forward and reverse directions of fault current [20]. Fig. 1 shows the time-current characteristics of the dual-setting DOCR. Each relay characteristic is identified using the characteristic coefficients shown in Table I.

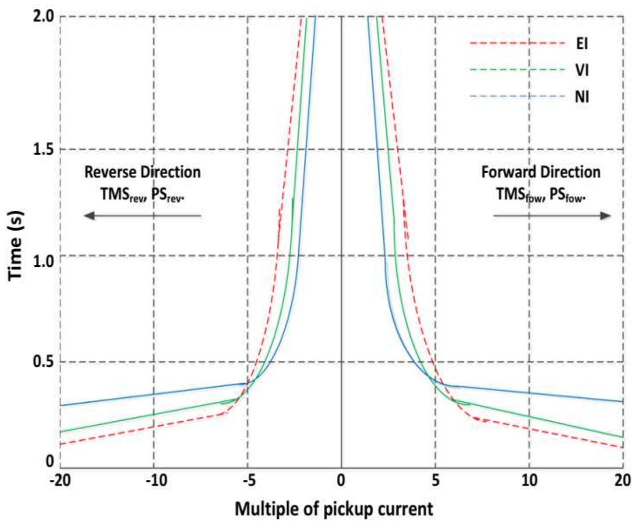

Fig. 1. Time–current characteristics for dual-setting DOCR [8].

TABLE I. Overcurrent relay characteristics coefficient, according to IEC-60255 standard.

Characteristic curve	α	β
Normal Inverse (NI)	0.14	0.02
Very Inverse (VI)	13.5	1
Extremely Inverse (EI)	80	2

A. Objective Function Formulation

The protection coordination problem is generally expressed as an optimization problem where the main objective is to minimize the total relay operating time. The operating time of the conventional inverse time DOCR is a function of the short circuit current (I_{sc}) and the two relay settings TMS and PS. This is expressed in the following equation [21]:

$$T_{op} = \frac{\alpha\ x\ TMS}{(\frac{I_{sc}}{PS\ x\ CTR})^{\beta} - 1} \tag{1}$$

Dual-setting relays can have two different sets of settings, each designated for a specific fault direction, as shown in Fig. 1. The relay will act as the primary or backup unit depending on which set of settings (forward or reverse) is used. The dual-setting relay operating times can be expressed as follows [22]:

$$T_{op\_FWD} = \frac{\alpha\ X\ TMS_{FWD}}{(\frac{I_{sc}}{PS_{FWD}\ x\ CTR})^{\beta} - 1} \tag{2}$$

$$T_{op\_REV} = \frac{\alpha\ X\ TMS_{REV}}{(\frac{I_{sc}}{PS_{REV}\ x\ CTR})^{\beta} - 1} \tag{3}$$

The relay characteristic coefficients α and β are selected according to the IEC-60255 standard as presented in Table 1. TMS_{FWD} and TMS_{REV} are the time multiplier settings, and PS_{FWD} and PS_{REV} are the plug settings of relays operating in the forward and reverse directions, respectively. CTR is the current transformer ratio of the relay.

The objective function (OF) for relay coordination is to minimize the total operating time of all primary relays for different fault locations, as expressed in the following equation:

$$OF = \min \sum_{i=1}^{n} T_{op\_FWD}^{i} \tag{4}$$

where, $T_{op\_FWD}^{i}$ is the operating time of the i-th relay in the forward direction, and n is the number of primary relays for different fault locations.

B. Constraint Formulation

The minimization of the objective function in (4) is subject to two sets of constraints. The first set of constraints relates to the relay's characteristics, including the time multiplier setting as specified in (5) and the time plug setting as described in (6). The second set of constraints ensures selective relay operation, as represented in (7).

$$TMS_{min} \leq TMS_{FWD}, TMS_{REV} \leq TMS_{max} \tag{5}$$

$$PS_{min} \leq PS_{FWD}, PS_{REV} \leq PS_{max} \tag{6}$$

$$T_{op\_REV} - T_{op\_FWD} \geq CTI \tag{7}$$

where, TMS_{min} and TMS_{max} are the minimum and maximum time multiplier settings for the relay, which are defined as 0.1 and 1.1, PS_{min} and PS_{max} are the minimum and maximum plug settings for the relay which are specified as 0.5 and 2, respectively. CTI is the coordination time interval, and its minimum value is 0.2 seconds.

III. Optimization Algorithm

The objective of optimization is to determine the optimal configuration for the DOCRs, aiming to minimize the total relay operating time while ensuring that all constraints are met. Each dual-setting DOCR involves twice the number of variables utilized in conventional DOCRs. In the case of the forward direction of fault current, the relay is associated to the forward settings (TMS_{FWD}, PS_{FWD}), and for the reverse direction, the same relay is associated with reverse settings (TMS_{REV}, PS_{REV}). In this article, genetic algorithm and an efficient hybrid approach that combines the modified firefly algorithm and genetic algorithm are used to determine the optimal settings of the relays.

In the hybrid algorithm proposed in [7], the firefly algorithm is modified to achieve a global solution by updating the brightness of fireflies and preventing excessive distances between individual fireflies. This modification aims to enhance convergence rates while ensuring controlled, randomized movements. Then, the optimization problem is solved using the genetic algorithm. The solution obtained from the modified firefly algorithm serves as the initial population for the genetic algorithm, further enhancing the overall optimization process.

The proposed methodology for utilizing dual-setting DOCR starts with identifying the microgrid's operating mode. Following this, short circuit analysis is conducted to calculate the three-phase fault current at each line's midpoint. Based on this analysis, the suitable relay pair is identified. Finally, the optimization algorithm is initiated to determine the optimal settings for these relays.

IV. Test System Description

In this article, 7-bus AC microgrid derived from the IEEE 14-bus test system, as shown in Fig. 2, is considered to study and analyze the proposed protection scheme and demonstrate the effectiveness of dual-setting DOCRs over conventional DOCRs.

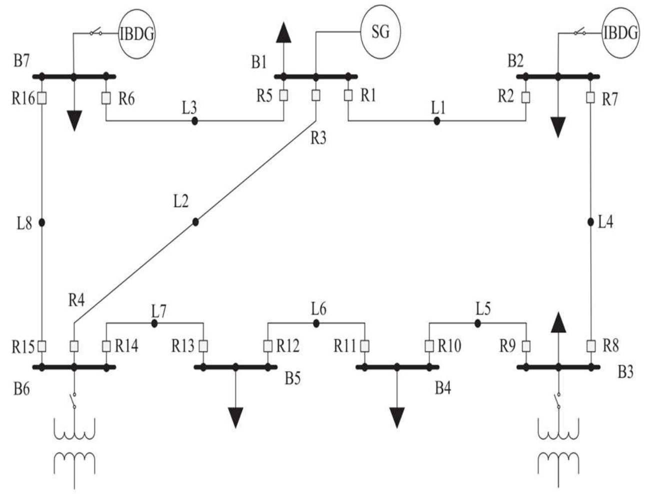

Fig. 2. Single line digaram of the 7-bus AC microgrid system [3].

The 7-bus AC microgrid powered by a synchronous generator (SG) connected at bus 1 and two Inverter-Based Distributed Generators (IBDGs) connected at buses 2 and 7. Additionally, in the grid-connected mode, this system is designed to receive power through two specific buses (B3 and B6). Detailed information about the original system is available in [23]. The AC microgrid test system has 8 lines, each protected by two dual-setting DOCRs, one at each end. The CTR for each dual-setting DOCRs are given in Table II. Table III shows the short-circuit current magnitudes for different fault locations in both operating modes of the microgrid. The short circuit current results show that the microgrid's operating modes create diverse fault scenarios, challenging the protection system's selectivity, sensitivity, and speed.

V. Optimization Results and Discussion

The main objective of this study is to demonstrate the effectiveness of utilizing dual-setting DOCR over conventional DOCRs in minimizing the operating time for AC microgrid protection, considering various standard characteristics. In this section, simulation results for conventional DOCRs using genetic algorithm (GA) are obtained from [3]. Simulation results for dual-setting DOCRs using GA and the hybrid firefly genetic algorithm (FA-GA) in both microgrid operating modes are also presented.

TABLE II. CTR values for each DOCRs.

Relay	CTR	Relay	CTR	Relay	CTR	Relay	CTR
1	400	5	320	9	500	13	160
2	200	6	200	10	240	14	600
3	600	7	500	11	240	15	320
4	400	8	320	12	500	16	320

TABLE III. Primary-backup relay pairs and short circuit currents in the 7-bus microgrid.

Faulty Line	Relay Pair	Primary Relay	Backup Relay	Grid Connected Mode		Islanded Mode	
				Short circuit current (primary) (A)	*Short circuit current (backup) (A)*	*Short circuit current (primary) (A)*	*Short circuit current (backup) (A)*
L1	1	1	3	4830	1914	3612	384
	2	1	5	4830	809.6	3612	563.2
	3	2	7	3435	2065	2304	725
L2	4	3	1	5736.6	1640	4842	956
	5	3	5	5736.6	691.2	4842	332.8
	6	4	14	6430	1584	2140	954
	7	4	15	6430	540.8	2140	1056
L3	8	5	1	5502.72	1308	3968	928
	9	5	3	5502.72	1602	3968	322.8
	10	6	16	3357	1977.6	2344	832
L4	11	7	2	3519	1988	3087	1468
	12	8	9	5373.76	1170	1962.9	1400
L5	13	9	8	8019	1945.6	2678	2086.4
	14	10	11	2792.16	2606.4	2076	1884
L6	15	11	10	4776	4648.8	2197	2006.4
	16	12	13	3590	3544	2470	2417.6
L7	17	13	12	2924.8	2875	1548	1485
	18	14	4	6624	2204	3858	2548
	19	14	15	6624	998.4	3858	1171.2
L8	20	15	4	5672.96	1218.8	3046.4	2088
	21	15	14	5672.96	1245	3046.4	861
	22	16	6	3114.88	1829	2604.8	1233

A. Grid Connected Operating Mode

The optimal settings achieved for the 7-bus microgrid test system using various relay curves for both dual-setting DOCR and conventional DOCR, are presented in Tables IV, V, and VI for the grid-connected mode.

The objective function values for all 16 conventional relays, considering NI, VI, and EI characteristics, are 7.2041, 2.4392, and 1.6681 seconds, respectively, achieved using genetic algorithm. In contrast, the total operating times of the 16 dual-setting DOCRs, with NI, VI, and EI parameters, are reduced to 3.65379, 1.6258, and 1.6100 seconds, respectively, using the genetic algorithm. Additionally, the hybrid firefly genetic algorithm further optimized the objective function values, indicating its effectiveness in obtaining better relay settings. Furthermore, the optimal settings corresponding to the EI characteristic curves of the relays are the best, as they achieve the shortest total operating time of all 16 DOCRs in the grid-connected operating mode of the 7-bus system.

TABLE IV. OPTIMAL RELAY SETTINGS WITH NORMAL INVERSE STANDARD CHARACTERISTIC FOR DUAL-SETTING DOCR IN GRID-CONNECTED MODE

Normal Inverse Characteristic										
Relay	Conven. DOCR		Dual Setting DOCR							
	GA [3]		*GA*				*FA-GA*			
	PS	*TMS (Sec)*	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)
1	0.635	0.224	0.500	0.111	1.450	0.600	0.501	0.351	1.722	0.351
2	0.789	0.210	0.500	0.100	0.532	0.997	0.504	0.546	1.845	0.546
3	0.917	0.142	0.500	0.100	0.500	0.351	0.500	0.463	1.017	0.463
4	1.045	0.158	0.500	0.105	0.683	0.863	0.501	0.549	1.428	0.549
5	0.518	0.217	0.500	0.100	0.505	0.668	0.501	0.433	0.870	0.433
6	1.359	0.113	0.500	0.100	1.383	1.100	0.525	0.808	0.766	0.808
7	1.069	0.150	0.657	0.100	0.750	0.656	0.502	0.636	0.564	0.636
8	1.210	0.162	0.500	0.119	0.512	0.449	0.502	0.481	1.346	0.481
9	1.082	0.237	0.500	0.190	0.574	0.463	0.500	0.263	1.025	0.263
10	1.431	0.110	0.500	0.101	1.374	0.853	0.511	0.737	1.956	0.737
11	1.201	0.228	0.500	0.100	2.000	0.983	0.502	0.683	1.311	0.683
12	0.759	0.157	0.500	0.111	1.982	0.615	0.513	0.735	0.581	0.735
13	0.737	0.227	0.500	0.100	2.000	1.100	0.507	0.824	1.789	0.824
14	0.915	0.184	0.500	0.100	1.563	0.162	0.504	0.291	1.016	0.291
15	0.746	0.157	0.500	0.101	0.506	0.863	0.500	0.348	1.318	0.348
16	0.525	0.179	0.562	0.100	1.664	0.423	0.506	0.434	1.577	0.436
OF	7.2041 Sec		3.65379 Sec				3.3479 Sec			

Fig. 3 shows the CTI values for dual-setting DOCRs in the grid-connected mode of the 7-bus microgrid system, as obtained using the FA-GA algorithm. The CTI is the difference in operating times of the primary and backup relays when the TMS and PS settings are optimized. In all cases, the CTI is greater than the minimum value of 0.2 seconds, which is the required time gap between primary and backup relays for each relay pair. The optimal results satisfy all of the considered constraints in the relay coordination problem.

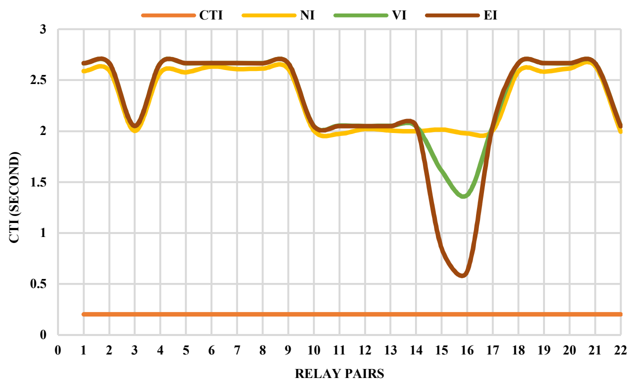

Fig. 3. CTI values of dual-setting DOCRs for different relay standard characteristics in grid-connected mode.

B. Islanded Operating Mode

Tables VII, VIII, and IX present the optimal settings for the 7-bus test system using various relay curves in the islanded mode. Fig. 4 illustrates the actual CTI values for each relay pair. The total operating times of all 16 conventional DOCRs, considering NI, VI, and EI, are 7.3148, 3.2457, and 6.7142 seconds, respectively. Utilizing the dual-setting DOCRs has significantly reduced the total operating times to 4.1794, 2.27818, and 1.71294 seconds for NI, VI, and EI parameters, respectively. As in the previous case, the hybrid algorithm achieves better results that satisfy all of the considered constraints in the relay coordination problem, indicating its effectiveness in obtaining better relay settings.

TABLE V. OPTIMAL RELAY SETTINGS WITH VERY INVERSE STANDARD CHARACTERISTIC FOR DUAL-SETTING DOCR IN GRID-CONNECTED MODE

Very Inverse Characteristic										
Relay	Conven. DOCR		Dual Setting DOCR							
	GA [3]		*GA*				*FA-GA*			
	PS	*TMS (Sec)*	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)
1	0.795	0.163	0.500	0.171	1.266	0.459	0.719	0.117	1.410	0.391
2	0.759	0.242	0.500	0.250	1.271	1.092	0.898	0.134	1.519	0.886
3	0.855	0.100	0.534	0.125	0.516	1.064	0.615	0.108	1.420	0.255
4	0.809	0.140	0.521	0.221	1.250	0.698	0.577	0.199	1.722	0.451
5	0.803	0.151	0.500	0.247	0.562	0.719	0.838	0.145	0.642	0.602
6	0.699	0.170	0.801	0.148	1.941	1.100	1.087	0.107	1.868	0.621
7	0.670	0.153	0.511	0.100	0.705	0.776	0.500	0.100	0.639	0.870
8	0.929	0.155	0.500	0.241	0.914	0.138	1.083	0.107	1.572	0.457
9	0.687	0.381	0.500	0.271	0.526	0.550	1.096	0.101	1.392	0.109
10	0.894	0.107	0.500	0.165	1.927	1.100	0.700	0.116	2.000	1.100
11	0.838	0.353	1.109	0.125	2.000	1.100	0.898	0.157	1.834	0.783
12	0.646	0.168	0.500	0.100	1.269	1.046	0.500	0.100	0.947	0.808
13	0.709	0.289	0.500	0.263	2.000	1.100	0.588	0.223	2.000	1.100
14	0.931	0.168	0.507	0.154	1.536	0.104	0.667	0.115	1.044	0.202
15	0.638	0.198	1.018	0.122	0.622	0.824	0.531	0.240	0.874	0.527
16	0.532	0.141	0.629	0.107	1.169	0.683	0.609	0.111	1.737	0.408
OF	2.4392 Sec		1.6258 Sec				1.6043 Sec			

TABLE VI. OPTIMAL RELAY SETTINGS WITH EXTREMELY INVERSE STANDARD CHARACTERISTIC FOR DUAL-SETTING DOCR IN GRID-CONNECTED MODE

Extremely Inverse Characteristic										
Relay	Conven. DOCR		Dual Setting DOCR							
	GA [3]		*GA*				*FA-GA*			
	PS	*TMS (Sec)*	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)	PS_{FWD}	TMS_{FWD} (Sec)	PS_{REV}	TMS_{REV} (Sec)
1	0.873	0.238	0.500	0.753	1.107	0.441	1.278	0.110	1.428	0.251
2	0.859	0.498	0.619	0.961	1.537	1.100	0.737	0.678	1.552	1.075
3	0.902	0.139	0.519	0.424	0.564	1.071	0.855	0.155	0.861	0.440
4	0.805	0.498	0.704	0.651	0.926	1.100	0.630	0.814	1.106	0.825
5	1.226	0.245	0.926	0.430	0.563	0.664	1.030	0.347	0.550	0.696
6	0.871	0.463	1.625	0.132	1.907	1.100	0.795	0.556	1.541	0.919
7	0.508	0.239	0.783	0.100	0.699	0.936	0.695	0.127	0.782	0.722
8	0.940	0.397	0.997	0.353	0.920	0.160	0.634	0.876	1.026	0.915
9	0.851	0.457	0.541	1.097	0.543	0.472	0.891	0.403	0.826	0.189
10	0.752	0.298	0.500	0.717	2.000	1.100	0.866	0.225	2.000	1.100
11	1.124	0.424	1.046	0.451	2.000	1.100	1.173	0.359	1.873	0.877
12	0.885	0.127	0.500	0.257	0.967	0.835	0.648	0.152	1.425	0.411
13	1.325	0.237	0.860	0.564	2.000	1.100	0.862	0.561	2.000	1.100
14	1.216	0.102	0.512	0.580	0.800	0.287	0.881	0.195	0.581	0.407
15	0.844	0.551	0.779	0.646	0.615	0.856	0.819	0.584	0.799	0.492
16	0.503	0.466	0.658	0.272	1.015	0.961	0.801	0.183	1.518	0.418
OF	1.6681 Sec		1.6100 Sec				1.60004 Sec			

C. Comparitive Analysis of Obtained Results

The performance of dual-setting DOCR in terms of the total relay operating time is compared with conventional DOCR in Table X. For the grid connected mode, using NI characteristic curves, the conventional DOCRs obtain an OF value of 7.2041 seconds, whereas the dual-setting DOCRs, optimized using GA, reduced this time to 3.65379 seconds, demonstrating a significant reduction of 49.282%. Furthermore, using the hybrid FA-GA increased the reduction to 53.528%. Similarly, for VI curve, the reduction percentages reached at 33.347% with GA and increased to 34.228% with FA-GA. Using EI curve, GA led to a reduction of 3.4830%, while FA-GA achieved a 4.0801% reduction in total relay operating time. In the islanded mode, the reduction percentages were significant across all characteristic curves. For NI curve, the reduction was 42.864% with GA and increased to 45.528% with FA-GA. Using VI curve, GA resulted in a reduction of 29.809%, while FA-GA outperformed with a 45.064% reduction. EI curve showed the most significant improvement, with GA reducing the operating time by 74.488% and FA-GA further reducing it to 76.169%.

This analysis not only demonstrates the superior performance of dual-setting DOCRs over conventional DOCRs but also shows the effectiveness of the hybrid FA-GA algorithm, which consistently outperforms GA, ensuring more efficient and responsive microgrid protection across various operating scenarios.

TABLE VII. OPTIMAL RELAY SETTINGS WITH NORMAL INVERSE STANDARD CHARACTERISTIC FOR DUAL SETTING DOCR IN ISLANDED MODE

Normal Inverse Characteristic										
Relay	**Conven. DOCR**		**Dual Setting DOCR**							
	GA [3]		***GA***				***FA-GA***			
	PS	***TMS (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***
1	1.621	0.100	0.500	0.100	1.096	0.348	0.500	0.100	1.734	0.142
2	1.449	0.131	0.500	0.100	0.817	0.898	0.500	0.100	1.905	0.540
3	0.552	0.220	0.500	0.100	0.500	0.100	0.500	0.100	0.508	0.102
4	0.503	0.106	0.500	0.100	0.566	1.097	0.500	0.100	0.928	0.867
5	0.545	0.201	0.500	0.100	0.501	0.607	0.500	0.100	1.400	0.101
6	0.519	0.148	0.500	0.100	0.932	1.100	0.500	0.100	1.104	0.690
7	0.761	0.199	1.099	0.100	0.500	0.335	0.500	0.100	0.518	0.409
8	0.762	0.100	0.500	0.100	0.700	0.347	0.500	0.100	1.424	0.611
9	0.766	0.171	0.500	0.100	0.706	0.570	0.500	0.100	1.283	0.311
10	0.514	0.188	0.500	0.100	0.560	1.098	0.500	0.100	1.930	0.587
11	0.917	0.171	0.500	0.100	2.000	0.792	0.500	0.100	0.869	0.887
12	0.590	0.177	0.500	0.100	1.307	0.473	0.500	0.100	1.142	0.380
13	0.744	0.155	0.500	0.100	2.000	1.100	0.500	0.100	1.395	0.966
14	1.352	0.122	0.787	0.100	0.752	0.372	0.500	0.100	0.512	0.459
15	0.536	0.120	0.500	0.100	0.768	0.907	0.500	0.100	1.412	0.425
16	0.616	0.191	0.539	0.100	1.110	0.339	0.500	0.100	0.950	0.400
OF	7.3148 Sec		4.1794 Sec				3.98526 Sec			

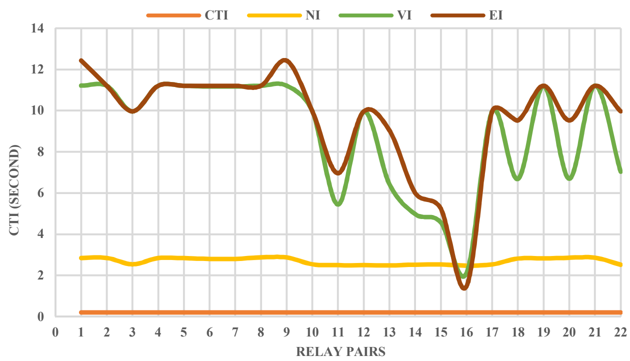

Fig. 4. CTI values of dual-setting DOCRs for different relay standard characteristics in islanded mode.

TABLE VIII. OPTIMAL RELAY SETTINGS WITH VERY INVERSE STANDARD CHARACTERISTIC FOR DUALSETTING DOCR IN ISLANDED MODE

Very Inverse Characteristic										
Relay	**Conven. DOCR**		**Dual Setting DOCR**							
	GA [3]		***GA***				***FA-GA***			
	PS	***TMS (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***
1	0.523	0.239	0.500	0.182	1.099	0.990	0.623	0.100	1.197	0.835
2	0.641	0.208	0.502	0.163	1.575	1.100	0.791	0.100	2.000	1.100
3	0.772	0.163	0.500	0.117	0.500	0.110	0.500	0.112	0.562	0.117
4	0.500	0.100	0.529	0.100	2.000	1.100	0.500	0.100	2.000	1.100
5	0.578	0.164	0.564	0.179	0.783	1.054	0.512	0.172	0.562	1.053
6	0.554	0.149	0.581	0.142	2.000	1.100	0.528	0.157	2.000	1.100
7	0.508	0.276	0.516	0.100	0.614	1.012	0.500	0.100	1.019	0.315
8	0.500	0.100	0.500	0.108	1.899	1.100	0.500	0.100	2.000	1.100
9	1.007	0.101	0.500	0.100	1.383	0.758	0.500	0.100	1.276	0.891
10	1.122	0.100	0.500	0.122	1.954	1.100	0.525	0.115	2.000	1.100
11	0.989	0.156	0.557	0.114	1.997	1.094	0.500	0.128	2.000	1.100
12	0.512	0.190	0.500	0.177	1.286	0.985	0.500	0.100	1.307	0.949
13	0.596	0.226	0.500	0.486	1.991	1.100	0.500	0.136	2.000	1.100
14	0.678	0.182	0.500	0.102	1.046	0.412	0.500	0.100	1.168	0.192
15	0.626	0.105	0.500	0.173	1.902	1.026	0.657	0.100	1.836	0.833
16	0.823	0.125	0.562	0.100	1.271	0.789	0.501	0.114	1.605	0.462
OF	3.2457 Sec		2.27818 Sec				1.78305 Sec			

TABLE IX. OPTIMAL RELAY SETTINGS WITH EXTREMELY INVERSE STANDARD CHARACTERISTIC FOR DUAL SETTING DOCR IN ISLANDED MODE

Extremely Inverse Characteristic										
Relay	**Conven. DOCR**		**Dual Setting DOCR**							
	GA [3]		***GA***				***FA-GA***			
	PS	***TMS (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***	***PS_{FWD}***	***TMS_{FWD} (Sec)***	***PS_{REV}***	***TMS_{REV} (Sec)***
1	0.890	0.386	0.500	0.407	1.628	0.166	1.003	0.100	0.816	0.100
2	1.172	0.229	0.500	0.668	1.978	1.100	1.279	0.100	2.000	0.100
3	0.676	0.497	0.897	0.100	0.500	0.100	0.644	0.195	0.500	0.100
4	0.500	0.142	0.515	0.134	1.995	1.100	0.594	0.100	2.000	0.100
5	0.969	0.516	0.500	0.769	0.750	0.641	0.679	0.416	0.607	0.100
6	0.561	0.545	1.302	0.100	2.000	1.100	0.897	0.212	1.980	0.100
7	0.760	0.762	0.686	0.100	0.516	0.874	0.500	0.189	0.523	0.100
8	0.706	0.306	0.500	0.187	1.970	1.100	0.606	0.127	2.000	0.100
9	1.051	0.278	0.500	0.280	0.911	1.055	0.595	0.100	1.294	0.100
10	0.933	0.422	0.500	0.373	2.000	1.100	0.565	0.292	2.000	0.100
11	1.000	0.464	0.531	0.371	2.000	1.099	0.821	0.154	2.000	0.100
12	0.660	0.582	0.500	0.121	1.372	0.471	0.501	0.121	1.304	0.100
13	1.257	0.549	0.500	0.467	2.000	1.100	1.074	0.100	2.000	0.100
14	1.015	0.258	0.500	0.206	0.548	1.100	0.511	0.197	0.741	0.100
15	0.857	0.199	0.500	0.517	1.449	1.008	1.057	0.100	1.273	0.100
16	0.912	0.224	0.643	0.199	1.224	0.444	0.666	0.185	1.253	0.100
OF	6.7142 Sec		1.71294 Sec				1.60007 Sec			

D. Results Discussion

This study investigated the performance of dual-setting DOCRs for AC microgrid protection compared to conventional DOCRs. The results in Tables IV, V, and VI for grid-connected mode, and Tables VII, VIII, and IX for islanded mode, show that dual-setting DOCRs significantly outperform conventional DOCRs in reducing the total operating times of DOCRs. The results also show the effect of changing the standard characteristic curve on the DOCR performance. The EI characteristic performs the best, as it takes the least sum of operating time of all 16 DOCRs in both operating modes of the AC microgrid system. However, using the EI characteristic increases the operating time of the backup relay, which increases the CTI values in islanded mode, as shown in Fig. 4.

TABLE X. COMPARATIVE ANALYSIS OF CONVENTIONAL AND DUAL-SETTING DOCR FOR 7-BUS MICROGRID SYSTEM.

Operating Mode	Relay characteristics	Conven. DOCR OF value using GA	Dual-Setting DOCR OF value using GA	Dual-Setting DOCR OF value using FA-GA	Reduction in total relay operating time using GA	Reduction in total relay operating time using FA-GA
Grid Connected Mode	NI	7.2041	3.65379	3.3479	49.282%	53.528%
	VI	2.4392	1.6258	1.6043	33.347%	34.228%
	EI	1.6681	1.6100	1.60004	3.4830%	4.0801%
Islanded Mode	NI	7.3148	4.1794	3.98526	42.864%	45.528%
	VI	3.2457	2.27818	1.78305	29.809%	45.064%
	EI	6.7142	1.71294	1.60007	74.488%	76.169%

VI. CONCLUSION

This study investigated the effectiveness of dual-setting DOCRs for microgrid protection in comparison with conventional DOCRs. The evaluation was conducted under both grid-connected and islanded operating modes of a 7-bus test system, considering different standard characteristic curves. By using genetic algorithm and a hybrid approach that integrates the firefly algorithm and genetic algorithm, optimal relay settings were achieved. The results demonstrated the superior performance of dual-setting DOCRs in significantly reducing the total relay operating time compared to conventional DOCRs. The hybrid FA-GA algorithm further enhanced the optimization of relay settings, demonstrating its applicability for practical microgrid implementations. Additionally, the study revealed that selecting different standard relay characteristics according to the IEC standard can effectively reduce the total relay operating time. One possible direction for future work is to enhance the dual-setting DOCR by adding two decision variables corresponding to the standard characteristic curve. This could further improve the performance of the relay in different operating conditions.

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REFERENCES

[1] M. W. Siti, D. H. Tungadio, N. T. Nsilulu, B. B. Banza, and L. Ngoma, "Application of load frequency control method to a multi-microgrid with energy storage system," J Energy Storage, vol. 52, p. 104629, Aug. 2022, doi: 10.1016/J.EST.2022.104629.

[2] P. Singh, P. Paliwal, and A. Arya, "A review on challenges and techniques for secondary control of microgrid," in IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2019, p. 012075.

[3] M. N. Alam, "Overcurrent protection of AC microgrids using mixed characteristic curves of relays," Computers & Electrical Engineering, vol. 74, pp. 74–88, Mar. 2019, doi: 10.1016/J.COMPELECENG.2019.01.003.

[4] N. K. Choudhary, S. R. Mohanty, and R. K. Singh, "A review on microgrid protection," in 2014 International electrical engineering congress (iEECON), IEEE, 2014, pp. 1–4.

[5] M. W. Altaf, M. T. Arif, S. N. Islam, and M. E. Haque, "Microgrid Protection Challenges and Mitigation Approaches–A Comprehensive Review," IEEE Access, vol. 10, pp. 38895–38922, 2022, doi: 10.1109/ACCESS.2022.3165011.

[6] A. Hooshyar and R. Iravani, "A New Directional Element for Microgrid Protection," IEEE Trans Smart Grid, vol. 9, no. 6, pp. 6862–6876, 2018, doi: 10.1109/TSG.2017.2727400.

[7] T. Foqha et al., "Optimal Coordination of Directional Overcurrent Relays Using Hybrid Firefly–Genetic Algorithm," Energies (Basel), vol. 16, no. 14, p. 5328, 2023.

[8] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Coordination of dual setting overcurrent relays in microgrid with optimally determined relay characteristics for dual operating modes," Protection and Control of Modern Power Systems, vol. 7, no. 1, p. 6, 2022, doi: 10.1186/s41601-022-00226-1.

[9] T. Foqha, S. Alsadi, A. Elrashidi, and N. Salman, "Optimizing Firefly Algorithm for Directional Overcurrent Relay Coordination: A case study on the Impact of Parameter Settings," Information Sciences Letters, vol. 12, no. 7, pp. 3205–3227, Jul. 2023, doi: 10.18576/isl/120745.

[10] M. M. Mansour, S. F. Mekhamer, and N. El-Kharbawe, "A Modified Particle Swarm Optimizer for the Coordination of Directional Overcurrent Relays," IEEE Transactions on Power Delivery, vol. 22, no. 3, pp. 1400–1410, 2007, doi: 10.1109/TPWRD.2007.899259.

[11] D. Birla, R. P. Maheshwari, and H. O. Gupta, "A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach," IEEE Transactions on Power Delivery, vol. 21, no. 3, pp. 1176–1182, 2006, doi: 10.1109/TPWRD.2005.861325.

[12] M. Al Talaq and M. Al-Muhaini, "Optimal Coordination of Time Delay Overcurrent Relays for Power Systems with Integrated Renewable Energy Sources," Energies (Basel), vol. 15, no. 18, p. 6749, 2022.

[13] D. Vyas, P. Bhatt, and V. Shukla, "Coordination of directional overcurrent relays for distribution system using particle swarm optimization," International Journal of Smart Grid and Clean Energy, vol. 9, no. 2, pp. 290–297, 2020.

[14] G. U. Darji, M. J. Patel, V. N. Rajput, and K. S. Pandya, "A tuned cuckoo search algorithm for optimal coordination of directional overcurrent relays," in 2015 International Conference on Power and Advanced Control Engineering (ICPACE), IEEE, 2015, pp. 162–167.

[15] A. Korashy, S. Kamel, A.-R. Youssef, and F. Jurado, "Solving optimal coordination of direction overcurrent relays problem using grey wolf optimization (GWO) algorithm," in 2018 Twentieth International Middle East Power Systems Conference (MEPCON), IEEE, 2018, pp. 621–625.

[16] M. Zellagui and A. Y. Abdelaziz, "Optimal coordination of directional overcurrent relays using hybrid PSO-DE algorithm," International Electrical Engineering Journal (IEEJ), vol. 6, no. 4, pp. 1841–1849, 2015.

[17] M. A. Dehaghani, M. Soltani, S. M. Ahmadi, and P. G. Panah, "Application of Artificial Bee Colony Algorithm for Optimal Overcurrent Relay Coordination for Power System Including DGs," Life Sci J, vol. 9, no. 4, 2012.

[18] F. A. Albasri, A. R. Alroomi, and J. H. Talaq, "Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms," IEEE Transactions on Power Delivery, vol. 30, no. 4, pp. 1810–1820, 2015.

[19] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Performance Analysis of Optimization Technique for Protection Coordination in Single and Multi-Loop Distribution System," in 2019 International Conference on Electrical, Electronics and Computer Engineering (UPCON), 2019, pp. 1–6. doi: 10.1109/UPCON47278.2019.8980151.

[20] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Optimal Coordination of Dual Setting Directional Over Current Relays in Microgrid With Different Standard Relay Characteristics," in 2020 IEEE 9th Power India International Conference (PIICON), 2020, pp. 1–6. doi: 10.1109/PIICON49524.2020.9112883.

[21] 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, 2016.

[22] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E.-D. Abou El-Zahab, "Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays," IEEE Trans Smart Grid, vol. 6, no. 1, pp. 115–123, 2014.

[23] R. Christie, "Power system test cases. Aug. 1993."