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Optimal coordination of directional overcurrent relay based on combination of improved particle swarm optimization and linear programming considering multiple characteristics curve

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Abstract: Optimal coordination of directional over-current relays (DOCRs) is a crucial task in ensuring the security and reliability of power system network. In this paper, a hybridization of an improved particle swarm optimization and linear programming (IPSO-LP) is proposed to solve DOCRs coordination problem. The considered decision variables in the optimization are plug setting current, time multiplier setting, type of relay, and type of curve. By considering these parameters in the optimization, the best relay operating time can be determined. Furthermore, the proposed technique also considered the continuous values of pick-up current setting (PSC) and time setting multiplier (TMS). Test on the IEEE 8 bus system has proven the effectiveness of the technique, where an improvement between 2.36% and 45.8% of total relay operating time can be observed as compared to other techniques in literature. In addition, the obtained settings of the DOCRs from the proposed technique have been verified using industrial software to make sure no setting that cause violation to the DOCRs operation.

Key words: Directional over-current relay, hybrid optimization, protection system, ımproved particle swarm optimization, linear programming

1. Introduction

Directional over current relay (DOCR) is a common type of relay that has been used to protect power system network from fault. The main factor determining its effective operation is the optimal coordination setting in the power system network. There are two settings: pick-up setting current (PSC) and time setting multiplier (TMS) that need to be determined for DOCR. With optimal setting, the whole power system network can be protected effectively with the main and backup protection. The coordination setting is a challenging task when involving a large-scale network since the number of DOCR will be high. Moreover, the integration of distributed generations (DGs) in the network also adding to the complexity in coordinating these relays. DG will cause current to flow in bi-directional and may cause false tripping if the relays are not coordinated accordingly. Therefore, it is essential to ensure that the coordination settings of DOCR in the network is able to detect the fault current from any direction (i.e. upstream or downstream).

Various techniques have been proposed in the past to solve this coordination problem. The techniques can be commonly categorized as metaheuristic, linear programming, nonlinear programming, and hybrid methods[1–

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4]. Different metaheuristic techniques have been employed in order to achieve the optimal coordination of DOCR. In [5], the optimal coordination of DOCR is solved with ant lion optimizer, which simultaneously deals with PSC and TMS. Similarly, in[6], particle swarm optimization (PSO) is used to attain optimal coordination of DOCR, but the interior point method is used to initialize population of PSO. Although the methods were able to minimise the relay operating time (ROT), but it is time consuming. In [7], enhanced differential evolution (EDE) algorithm considers the dial reduction scheme which avoids the violation in DOCR constraint, reduces the standard deviation and improves the speed of execution of algorithms by reducing the number of populations. However, it is trapped in local optimal settings. The reported work in[8] proposed a technique based on teaching learning-based optimization (TLBO) algorithm to improve the solution quality of DOCR problem. In this technique, populations are updated by applying random weighted differential vector from current and desired mean. Even though the performance of the proposed algorithm is satisfactory in terms of reliable coordination margin, the miscoordination still occurs. In [9], modified-real coded genetic algorithm (MRCGA) was implemented for bound exponential crossover and power mutation (BEX-PM) wherein the power mutation is inserted in BEX to avoid optimum local trapping and preserve population diversity. The proposed method managed to achieve a feasible solution without imposing penalties on the objective functions. In [10], the random motion factor 'α' manipulated by modified fire algorithm (MFA) is adaptive to any iteration changes, thus ensuring quick convergence but manages to attain near optimal solution. Even though metaheuristic techniques are capable in finding a global optimum solution, due to the high complexity and large numbers of relay coordination constraint, a huge number of infeasible solutions will be generated during the searching process. Thus, updating process of these infeasible solutions will increase the time of computation and may converge to the local optima.

DOCR coordination problem is mathematically nonlinear in nature. Thus, [11, 12] introduced a technique to achieve optimal coordination on the basis of nonlinear programming (NLP). As a result, by applying to the small system, it manages to attain near optimal solution. However, NLP demands longer computational time because it simultaneously attains the optimal PSC and TMS for all relays and fulfilled the large number of constraints at the same time. In [13], the coordination problem was solved by the Seeker algorithm based on the formulated nonlinear mixed integer programming (MINLP), but MINLP is prone to be trapped in local minima. Therefore, researchers have reduced the complexity of the problem by linearizing the DOCR coordination problem.

In DOCR problem, linearization is attained by assuming predetermined PSC value. Therefore, TMS has become the only variable that needs to be optimised. To solve the linear programming problem (LPP) a two-phase simplex based algorithm was used in [14]. Likewise, in [15], a radial type network has incorporated nondirectional overcurrent relay, and mixed integer linear programming (MILP) technique is responsible to optimize the TMS. The computational time is reduced for both techniques. However, these techniques may not attain the minimum relay operating time due to the deterministic value of PSC.

With all of the above-mentioned reasons, the researchers have explored the combination of metaheuristic techniques with LP or NLP to address the shortcomings of the individual metaheuristics, NLP and LP techniques in solving DOCRs coordination problem. In [16], a hybrid gravitational search algorithm and sequential quadratic programming (GSA-SQP) is proposed to solve the DOCR problem. Although the convergence is fast, the technique only considers the standard inverse (SI) type of relay and discrete type. Similarly, genetic algorithm (GA) with LP [17] differential evaluation (DE) with LP [18] in GA with NLP [19] and biogeography-based optimization (BBO) with LP [20] are used in order to minimize the total operation time of DOCR problem. In[18], DE estimated the value of PSC based on the amount of current flowing at the primary of Current Transformer (CT), whereas the TMS is determined by the LP. The technique proposed a mathematical formulation to relieve the complexity of constraint, but less comparison was being made to justify the result. In [19], PSC and TMS were determined for all DOCRs using GA while considering prespecified iteration. These values of PSC and TMS were considered as the initial values for the NLP. The method is used to manage search for the quality solution but not by considering the miscoordination issues. In[20], the PSC and TMS were generated simultaneously in the initialization stage meanwhile LP was used in the evaluation stage to handle both parameters. Although a large number of combinations have been proposed to solve the optimal coordination of DOCRs, due to the highly complex search space, most of them only considered standard inverse characteristic of relay while minimizing the total operating time of relay. Therefore, further investigation on hybrid optimisation technique is required to improve the solution quality and to reduce the computational time.

Hybrid optimization techniques such as GA-LP, BBO-LP, and BBO-DE also have been used to solve the optimal coordination of DOCR problem. All of these techniques do not linearize the DOCR search space. In this paper, the optimal coordination of DOCR is proposed to be solved using a hybrid optimisation technique based on Improved particle swam optimization (IPSO) and linear programming (LP) referred as IPSO-LP. To the best of our knowledge, this is the first time IPSO-LP is used to solve DOCR coordination problem. In this technique, two-stage approach is considered; in the first stage, the IPSO is utilized to find the PSC. In second stage, the result of PSC from the first stage is used to find the TMS and RCOT based on LP technique. By attaining the TMS, RCOT against the fixed PSC, IPSO determines the best PSC. IPSO technique is chosen since it has a better performance as compared to conventional PSO. IPSO has the capability to solve the highly constraint coordination problem in fast computational time [support with reference please]. The effectiveness of the proposed technique is tested on IEEE 8-bus test system and DOCR coordination is also verified using Industrial software ETAP. This paper also considers various type of DOCR relay such as IAC, IEEE, and U.S type of relay in order to provide more flexibility in attaining the minimum total relay operating time.

The rest of this paper is organized as follows; section 2 presents the formulation of the protection coordination problem while section 3 explains the application of hybrid IPSO-LP technique where detailed procedure of the optimization is presented. In section 4, results and their significance, validation and comparison studies are discussed. Section 5 concludes the work and its findings.

2. Problem formulation

Formulation of the DOCRs coordination problem is as follows: a) objective function, b) relay setting constraints, and c) coordination constraints.

2.1. Objective function

The DOCR operates when the input current exceeds pick-up current (PSC) and with specific direction of the fault current. The operational time of these relays are determined by international standard such as the one of Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), Inverse Alternate Current IAC), and Unites State (U.S) [21].

In this work, minimum operating time of all primary relays in the network is set as the objective function, given in Eq.(1):

$$f_1 = \sum_{i=1}^{\text{g}} (ROT_1(Primary)) \tag{1}$$

where ROT_i is the relay operating time of primary relay and g is the total number of relays in the networks. Relay operating time (ROT) is given in Eq.(2):

$$ROT_i = RCOT_i * TMS_i \tag{2}$$

$$ROT_i = \frac{I_f i}{PSC_i} \tag{3}$$

$$RCOT_i = \frac{A}{PSM_i^P - 1} \tag{4}$$

$$RCOT_i = (\frac{A}{PSM_i^P - 1}) + B \tag{5}$$

$$RCOT_i = A + (\frac{B}{PSM_i^P - 1}) \tag{6}$$

$$RCOT_i = A + (\frac{B}{(PSM_i - C)}) + (\frac{D}{(PSM_i - C)^2}) + (\frac{E}{(PSM_i - C)^3}) \tag{7}$$

where $I_f i$ is the level of fault current flow at the R_i. TMS_i is the TMS of R_i. PSM_i in Eq.(3) is the plug setting multiplier which is related to the ROT, and it varies with the standard of R_i. PSM_i is the plug setting current of R_i.For relay characteristic operating time (RCOT), the following are four different characteristics based on IEC (Eq.4) , IEEE (Eq.5), U.S (Eq.6) and IAC standards (Eq.7). A, B, C, D, E and P are coefficients related to the curve type for R_i. These coefficients are according to standard ınverse (SI), very ınverse(VI), extremely ınverse(EI), long time ınverse (LTI), moderately ınverse (MI) and short time ınverse (ShI). The detailed values for these coefficients are provided in [21].

2.2. Relay setting constraint

Minimization of the objective function in Eq.(1) is bounded by sets of constraints. These constraints to ensure the upper and lower limits of TMS and PSC are fulfilled, as shown in Eq.(8) and Eq.(9).

$$TMS^{min} \leq TMS_f \leq TMS^{max} \qquad \forall f \in G \tag{8}$$

$$PSC^{min} \leq PSC_f \leq PSC^{max} \qquad \forall f \in G \tag{9}$$

where G is a set of relays,TMS_f is the time multiplier setting,TMS_{min} and TMS_{max} are the minimum and maximum limit of the time multiplier setting respectively. PSC_f is the plug setting current,PSC^{min} and PSC_{max} are the minimum and maximum limit, respectively. For the application of numerical relay, PSC is set as a continuous variable, PSC_f^C. For electromechanical relay, the PSC_f^D is determined by rounding-off the PSC_f^C value to the nearest discrete value as in Eq.(10).

$$PSC_f^D = floor(PSC_f^D * \sigma)/\sigma \qquad \forall f \in G \tag{10}$$

The σ represents a constant to round-off and the floor(x) function will return the lower integer value of PSC_f^D [22].

2.3. Coordination constraint

The coordination constraints ensure that the operating time of the primary and backup relays must be greater than the coordination time interval (CTI). CTI avoids the malfunctioning between the primary and backup tripping action, in the case when both of the relays simultaneously detects the fault [6]. The CTI holds the amount of the circuit breakers (CB) operating time correlated with the primary relay, backup relay overshoot time and the acceptable margin of protection. Considering Figure 1 as an example, the backup relay, R_J will tripped later than the primary relay, R_I.

$$ROT_{jk} - ROT_{fk} \leq CTI^{min} \qquad \forall k \in NRP \tag{11}$$

$$ROT^{min} \leq ROT_f \leq ROT^{max} \qquad \forall f \in G \tag{12}$$

where NRP is the number of relay pairs corresponding to the fault location, F. ROT_{jk} and ROT_{fk} are the operating times of the primary and backup relays, respectively, for a fault developing in front of the primary relay shown in Eq.(11). The CTI value may vary between 0.2 and 0.5s, depending on various circumstances and factors. ROT^{min} and ROT^{max} are defined as the minimum and the maximum primary operating time of the relay, respectively, shown in Eq.(12).

Figure 1. Primary and backup relay coordination in radial distribution system.

3. Proposed IPSO-LP approach for DOCRs coordination IPSO-LP

Particle swarm optimization is a metaheuristic technique that has been adopted by many researchers in the past. Similar to other metaheuristic techniques, PSO is inspired from the food searching behaviour of fish and bird. The improved PSO (IPSO) is using the same steps as in conventional PSO. The main difference is on the velocity calculation Eq.(18), where it considered the different weight of the previous velocity for each iteration. Table 1 shows the IPSO parameters that are applied in the optimization. In the initial step, particles are initialized with random positions. Their fitness value is then evaluated based on the objective function. These particles update their position and velocity in accordance to their local best and global best fitness values. The process repeats until all particles converge to the same fitness value or it reaches the maximum iteration. Table 1 shows the IPSO parameters that are applied in the optimization.

Table 1. IPSO setting parameter.

PSO setting parameter	Coefficients
Inertia weight minimum,ω_{min}	0.4
Inertia weight maximum,ω_{max}	0.9
Acceleration coefficients minimum,C_1^{min}	0.5
Acceleration coefficients maximum,C_1^{max}	2.5

The proposed hybrid IPSO-LP technique is a combination of IPSO and linear programming (LP). DOCRs coordination problem is nonlinear in nature. Therefore, to linearize it, a two-stage approach is proposed as shown in Figure 2. In the first stage, the IPSO is utilized to find the PSC and the result is sent to the second stage. In the second stage, the NLP DOCRs coordination problem is converted into a LP problem by attaining the fixed value of PSC from first stage. Then the LP is employed to find the TMS and RCOT. By attaining the TMS, RCOT against the fixed PSC, IPSO determines the best PSC based on the objective function given in Eq.(1). Once the PSC and TMS are obtained, these values will be used in numerical OCR such as GE Multilin brand F650 model and ABB brand SPAJ 110C model to protect faulted network. The detailed steps to solve the coordination problem are as follows:

Step 1: Determine inputs, such as the bus load and voltage, CT ratio, fault current, the values of the resistance and reactance of each line, and PSO parameters.

Step 2: Initialize the populations of particles based on Eq.(13) and Eq.(14);

$$X_i^{old} = X_i^{max} + r_1 * (X_i^{max} - X_i^{min}) \tag{13}$$

$$\left[X_i\right] = \begin{bmatrix} PSC_{11} & PSC_{12} & \cdots & PSC_{1g} \\ \vdots & \vdots & \vdots & \vdots \\ PSC_{h1} & PSC_{h2} & \cdots & PSC_{hg} \end{bmatrix} \tag{14}$$

where d denotes the size of population, g is the total number of the relays. r_1 is the set of random number from the uniform distribution function.

Step 3: Generate the upper boundaries and lower boundaries for TMS and RCOT based on the PSC from PSO as shown in Eq.(15).

$$\begin{bmatrix} CTI_{11} \\ CTI_{21} \\ CTI_{31} \\ \vdots \\ CTI_{s1} \end{bmatrix} = \begin{bmatrix} -RCOT_{11} & RCOT_{12} & \cdots & RCOT_{1T} \\ RCOT_{21} & -RCOT_{22} & \cdots & RCOT_{2T} \\ RCOT_{31} & RCOT_{32} & \cdots & RCOT_{pT} \\ \vdots & \vdots & \vdots & \vdots \\ RCOT_{p1} & RCOT_{p2} & \cdots & RCOT_{pT} \end{bmatrix} * \begin{bmatrix} TMS_1 \\ TMS_2 \\ TMS_3 \\ \vdots \\ TMS_R \end{bmatrix} \tag{15}$$

where p indicates the number of back-up and primary relays at one bus; T is the number of buses, s is the number of relays pairs,R number of TMS for relays;

Step 4: Evaluate the fitness of the population by solving LP model and considering all Eq.(10),Eq.(11), Eq.(12) and Eq.(15).

Step 5: Based on the fitness value found from LP, global best (G^{best}) is selected.

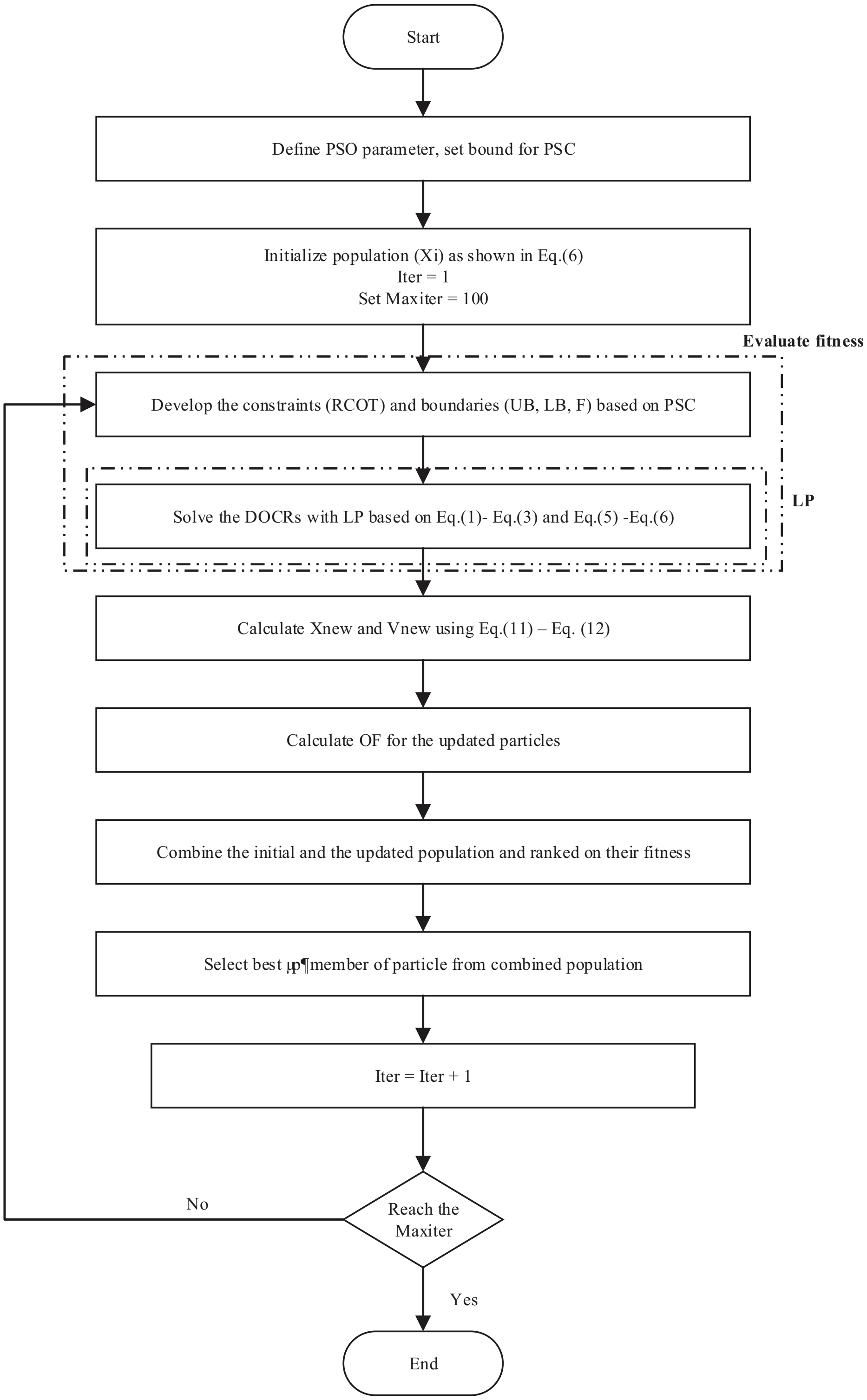

Figure 2. Flowchart of the proposed IPSO-LP.

Step 6: Calculate two acceleration constraint of PSO: cognitive parameter (c_1) and social parameter (c_2) using Eq.(19) and Eq.(17). All the particle updates their position and velocity based on Eq.(18), Eq.(**??**) and Eq.(20).

$$C_1 = (C_1^{max} + C_1^{min}) * (\frac{iter}{iter^{max}}) + C_1^m in \tag{16}$$

$$C_2 = 2 - C_1 \tag{17}$$

$$V_i^{new} = \omega * V_i^{old} + [C_2 * r_2 * (G_i^{best} - X_i^{old})] \tag{18}$$

$$\omega = (\frac{\omega_{max} - \omega min}{i_{ter}^{max}}) * i_{ter} \tag{19}$$

$$X_i^{new} = X_i^{old} + X_i^{new} \tag{20}$$

where,

ω is the inertia weight of the particle
i_{ter}^{max} is the maximum iteration
i_{ter} is the current iteration
X_i^{old} is a previous particle value of i_{th} population m^{th-1} iteration
X_i^{new} is the new generated particle from i_{th} population in m^{th-1}
G_i^{best} of the populations determined in m^{th-1}

Step 7: Calculate the fitness of the newly generated populations X_i^{new} found from LP.

Step 8: Combined last and new generated populations and ranked them according to their fitness value.The fitness of the top most population will be considered as the G^{best} in the m_{th} iteration and first r will be considered for m_{th+1} iteration.

Step 9: If all the populations have converged or reached the maximum iteration limit,stop the algorithm and the population of G^{best} is considered as optimum solution for relay operating time (ROT) of DOCR problem. If both conditions are not satisfied, the algorithm will go to step 6 for further searching.

4. Result and discussion

The proposed DOCRs coordination is tested on IEEE 8 bus system [20] shows in Figure 3. This test system comprises a 400MVA external generator and 2 synchronous generators connected at bus 7 and 8. Two DOCRs are considered to protect each branch and thus 14 DOCRs are required to protect this system. All relays are considered as the numerical relays. Current transformer (CT) ratios given for R3, R7, R9, and R14 are 800/5 while others are 1200/5. The minimum coordination time interval (CTI) value in this study is set to 0.2s.

The optimal value of TMS and PSC attained using the IPSO-LP approach are listed in Table 2. The total relay operating time gained using PSO is 6.132s; whereas, the IPSO-LP obtained 5.970s which reduces the ROT by 0.145s. Meanwhile, the comparison of ROT of proposed technique with other techniques is presented in Table 3. This comparison is conducted based on the same test system and the same relays location. It can be found that the proposed technique has succeeded in decreasing the total ROT by 5.077s, 5.014s, 4.963s,

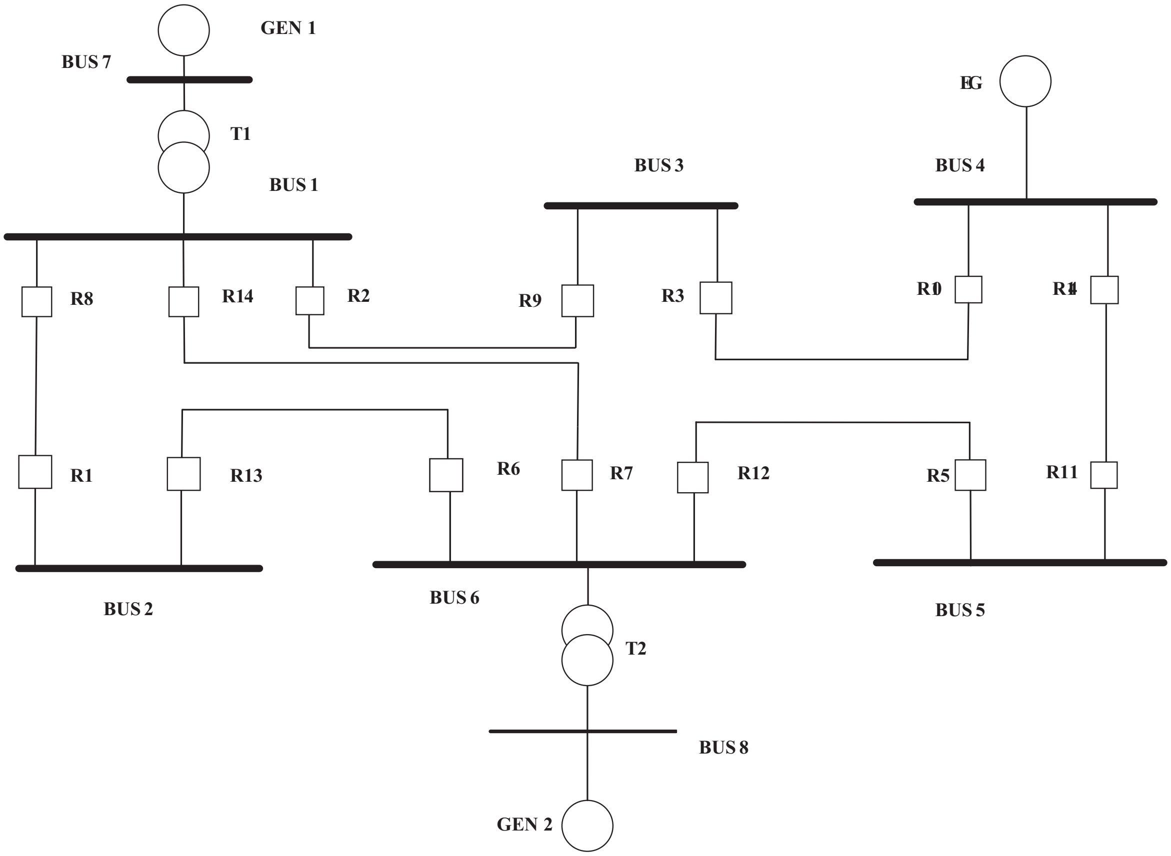

Figure 3. One-line diagram of IEEE 8-bus system.

2.769s, 2.44s, 2.019s, 1.514s, 1.209s, 0.425s, and 0.362s as compared to LM, GA, HGA-LP, BBO-LP, SA, MILP, WOA, HWOA, NLP, and MEFO, respectively. In addition, Figure 4 illustrates the convergence of the proposed optimization technique which implies that the IPSO-LP is able to attain the improved objective functions value in less iterations. The percentage of objective function (OF) improvement is shown in Figure 5. The result shows the gap of percentage in the literature between optimized total ROT of IPSO-LP and other suggested technique.

Instead of optimising the placement of relays, this paper carried out an analysis on each and every characteristic available in multiple types of relay which are IEEE, IEC, IAC, and U.S types. The evaluation is conducted to check the impact of multiple relay characteristics on the relay operating times and the performance of all types of relay being analysed. As observed from Table 4 for the IEC type, in most of the cases, minimum ROT is attained by the EI characteristic and the maximum ROT is produced by SI. The percentage improvement of an 8-bus system for the EI characteristic as compared to VI, LTI, and SI are 53.9%, 80.9% and 82.3% respectively. Meanwhile, for the IEEE type, the EI characteristic attains the lowest ROT, and the highest ROT is produced by the MI type. The percentage of improvement gained by EI as compared to MI and VI are 77.54% and 46.06%respectively. As for the IAC type relay, EI still attains the minimum ROT and SI has the maximum ROT. The percentage of improvement by EI is 91.1%, 84.88%, and 51.504% as compared to SI, VI, and ShI, respectively. The U.S type of relay indicates that EI produces the lowest ROT and SI produces the highest. The EI characteristic improves by 14.43%, 74.58%, 74.1%, and 51.59% from ShI, SI, MI, and

Table 2. TMS and PSC using PSO and the proposed IPSO-LP for IEEE 8-bus system.

Relays	PSO		IPSO-LP	
	TMS	PSC	TMS	PSC
1	0.4640	0.2170	1.6340	0.1000
2	1.0720	0.5060	2.5000	0.1820
3	0.5680	0.6440	2.5000	0.1600
4	0.4550	0.7810	2.5000	0.1180
5	0.4860	0.2290	1.7050	0.1000
6	1.1820	0.2340	2.5000	0.1280
7	0.5460	0.5240	2.5000	0.1670
8	0.5510	0.7420	2.5000	0.1240
9	0.6180	0.1460	2.5000	0.1180
10	0.3640	1.0290	2.5000	0.1180
11	0.4390	1.0470	2.5000	0.1250
12	0.4390	1.0470	2.5000	0.1250
13	0.4390	1.0470	2.5000	0.1250
14	0.4390	1.0470	2.5000	0.1250
$\sum_{i=1}^{N}(ROT_1(s))$	6.1320		5.9870	

Table 3. Comparison of IPSO-LP with the other methods proposed in the literature for IEEE 8-bus system.

Method	Objective function $\sum_{i=1}^{N}(ROT_1(s))$
LM[23]	11.0640
GA[17]	11.0010
HGA-LP[17]	10.9500
BBO-LP[20]	8.7560
SA[13]	8.4270
MILP[24]	8.0060
WOA[25]	7.5010
HWOA[26]	7.1960
NLP[23]	6.4120
MEFO[24]	6.3490
PSO	6.1320
PROPOSED IPSO-LP	5.9870

VI, respectively. For this case, the EI type characteristic should be considered for the capability of generating the lowest ROT among all characteristic curve. For the performance analysis, the lowest standard deviation is found from the SI of IEC type and the MI IEEE type, which are both zero. The highest standard deviation is found from the LTI of IEC type, which is 0.2737.

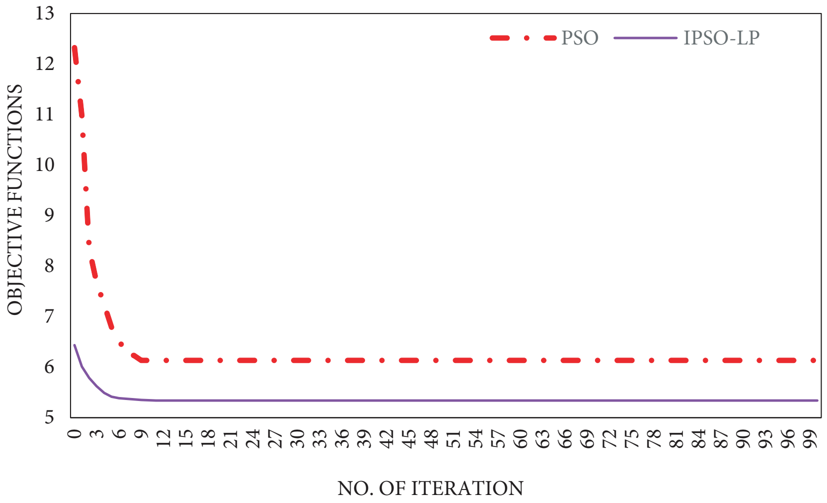

Figure 4. Convergence characteristic of the IPSO-LP and PSO for IEEE 8-bus system.

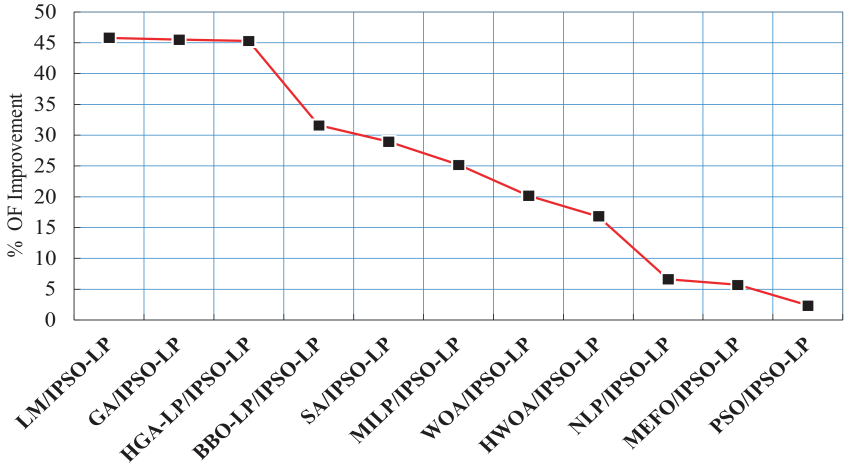

Figure 5. Graphical illustration of the percentage of objective function (OF) improvement of the IPSO-LP as compared to the literature for IEEE 8-bus system.

5. Verification of IPSO-LP using STAR package of ETAP

In this work, the results are verified by using ETAP software. ETAP is the industrial power system software used worldwide and has a capability to perform comprehensive power system analysis. One of the important features provided by the ETAP is to validate the DOCR relay coordination settings using STAR ETAP package. Furthermore, the models of all DOCR relays used by the industry are available in ETAP and it is also possible to build a customized relay. In this work, the built-in relay models are used. Meanwhile, the embedded features are for protection coordination, the selectivity of operation relay and illustration of the time characteristic curve (TCC) for the purpose of viewing the coordination relay time and current setting. The IEEE 8 bus system is modelled in ETAP by using GE Multilin brand F650 model and ABB brand SPAJ 110C model. Using the optimized settings of overcurrent relays obtained from the proposed technique, 3 phase fault analysis is applied to observe the time current curves (TCC) on the basis of IEC, IEEE, IAC, and U.S types of the relays. Some

Table 4. The performance evaluation for multiple types of relay for IEEE 8-bus system.

Relays Standard type	Curve type	$\sum_{i=1}^{N}(ROT_1(s))$	Min	Max	Standard deviation
IEC	SI	5.9870	5.9875	5.9875	0
	VI	2.3000	2.3006	2.3111	0.0052
	EI	1.0600	0.4855	1.0640	0.1983
	LTI	5.5730	5.5686	7.4186	0.2737
IEEE	EI	1.3092	1.3075	1.4456	0.0475
	VI	2.4273	2.4274	2.8693	0.0649
	MI	5.8311	5.8293	5.8293	0
US	MI	2.1375	2.1114	2.4525	0.0690
	VI	1.1438	1.0726	1.2140	0.0380
	SH.I	0.6471	0.4721	0.6803	0.0580
	SI	2.1783	1.9279	2.1837	0.0690
	EI	0.5537	0.4158	0.4571	0.0110
IAC	EI	0.2868	0.2487	0.0339	0.0209
	VI	1.8966	1.2767	1.4429	0.0469
	SI	3.2038	3.0301	3.4717	0.0779
	Sh.I	0.5916	0.3168	0.6657	0.0750

examples of the TCC are discussed in the next paragraph for the specific buses.

The TCC of multiple relay type analysis was conducted on bus 3, whereby relay 9, R9 is coordinated as back-up for relay 3 for VI characteristic of the IEEE type shown in Figure 6 and SI for the IEC type shown in Figure 7. The TCC illustrated the CTI between relay 9 with relay 3 more than 0.2s. The coordination constraint for CTI for all types of relay holds.

6. Conclusion

This paper set out a new technique for optimal coordination of DOCRs based on the combination of improved particle swarm optimization (IPSO) and linear programming (LP) technique, referred as hybrid IPSO-LP. The proposed technique linearized the DOCRs coordination problem to relax the search space and prohibit it from trapping at local optima. In this technique, IPSO solves PSC value and LP solves TMS value and at the same time fulfills all the constraints. The IEEE 8-bus system is employed to assess the performance of the proposed IPSO-LP. The proposed technique also optimized different types of relay based on the IEC, IEEE, IAC and U.S standards to find the best relay operating time by handling different complexity of relay characteristic constraints. Thus, selecting the best type of relay for different characteristics would improve the overall quality of the solution. As for the 8-bus system, the total relay operating time attained by the proposed technique is 0.5537s for EI, IAC type of relay. For any country applying the IEC and IEEE regulation, EI is the best characteristic to produce the lowest relay operating times. This result has shown great improvement in range of 2.36% up to 45.8% as compared to other techniques in literature. At the same time, utilization of the multiple IEC, IEEE, IAC, and U.S characteristics (VI, SI, EI, LTI, MI and Sh.I) in the network also lead to the optimal solution by the proposed technique. It is also found that EI produces the lowest ROT compared to SI, VI,

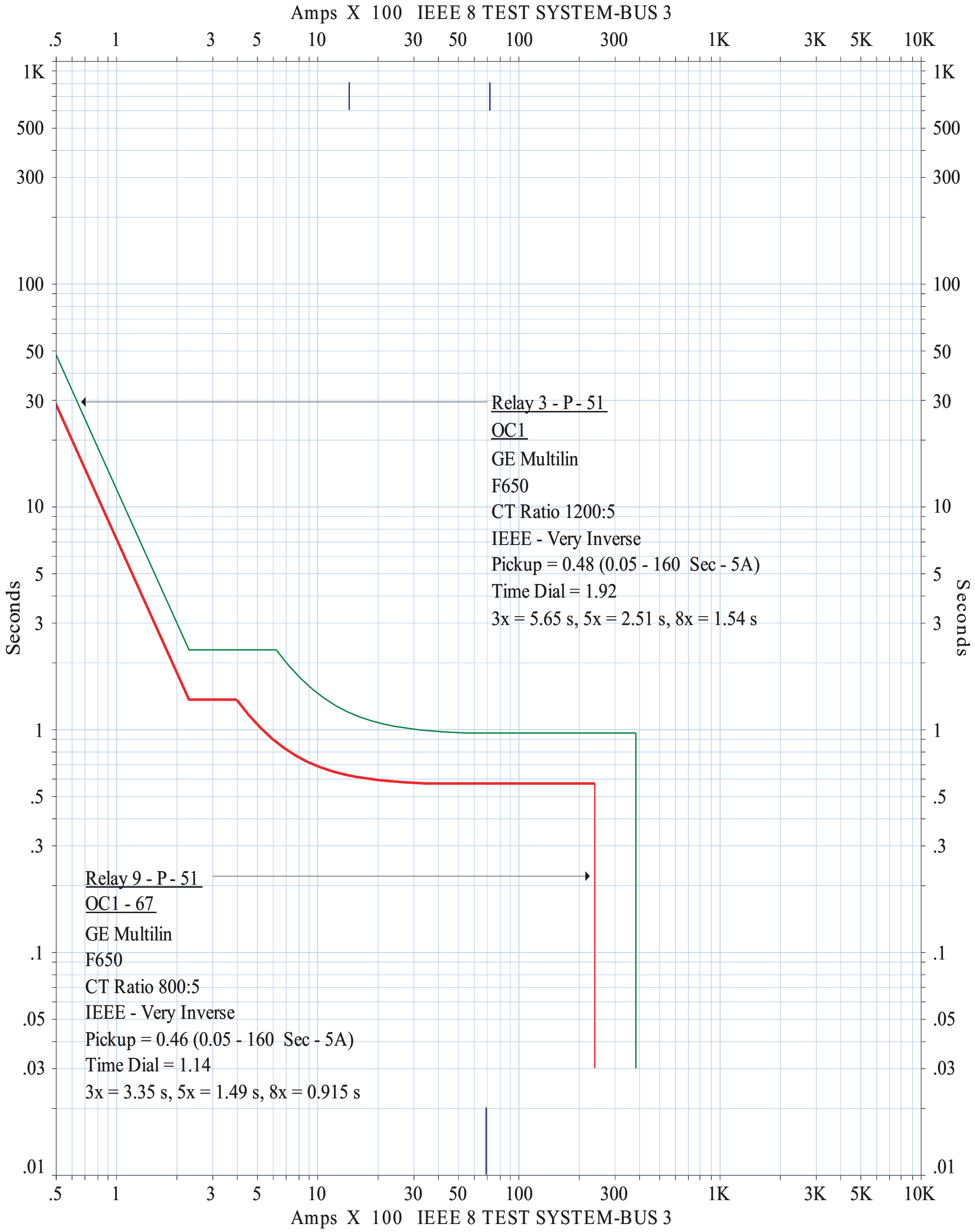

Figure 6. IEEE type relay for VI TCC analysis of IEEE 8-bus system using optimized setting at bus 3 for R9(primary) and R3(back-up).

LTI, MI, and Sh.I. In addition, ETAP power tool simulation software is also used to validate the results of proposed technique. From the primary back-up pair generated by TCC, it can be observed that there is no overlap between both the primary and the back-up curves. This establishes that the setting of primary and

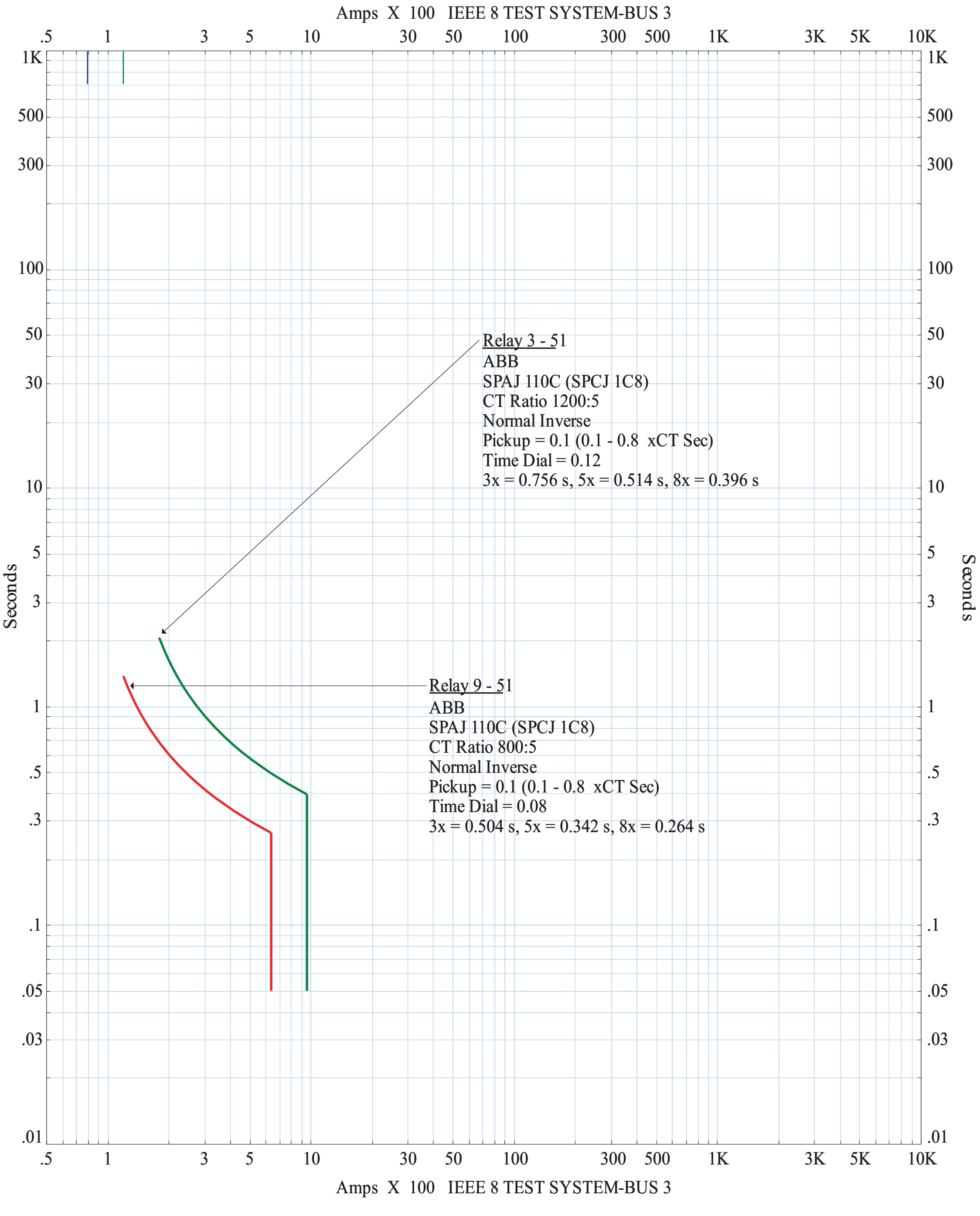

Figure 7. IEC type relay for SI TCC analysis of IEEE 8-bus system using optimized setting at bus 3 for R9(primary) and R3(back-up).

backup relays developed from the proposed technique is suitable and capable of avoiding mal-operation with the relay. In the future, the proposed technique can be tested for large and practical networks. Furthermore, it can be also extended by adding more decision variables, which are nonstandard characteristics coefficient curve relay to provide more flexibility towards solving the relay coordination problem.

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