



Optimal Overcurrent Relay Coordination Considering Multiple Characteristic Curve for Microgrid Protection using Hybrid PSO-MILP Technique

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Abstract: This paper proposes an approach for the optimal setting parameters of overcurrent relay (OCR) coordination considering multiple characteristic curves. The proposed approach considers time multiplier setting (TMS) and the relay characteristic curve setting (CS) as decision variables. As an inventiveness, the CS of OCR can be chosen as decision variables, instead of fixing a single type of curve for all relays that used in many existing works. The proposed approach allows three different curve types of IEC standard characteristic curves for combination results in the optimal protection coordination, including the standard inverse (SI) curve, very inverse (VI) curve, and extremely inverse (EI) curve. The proposed technique for solving this problem is hybrid particle swarm mixed integer linear programming (PSO-MILP). To show the effectiveness of the proposed approach, several tests were carried out using the standard IEC benchmark microgrid system. A comparison with previous existing methods illustrated that the proposed technique can absolutely decrease the total operating time of the OCR by around 34 percent for OM1, around 44 percent for OM2, and slightly decrease the total CTI of the test system. Therefore, the proposed approach is outstanding in finding lower the operating times and provides suitable operation of microgrid protections under different fault allocation and operating conditions.

Keywords: Optimal overcurrent relay coordination, Microgrid protection, Artificial intelligence.

1. Introduction

One of the most appealing features of microgrid systems is that the power delivered to consumers who prefer an uninterruptible power resource with reliable and high quality. Furthermore, there are savings in power generation costs through the implementation of photovoltaic (PV), wind turbine (WT), distributed generator (DG), and energy storage systems (ESS) into micro-networks. Nevertheless, the penetration of DG plays a role in significantly contributing fault current into the system [1]. Therefore, the protection strategy of microgrids is a new challenge for protection engineers.

An overcurrent relays (OCR) can extensively be applied as the primary protection strategy in distribution systems, sub-transmission systems, and microgrid systems or as backup protection in transmission systems. In order to improve the fast

and reliability of the protection strategy, OCRs must be operated with minimum time and able to coordinate with another relay to improve the system reliability. Consequently, the OCR can adjust the operating point by adjusting the setting parameters, including the pickup current setting (*PS*), the time multiplier setting (*TMS*), and characteristic curve settings (*CS*). Hence, OCRs coordination can be variously formulated in optimization problems. The coordination between primary and backup relay leading highly non-linear inequality constraints to this problem.

In order to obtain better results, numerous approaches and techniques for solving the optimal setting parameter of OCR was published. In the earliest era, the *PS* has been predetermined, and *CS* of each relay have been set to specific characteristic curve, hence this problem has been formulated as a linear optimization. The minimum total operating time of the primary relay is the objective function

subjected to the coordination constraint. As a result, the *TMS* of each relay is the output for the optimal result. The linear programming optimization [2], the dual simplex approach [3], the Big-M strategy [4], and the reverse simplex method by [5], and artificial bee colony [6] have all been proposed as solutions to these problems. Subsequently, the problem was improved to the nonlinear optimization by considering the *PS* and the *TMS* as a decision variable, whereas the *CS* has remained unchanged. The objective function was minimized by avoiding the limit boundary of *TMS* and *PS*, the coordination constraint, and the minimum operating time. In order to solve this issue, several artificial intelligence techniques were proposed. For example, adaptive modified fly fire algorithm (AMFA) was introduced in [7]. The seeker optimization (SOA), the gravitational search method (GSA), and the hybrid genetic algorithm-nonlinear programming approach (GA-NLP) were proposed in [8-10], respectively. Meanwhile, [11] developed the symbiotic organism search algorithm (SOS). Afterward, the researchers proposed that the *PS* could be considered to be the step/discrete variable instead of the continuous variable to illustrate the realized industrial OCR. The problem was transformed into a mixed-integer nonlinear optimization problem (MINLP). Numerous techniques were proposed to solve this problem, for example, modified seeker algorithm (MSA) [12], hybrid whale optimization (HWOA) [13], ant lion optimization (ALO), and the artificial immune system (AIS) [14], hybrid GA-LP [15]. In recent years, various novel constraints were implemented for representing the practical industrial OCR such as the plug setting multiplier (*PSM*) constraint to be within the range of 1.1 times to 20 times [16], and the range of 1.1 times to 100 times [17]. Then, researchers have focused on the maximum *PSM* as a decision variable that can reduce the total operating time and total *CTI* of the relay [18], considering the transient stability constraint to ensure the network transient stability in [14]. In another way, the researcher demonstrated that various types of *CS* have an impact on the relay's operating time. According to the results, the mixed *CS* type solutions outperformed the fixed *CS* type solution [19]. Consequently, the researcher proposed that the *CS* and *TMS* are decision variables by fixed one integer variable of each OCR for represented the *CS*, while the *PS* is predefined. Then the problem became mixed-integer linear programming (MILP). The problem was solved by integer code genetic algorithm (ICGA) subjected to coordination constraint, operating time constraint, and *PSM*

constraint. The results show that this method is the most effective in decreasing the total operating time of the relay [20].

As a result, this paper proposes an approach for optimal OCR coordination considering multiple *CS*, that consider *TMS* and *CS* as decision variables. The formulation of this paper is MILP optimization. As a novelty, this paper represents a novel problem formulation by dividing *CS* into multiple sections depending on the number of *CS* types that are considered, instead of using a single integer variable of each OCR for representing *CS* as in recent existing work [20]. The hybrid PSO-MILP technique was developed to solve this problem. The coordination constraint, the operating time constraint, and the *PSM* constraint were considered in this paper. To show the capability of the proposed technique, the result was compared with those previous papers [16-18, 20], in the same test system.

The following are the five sections of this paper. The formulation of the objective function, the determination of all variables, the limit boundary, and all of the constraints in this problem are all represented in section 2. The procedure of proposed technique is obtained in section 3. The optimal results and discussions of the proposed technique on the IEC benchmark microgrid test system is presented in section 4. The conclusion is contained in section 5.

2. Mathematical formulation

The IEC standard OCR has inverse time-current characteristics. The operating time of OCR is depending on short circuit current flowing through relay and setting parameters include *TMS*, *PS*, and *CS*. In this paper, the decision variables are *TMS* and *CS*, while *PS* is predetermined of each OCR. The objective function (*OF*) of this problem is to minimize the total operating time of all the OCRs present in the system. The function is to be minimized so that each relay operates in minimum time and the reliability of the system is maintained by the constraints. The mathematical formulation can be expressed as follow.

Minimize,

$$OF = \sum_{k=1}^{NF} \sum_{j=1}^{NR} (C_{SI,j} T_{SI,j,k} + C_{VI,j} T_{VI,j,k} + C_{EI,j} T_{EI,j,k}), \quad (1)$$

where,

$$T_{SI,j,k} = \frac{0.14 TMS_j}{(PSM_{jk})^{0.02} - 1}, \quad (2)$$

$$T_{VI,j,k} = \frac{13.5 TMS_j}{(PSM_{jk})^1 - 1}, \quad (3)$$

$$T_{EI,j,k} = \frac{80 TMS_j}{(PSM_{jk})^2 - 1}, \quad (4)$$

$$PSM_{jk} = \frac{I_{jk}}{(PS_{jCTR_j})}. \quad (5)$$

Subjected to the standard curve selection constraint,

$$C_{SI,j}, C_{VI,j}, C_{EI,j} \in \{0,1\}, j = 1, \dots, NR, \quad (6)$$

$$C_{SI,j} = \begin{cases} 0, & \text{if the relay is not SI curve} \\ 1, & \text{if the relay is SI curve} \end{cases}, \quad (7)$$

$$C_{VI,j} = \begin{cases} 0, & \text{if the relay is not VI curve} \\ 1, & \text{if the relay is VI curve} \end{cases}, \quad (8)$$

$$C_{EI,j} = \begin{cases} 0, & \text{if the relay is not EI curve} \\ 1, & \text{if the relay is EI curve} \end{cases}, \quad (9)$$

$$C_{SI,j} + C_{VI,j} + C_{EI,j} = 1, j = 1, \dots, NR, \quad (10)$$

the time multiplier limit boundary,

$$TMS_j^{min} \leq TMS_j \leq TMS_j^{max}, j = 1, \dots, NR, \quad (11)$$

the plug setting multiplier constraint,

$$PSM_j^{min} \leq PSM_j \leq PSM_j^{max}, j = 1, \dots, NR, \quad (12)$$

the coordination constraint,

$$T_{b,k} - T_{p,k} \geq CTI, k = 1, \dots, NF, \quad (13)$$

the operating time constraint,

$$T_{j,k}^{max} \geq T_{j,k} \geq T_{j,k}^{min}, j = 1, \dots, NR. \quad (14)$$

Where,

$T_{SI,j,k}$ is the operating time of relay j with standard inverse curve type when the fault occurs at point k ,

$T_{VI,j,k}$ is the operating time of relay j with very inverse curve type when the fault occurs at point k ,

$T_{EI,j,k}$ is the operating time of relay j with extremely inverse curve type when the fault occurs at point k ,

TMS_j is the time multiplier setting of relays j ,

TMS_j^{max} is the maximum time multiplier of relay j ,

TMS_j^{min} is the minimum time multiplier of relay j ,

PSM_j is the plug setting multiplier of relay j ,

PSM_j^{max} is the maximum plug setting multiplier of relay j ,

PSM_j^{min} is the minimum plug setting multiplier of relay j ,

$T_{b,k}$ is the operation time of the backup relay b when fault k occurs,

$T_{p,k}$ is the operation time of the primary relay p , for the same fault,

CTI is the coordination time interval,

$T_{j,k}^{min}$ is the minimum operating of each relay j when fault k occurs,

$T_{j,k}^{max}$ is the maximum operating of each relay j when fault k occurs.

I_{jk} is the short-circuit current flowing through relay j when fault at k is occurred (A),

PS_j is the pickup setting of relay j (A),

CTR_j is the CT ratio of relay j ,

NF is a number of faults that can take place in the system,

NR is a number of the operating relays when fault occur at point k .

By Eqs. (6-10), the OCR standard CS of each relay can be chosen only one from SI, VI, or EI.

3. PSO-MILP technique

The TMS of each OCR is a continuous variable while the CS_i , C_{VI} , and C_{EI} are a binary integer variable. Thus, the mathematical formulation of this problem is adapted to the mixed-integer nonlinear optimization. Meanwhile, traditional particle swarm optimization (PSO) can only solve problems with continuous variables [21]. Hence, the PSO-MILP technique is implemented to solve this problem. The proposed method including two computational phases consist of a main loop and subroutines. A main loop is used the PSO technique to find the optimal TMS of each OCR. A subroutine is used the MILP technique to obtain the optimal CS_i , C_{VI} , and C_{EI} . The proposed technique computation of each population is shown step by step as bellow.

Step 1: Random initial position of the population matrix (\mathbf{X}_{TMS}) within the TMS limited boundary in Eq. (11),

$$\mathbf{X}_{TMS} = [TMS_1, \dots, TMS_{NR}]. \quad (15)$$

$$TMS_i = rand(TMS_i^{min}, TMS_i^{max}), i = 1, \dots, NR, \quad (16)$$

Step 2: Calculate $T_{SI,j,k}$, $T_{VI,j,k}$, and $T_{EI,j,k}$ value in Eq. (1) by substitute \mathbf{X}_{TMS} from Eq. (16) to Eqs. (2-5). Then, the OF_{new} will be integer programming optimization with binary integer decision variables (C_{SI} , C_{VI} , and C_{EI}) of each OCR.

$$OF_{new} = OF_{old}(\text{substitute } TMS \text{ in Eq.(1-5)}) \quad (17)$$

Step 3: Solve MILP with objective function form Eq. (17) subjected to constraints in Eqs. (6-10), and Eqs. (12-14) to obtain optimal C_{SI} , C_{VI} , and C_{EI} of each population matrix.

Minimize the objective function in: Eq. (17)

Subjected to: Eq. (6-10), and Eqs. (12-14)

$$\text{Obtain: } \mathbf{X}_{CS} = \begin{bmatrix} C_{SI,i}, \dots, C_{SI,NR} \\ C_{VI,i}, \dots, C_{VI,NR} \\ C_{EI,i}, \dots, C_{EI,NR} \end{bmatrix}, i = 1, \dots, NR. \quad (18)$$

Step 4: Find the $pbest$ and $gbest$ of each population matrix form Eqs. (17, 18).

Step 5: Update velocity and position of each population matrix from Eq. (16) by Eqs. (19-22).

$$\mathbf{V}^{k+1} = w\mathbf{V}^k + A_1 + A_2, \quad (19)$$

$$A_1 = c_1 r_1 (pbest_i^k - \mathbf{X}^k), \quad (20)$$

$$A_2 = c_2 r_2 (gbest^k - \mathbf{X}^k), \quad (21)$$

$$\mathbf{V}_i^k = [V_1^k, \dots, V_{3NR}^k], \quad (22)$$

$$\mathbf{X}_i^{k+1} = \mathbf{X}^k + \mathbf{V}^{k+1}, \quad (23)$$

$$\mathbf{X}_{TMS}^{new} = \mathbf{X}_i^{k+1}, \quad (24)$$

where, k indicates the iteration, w is the inertia weight, v_k^i is the i particle's velocity vector, x_k^i is the i particle's vector, $gbest^k$ is the historically best position of the entire swarm, $pbest_i^k$ is the historically best position of particle i , c_1 and c_2 are the personal and global learning coefficients, respectively, while r_1 and r_2 are uniformly distributed random numbers in the range $[0,1]$.

Step 6: Repeat step 2-5 until the maximum iteration.

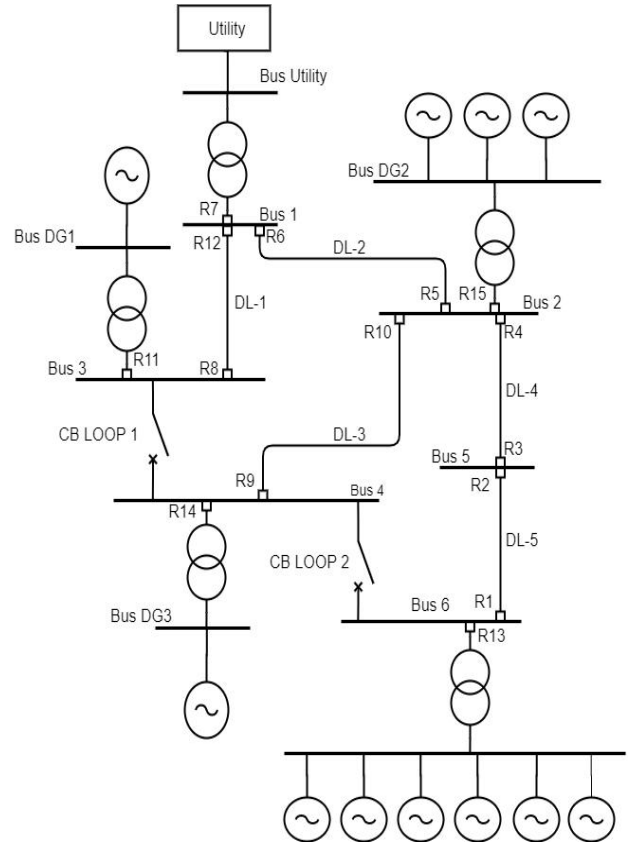


Figure. 1 an IEC benchmark micro-grid test system [20]

Table 1. The circuit breaker status of each OM

OM	Utility	DG1	DG2	DG3	DG4
OM1	on	off	off	off	off
OM2	on	on	on	on	on

4. Results and discussions

4.1 Test case

The proposed approach was investigated on the IEC benchmark microgrid test system [16-18, 20] with various operating modes (OMs) as shown in Fig. 1. In this system, the OM can be classified into two conditions (OM1 and OM2) depend on the circuit breaker status as show in Table 1. The IEC benchmark microgrid consist of main six buses, six constant power loads, two distributed synchronous generators (DG1 and DG3), two wind turbines generator (DG-2 and DG-4), and five distribution lines (DL-1, DL-2, ..., DL-5). The three-phase faults occur in the middle point of each distribution line (F1-F5).

Therefore, F1 denote the fault on distribution line DL-5. F2, F3, and F4 represents the fault on distribution lines DL-4, DL-2, and DL-1, respectively. F5 indicates the fault on lines DL-3. The fault level on each distribution line within various OMs can be seen in Fig. 2. To address these

faults that can be occurred in this system, the relay was established at every end of the distribution line and the common coupling point of each DG (R1-R15). The parameters and fault levels of the system are referred to [22-23]. To avoid the complexity of the system, CB LOOP 1 and CB LOOP 2 are considered in open circuit status on any OM.

4.2 Simulation setup

The limit boundary of decision variables and the constant parameters of every constraint utilized are the same as in [20] for compare the optimal solutions. Therefore, the TMS_j limit was set between TMS_j^{min} and TMS_j^{max} , with TMS_j^{min} at 0.05 and TMS_j^{max} at 15. Table 2 shows the CT ratio and PS of each OCR. PSM_j has a range of 1.1 PSM to 100 PSM as its limit. $T_{j,k}$ has a range of 0.01 to 2 seconds, and the CTI utilized is 0.3 seconds. As a result, a variety of optimal solutions are accessible. Five hundred swarm sizes are used to find the closest global optimum solution. To reduce variation, the 30 trials test is used. In this paper c_1 and c_2 are 1.49.

4.3 Simulation results

4.3.1. OM1 results

In OM1, the test system which is connected to the utility, but all of DG is not energized. As a result, the power flow and the short circuit flow are in the same direction. Current flows from the utility to the load point or fault location. As a result, under this operational mode, just six relays are desired to detect (R2, R4, R6, R7, R10, R12). Table 3 demonstrates the coordination schemes and short circuit current passing through each OCR in this operating mode. Table 4 provides the optimal results of the proposed approach for each OCR. Table 5 shows the operating time of each relay when a fault occurs.

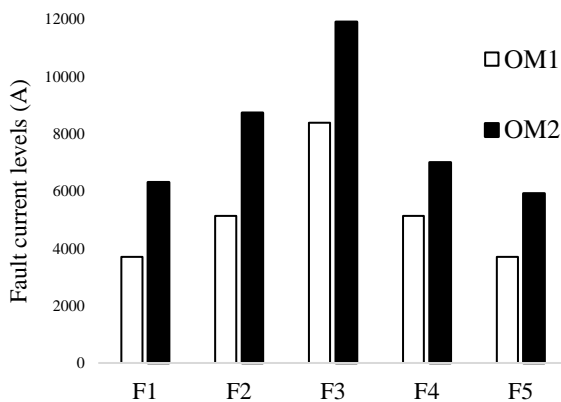


Figure. 2 Fault current level of both OM [21]

Table 2. The CT ratio and PS of each OCR

Relay	CT ratio	PS	Relay	CT ratio	PS
R1	400	0.50	R9	400	0.50
R2	400	0.50	R10	400	0.50
R3	400	0.50	R11	400	0.65
R4	400	0.50	R12	400	0.50
R5	400	0.50	R13	400	0.88
R6	400	0.50	R14	400	0.65
R7	1200	1.00	R15	400	0.65
R8	400	0.50			

Table 3. The coordination schemes of OM1 [16]

Fault Point	RP1	RB1.1	RB1.2	RP2	RB2.1
F1	R2 3695	R4 3695	-	R1 -	R13 -
F2	R4 5130	R6 5130	R15 -	R3 -	R1 -
F3	R6 8375	R7 8375	R8 -	R5 -	R15 -
F4	R12 5130	R7 5130	R5 -	R8 -	R11 -
F5	R10 3695	R6 3695	R15 -	R9 -	R14 -

Table 4. The optimal results for OM1

Relay	Proposed Approach				
	TMS	CS_I	C_{VI}	C_{EI}	CS
R1	-	-	-	-	-
R2	0.05	0	0	1	IEC-EI
R3	-	-	-	-	-
R4	1.3262	0	0	1	IEC-EI
R5	-	-	-	-	-
R6	3.7897	0	0	1	IEC-EI
R7	0.1339	1	0	0	IEC-SI
R8	-	-	-	-	-
R9	-	-	-	-	-
R10	0.05	0	0	1	IEC-EI
R11	-	-	-	-	-
R12	0.0821	0	0	1	IEC-EI
R13	-	-	-	-	-
R14	-	-	-	-	-
R15	-	-	-	-	-

Table 3. shows that the primary and backup relay can see the same magnitude fault current for a one fault source because this operating condition has a radial topology. Thus, the fault current level is increase when the fault point near the fault source and decrease when fault point far from fault source. From the optimal results in Table 4, we can observe that, with the setting of CS as decision variable, the proposed method can completely decrease the minimum operating time of the system form fixed

CS method in [7-10].

The proposed algorithm provides the results with several types of CS, not a single type of curve. The CSs obtained by the proposed method are mostly IEC-EI, because it provides the minimum operating time than other curves. Meanwhile, the trend of *TMS*s are converge to the lower bound, but they can slightly increase to avoid the constraint violation. The proposed method improves the objective function by around 34 % from the previous paper [20] while the total *CTI* of the system is slightly decrease from [20]. The coordination curve of each OCR for the proposed approach are shown in Fig. 3.

Table 5. The operating times of OCRs for OM1

Fault Point	Relay	ICGA [20]		Proposed	
		$T_{j,k}$	CTI	$T_{j,k}$	CTI
F1	R2	0.0118	0.30	0.0118	0.30
	R4	0.3118		0.3118	
F2	R4	0.2976	0.30	0.1615	0.30
	R6	0.5976		0.4615	
F3	R6	0.5976	0.34	0.173	0.3
	R7	0.9372		0.473	
F4	R12	0.01	1.00	0.01	0.6257
	R7	1.01		0.6357	
F5	R10	0.0118	0.604	0.0118	0.879
	R6	0.6159		0.8908	
Total		4.19	2.544	3.14	2.405

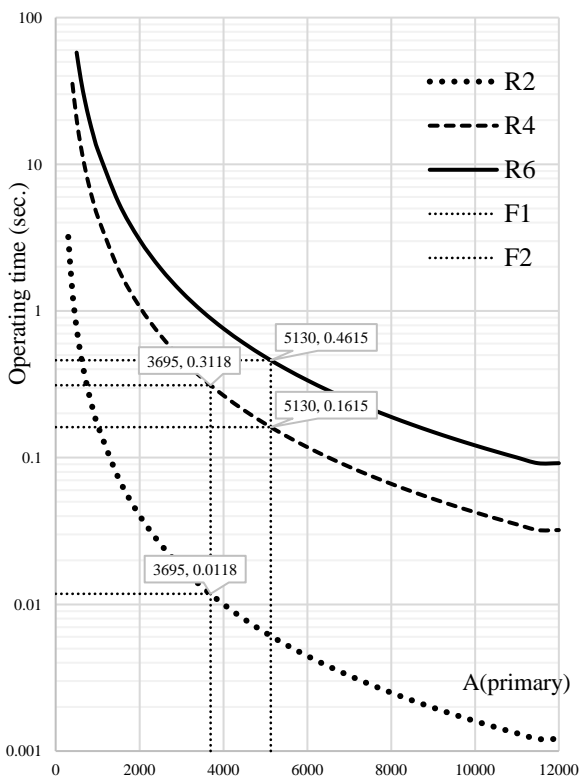


Figure. 3 The coordination curve of OCR in OM1

Table 6. The coordination schemes of OM2 [16]

Fault Point	RP1	RB1.1	RB1.2	RP2	RB2.1
F1	R2 4648	R4 4648	-	R1 1648	R13 1648
F2	R4 7260	R6 5443	R15 920	R3 1465	R1 1465
F3	R6 9256	R7 8375	R8 923	R5 2635	R15 737
F4	R12 5998	R7 4572	R5 1439	R8 991	R11 991
F5	R10 4913	R6 3416	R15 578	R9 991	R14 991

Table 7. The optimal results for OM2

Relay	Proposed Approach				
	<i>TMS</i>	CS_I	C_{VI}	C_{EI}	CS
R1	0.2475	0	0	1	IEC-EI
R2	0.0674	0	0	1	IEC-EI
R3	0.05	0	0	1	IEC-EI
R4	2.089	0	0	1	IEC-EI
R5	0.1967	0	0	1	IEC-EI
R6	3.9472	0	0	1	IEC-EI
R7	0.1266	1	0	0	IEC-SI
R8	0.1135	0	0	1	IEC-EI
R9	0.05	0	0	1	IEC-EI
R10	0.0753	0	0	1	IEC-EI
R11	0.1428	0	1	0	IEC-VI
R12	0.1123	0	0	1	IEC-EI
R13	0.1625	0	1	0	IEC-VI
R14	0.0978	0	1	0	IEC-VI
R15	0.0885	1	0	0	IEC-SI

4.3.2. OM2 results

In the OM2, the test system is connected to the utility and all of DG are energized. The power flow and the short circuit current flow can be in bi-direction and complex. The direction of current flow is from utility and DGs to load point or fault point. All relays are required to protect the system under this operating condition. The coordination schemes and short circuit current flowing through each relay of this operating mode are shown in Table 6. Table 7 provides the optimal results of the proposed approach for each OCR. Table 8 shows the operating time of each relay when fault occurs

Table 6 shows that when F1 occurs, the fault flows current from DG4 is detected by relays R1 and R13. The fault current flows in a different direction from the utility and upstream DGs (DG1, DG2, DG3). Relays R2 and R4 detect these fault current flows. Similarly, to when F2 occurs, the R3 and R1 must operate together to clear this fault from DG4. Meanwhile, fault flows current from the utility and upstream DGs are necessary to operate R4, R6, and R15. As a result, when F3 occurs, R5 and R15

will operate to clear the fault from downstream DG (DG2, DG3, DG4). For this fault from the utility and DG1, R6, R7, and R8 must be operational. As a result, when fault F4 occurs, R8 and R11 from DG1 are required to operate for this fault. R12, R7, and R5 are required to operate for this fault from the utility and downstream DGs. On the other hand, R9 and R14 are required to operate for this fault from DG3 when F5 occurs. In the meantime, R10, R6, and R15 must operate for this fault from a different fault source. As a consequence, when the number of fault sources increases, the coordination schemes must become more sophisticated in order to preserve system reliability.

From Table 7, the CS were provided by the proposed algorithm are mostly IEC EI, similar to OM1, the trend of TMS still converged as close as possible to lower bound. The proposed algorithm results to the best objective function value, around 44 % lower than [20]. The results also shown that the proposed algorithm can effectively improve the system reliability from [20] as illustrated in Table 8. The coordination curve of each OCR for the proposed approach can be seen in Fig. 4.

4.3.3. The summary results of the proposed technique

With the proposed method, the total operating

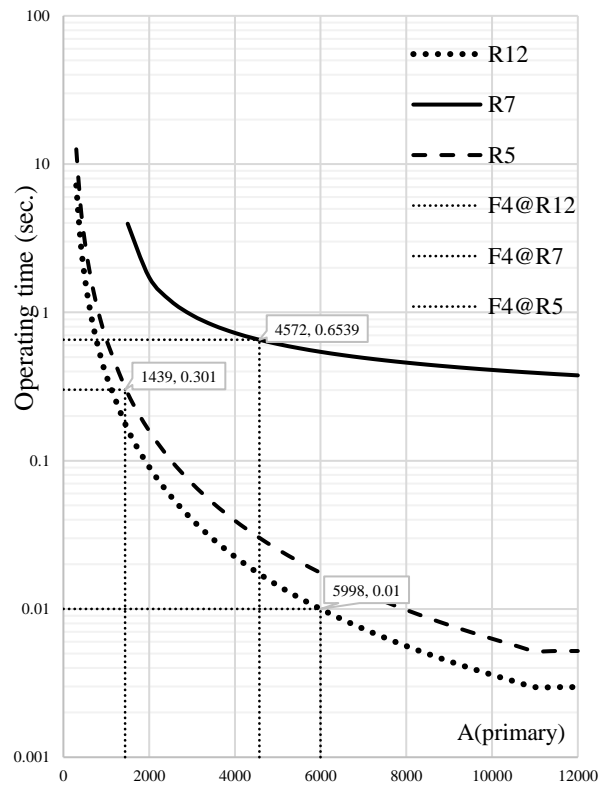


Figure. 4 The coordination curve of OCR in OM2

Table 8. The operating times of OCRs for OM2

Fault Point	Relay	ICGA [20]		Proposed	
		$T_{j,k}$	CTI	$T_{j,k}$	CTI
F1	R2	0.0405	0.3	0.01	0.3
	R4	0.3405		0.31	
	R1	0.2858	0.3	0.2959	0.3
	R13	0.5858		0.5959	
F2	R4	0.3405	0.625	0.1269	0.6
	R6	0.6629		0.4269	
	R15	0.6406		0.4269	
	R3	0.0302	0.3	0.0759	0.3
	R1	0.3301		0.3759	
F3	R6	0.6629	0.6	0.1475	0.6
	R7	0.9628		0.4475	
	R8	0.9629		0.4475	
	R5	0.186	0.553	0.0911	0.415
	R15	0.7386		0.5063	
F4	R12	0.0405	1.66	0.01	0.944
	R7	1.4		0.6539	
	R5	0.3405	0.3	0.301	0.3
	R8	0.8467		0.3857	
	R11	1.14		0.6857	
F5	R10	0.0405	1.157	0.01	1.701
	R6	0.3405		1.0861	
	R15	0.8976		0.6353	
	R9	0.1792	0.3	0.1698	0.3
	R14	0.4792		0.4698	
Total		12.48	6.09	8.701	5.76

Table 9. A comparative study with previous works

Operating modes	[16]	[17]	[18]	[20]	Proposed
OM1	7.53	6.64	4.99	4.19	3.09
OM2	19.18	17.48	13.66	12.48	8.77
Total time	26.71	24.12	18.65	16.67	11.84
Total CTI	9.08	8.93	8.56	8.29	8.165

Table 10. The results of 30 trials test

Operating mode	OM1	OM2
Best	3.14	8.701
Mean	3.14	8.847
Worst	3.14	8.984
STD	10^{-8}	0.111
Range	10^{-8}	0.283

time of the OCR protection for the IEC benchmark microgrid has decrease over time, by enhancing the constraint and demonstrating the ability of the proposed technique on the OCR’s parameters setting.

In comparison to existing works, the proposed technique is successfully reduced the total operating time and total CTI of the OCR as shown in Table 9.

The proposed algorithm has been tested with 30 trials to verify the optimal results. Table 10 shows the best, mean, worst, range, and standard deviation

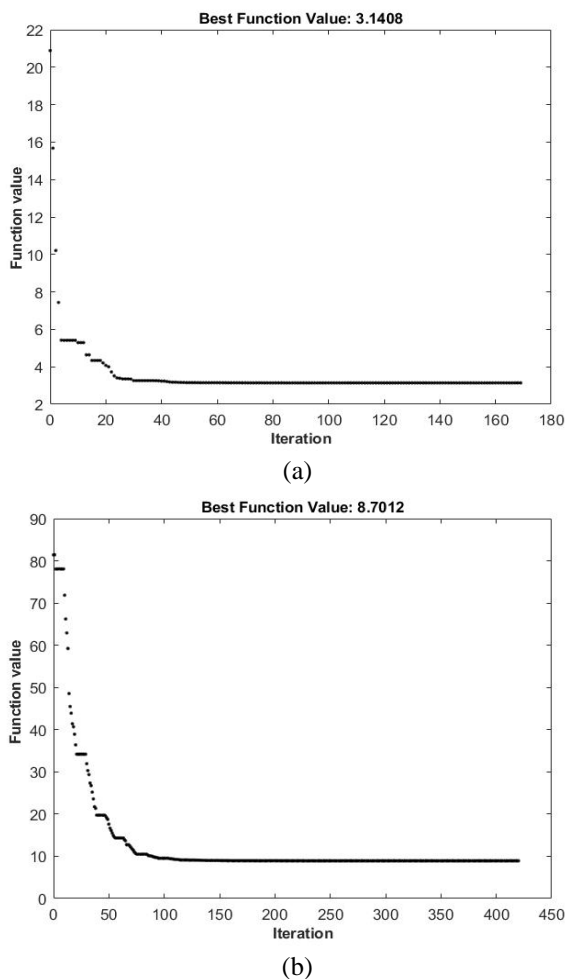


Figure. 5 Convergences plots of the proposed method:
(a) OM1 and (b) OM2

(STD) of the optimal results. From Table 10, it is clear that the biggest advantage of the proposed technique is that it provides the optimal results with significantly low STD. Hence, the proposed hybrid PSO-MILP technique is suitable for finding the global minimum objective function value of the overcurrent relay coordination. The convergence plot of the proposed method is shown in Fig. 5.

5. Conclusion

The PSO-MILP technique is used, in this paper, for obtaining the optimal setting parameters of OCR coordination, which are TMS and CS . The total operating time of the relay in the system is minimized by maintaining the reliability of the system through the coordination constraint. As a result, the proposed technique provides the results with multiple curve types instead of single curve types. When compared to previous researches, the proposed technique can absolutely decrease the total operating time of the OCR by around 34 percent for OM1 and around 44 percent for OM2. Therefore, it

can be concluded that the proposed method is suitable for the microgrid protection strategy. To demonstrate the usefulness of the proposed technique, the larger system, and other CS types can be considered in further work.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, methodology, validation, formal analysis, and investigation, C. Plongkrathok and K. Chayakulkheeree; writing original draft preparation, visualization, C. Plongkrathok; writing-review and editing, supervision, K. Chayakulkheeree.

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