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Improved Firefly Algorithm for the Optimal Coordination of Directional Overcurrent Relays

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ABSTRACT In an electrical power network linear and non-linear models are used for directional overcurrent relay (DOCR) coordination issue by applying different heuristic techniques. Nature inspired algorithms (NIA) have found great interest in power system optimization issues. This paper proposes the recently developed meta-heuristic technique known as Firefly Algorithm (FA) that mimics the flashing behavior of fireflies. The implementation of the proposed algorithm has been utilized to solve the coordination of DOCR problems. The main aim of this paper is to find out the optimum values of the Time Dial Setting (TDS) to minimize the relay operating time. The modifications to original FA has been implemented in this paper to solve the DOCR coordination issues. Self-adaptive weight and experience-based learning strategy are added in the original FA, named as improved firefly algorithm (IFA). In IFA, a self-adaptive weight is presented to change the propensity of moving the best solution and ignoring the worst solution. In addition, an experience-based learning system is created and utilized arbitrarily to keep up the populace-assorted variety and improve the exploration capacity. The IFA has been tested on IEEE 6 and 30-bus systems and tested on IEEE 9-bus system for numerical DOCRs and the results had been compared with results of Whale optimization algorithm to validate the performance of IFA in case of numerical DOCR. The obtained results show that the IFA provides efficient and promising results compared to other meta-heuristic techniques mentioned in the literature. The IFA has been successfully implemented on MATLAB software programming.

INDEX TERMS Improved firefly algorithm (IFA), directional overcurrent relay coordination (DOCR), time dial setting (TDS), power system protection.

I. INTRODUCTION

Recently power system is growing day by day which makes some unwanted and security threat to power system engineers. To overcome this security threat a precise and reliable system is of high importance to transfer the real power continuously without any delay and interruption. To design such system we need a fast relaying strategies composed of protective devices. More recently, directional over current relays are evolved as a primary counter agent to deal with such security threats. The proper coordination of the DOCRs overcome the power outages and isolate the fault in minimum period of time and keep the system secure and trust worthy. A fitly coordinated protection arrangement is among the essential requirements to operate a power system with highest reliability. In order to carry out the power system safe and reliable zero fault should occur during its operation. The aim for optimal coordination of directional overcurrent relays (DOCR) is to objectify the optimal settings of all the relays working in the system. The coordination of DOCR's is to vanish the Mal-function of the relays. The conditions that happen amid mal-function are faults. So forth the blackouts will prompt interference of supply and can harm the gadgets associated with an electrical power system. So as

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to dispose these variations from the norm there shows up the significance of keeping up a dependable defensive power network. For keeping up the secure and solid protection, there ought to be downstream or upstream assurance if the upstream protection scheme falls flat. Directional overcurrent relays have been used for the essential or optional assurance of intensity framework. This will possibly lead into reality if and only if the principle line of defense got some issues or if the primary security conspire fizzles. DOCRs work after a period delay called as coordination time deferral or coordination time interim (CTI), giving a completion for the fundamental/essential plan to work. DOCRs are an economic option and are simple to apply for the wellbeing of the attached sub transmission power systems and secondary layer of backup protection in transmission framework [1]. In previous years trial and error approach had been applied by power system engineers for optimal relay settings that is a time consuming process. In [2] the application of linear programming was utilized by the researchers to tackle with the relay coordination problem. In [3] the optimal coordination of directional overcurrent relays in interconnected power systems. A review on relay coordination had been taken out by the researchers [4]. A random search method in [5] was used for the optimal relay settings. In [6], the modified electromagnetic field optimizer was implemented to see the behavior on DOCR. In [7]–[11] the different applications of genetic algorithm had been applied for the relay coordination convergence characteristics. In [12] grey wolf optimizer was used for accurate coordination of DOCR. In [13]–[19] various applications of particle swarm optimization had also been utilized to get the minimum relay coordination. In [20], the application root tree optimization is utilized to tackle with the directional overcurrent relay issues. In [21] the relay coordination problem is solved using different metaheuristic techniques. In [22], Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm has been explained. In [23] relays using modified differential evolution algorithms has been solved. The hybridized symbiotic organism search algorithm for the optimal operation of directional overcurrent relays was utilized in research by [24]. A robust optimization methodology had been utilized for the protection of security of smaller scale frameworks utilizing chip-based relays [25]. In [26] a new approach for optimal coordination of distance and directional over-current relays using multiple embedded crossover PSO. Reference [27] planned a protection plot for a distribution system taking into account the numerous modes of operation. In reference [28], adaptive protection coordination scheme using numerical directional overcurrent relays. In [29]–[36] Optimal Coordination of DOCRs had been implemented Using different optimizers. In [37] the problem of DOCRs in a power system is handled with the firefly algorithm (FA). In [38] invasive weed optimizer had been used for the DOCR problem. In [39], a modification to teaching learning based optimizer (TLBO) was implemented for DOCR problem.

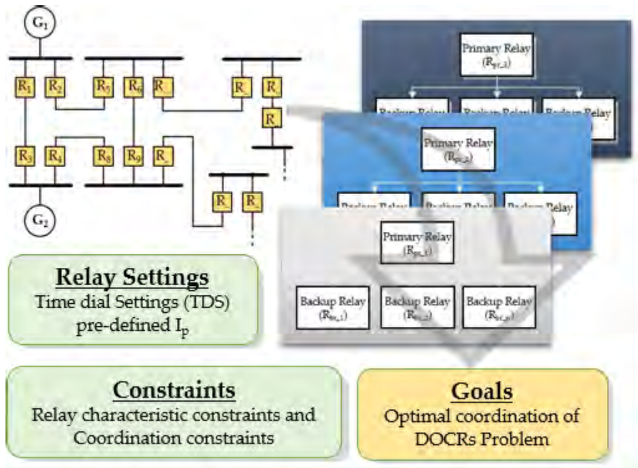

FIGURE 1. Optimal coordination block diagram.

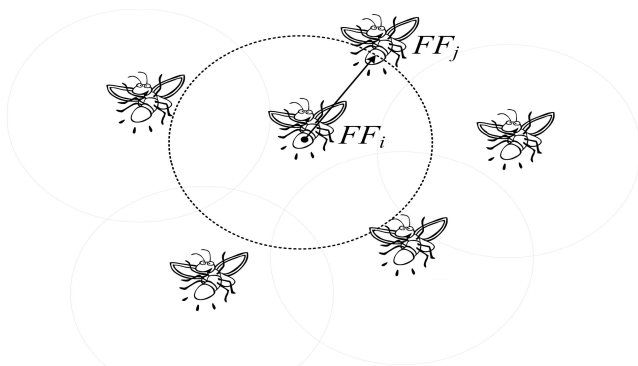

FIGURE 2. Representation of the fireflies.

In [40], the biogeography-based optimizer (BBO) was used for the DOCR issue.

Firefly algorithm is a recently developed nature-inspired optimization technique based on the flashing behavior of the fireflies. This paper proposes improved firefly optimization (IFA) methodology that can accomplish the ideal coordination of directional overcurrent relays. The implementation of the improved firefly optimizer utilized to test for IEEE 6 and 30-bus system and implemented on IEEE 9-bus system for numerical DOCRs considering MATLAB programming software.

II. COORDINATION PROBLEM FORMULATION

Figure 1 portrays the outline for the coordination of DOCRs in an electrical power network. The optimum coordination of DOCRs goals to decline the operational time of the relays improving to minimize the faults in the primary zone of protection and however if primary zone of protection fails then the second zone of protection like backup relays take the responsibility within the coordination constrains.

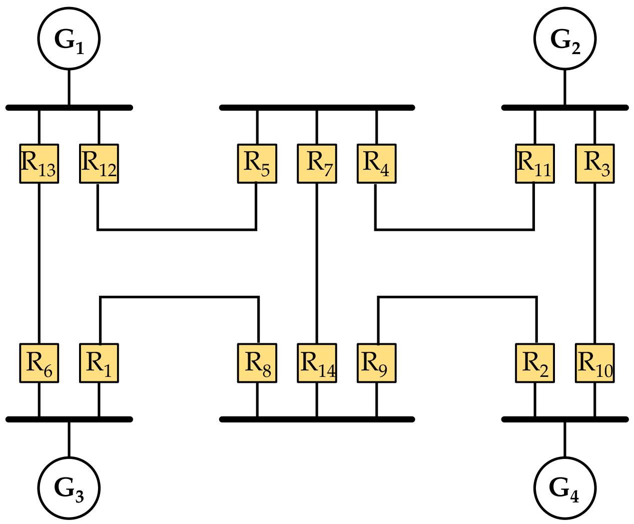

FIGURE 3. 6-Bus system.

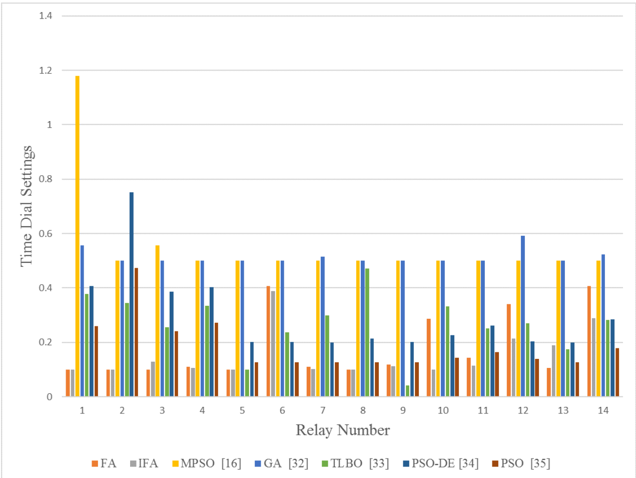

FIGURE 4. Graphical representation of the TDS for 6-bus system with literatures.

The objective function for the proposed algorithm is written as:

$$\min f = \sum_{i=1}^{n} TDS_{ij} \tag{1}$$

TDS_{ij} denotes the operational time of the primary relay for a fault at zone j.

The objective function of DOCR coordination problems is to minimize the totality of operational time of relays connected to the power network, associated with the constraints explained as below [16].

A. COORDINATION CRITERIA

In an electrical protection scheme i.e., the main and the backup protection pattern needs simultaneously coordinated by coordination time interval *(CTI)*. The *CTI* for the electromechanically relays has been assigned as 0.3 to 0.4s and for digital or microprocessor based relays is 0.1 to 0.2s.

TABLE 1. Primary/Backup and the close in fault currents.

Primary Relay		Backup Relay	
Relay No.	Fault Current (kA)	Relay No.	Fault Current (kA)
1	18.172	13	0.601
2	4.803	3	1.365
3	30.547	4	0.5528
4	5.186	12	3.422
4	5.186	14	1.764
5	2.838	11	1.074
5	2.838	14	1.764
6	18.338	8	0.767
7	4.496	11	1.074
7	4.496	12	3.422
8	2.351	2	0.869
8	2.351	7	1.483
9	6.072	1	4.589
9	6.072	7	1.483
10	4.077	9	0.639
11	30.939	10	0.9455
12	17.705	6	0.861
13	17.821	5	0.977
14	5.457	1	4.589
14	5.457	2	0.868

The proceedings can be written as

$$T_b - T_p \geq CTI \tag{2}$$

where,

Tb: the backup relay operating time

Tp: the primary (or main) relay operating time.

B. OPERATIONAL CHARACTERISTICS OF THE RELAY

The performance of OCR (over current relay) defined as the curve of T versus M, where M stands for multiple of pickup current and defined as the ratio of relay current 'I_R' to the pickup current 'I_P'.

$$M = \frac{I_R}{I_P} \tag{3}$$

From maker perspective, they give current-time curves to portray the working of the electromechanical relays. The inverse OCR attributes has been spoken to by the accompanying equations in this article [14].

$$T = k\frac{TDS}{M^{k_1} + k_2} \tag{4}$$

$$T = PTDS \times PI_P \tag{5}$$

where,

$$PTDS = a_0 + a_1\,(TDS) + a_2\,(TDS)^2 + a_3\,(TDS)^3 \tag{6}$$

$$PI_P = b_0 + \frac{b_1}{(M-1)} + \frac{b_2}{(M-1)^2} + \frac{b_3}{(M-1)^3} + \frac{b_4}{(M-1)^4} \tag{7}$$

where, k, k_1, k_2, a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3 *and* b_4 are constants.

TABLE 2. CT ratios and pickup tabs.

Relay No.	CT Ratio	Pick-up Tab
1	1200/5	0.8
2	800/5	0.8
3	800/5	1.0
4	800/5	0.5
5	800/5	0.5
6	1200/5	0.5
7	800/5	1.0
8	800/5	0.8
9	800/5	0.5
10	600/5	1.0
11	800/5	1.0
12	800/5	1.5
13	1200/5	0.5
14	800/5	1.0

C. RELAY SETTING BOUNDS

The DOCR coordination procedure can streamline the *TDS* minimization. The constraints connected in this investigation permit ceaseless time dial settings. The limitations are.

$$\begin{aligned} TDS_{j_{min}} &\leq TDS_j \leq TDS_{j_{max}} \\ PS_j^{min} &\leq PS_j \leq PS_j^{max} \end{aligned} \tag{8}$$

Mathematically the above footings can be written as

$$min \sum_i \sum_j T_{ij_{primary}} \tag{9}$$

$T_{ij_{primary}}$ is the operating time of primary relay j for a fault i subject to following constraints

$$L(T) \leq 0\,(cordination\ criteria) \tag{10}$$

$$T = g(S)\,(relay\ characteristics) \tag{11}$$

$$S_{j\,\min} \leq S_j \leq S_{j\,\max}\,(Bounds\ on\ relay\ settings) \tag{12}$$

where, $L(T)$ is the coordination criteria represented by (1); S is the set of feasible settings used in *TDS*;

$g(S)$ is the relay characteristics shown by (4) and (5).

In order to obtain the values of TDS, equation 5 is reduced to

$$T = b \times TDS \tag{13}$$

where,

$$b = \frac{k}{M^{k_1} + k_2} \tag{14}$$

The issue is limited to linear problem.

For this situation, the issue is settled as the linear one, so as to take care of the issue without contemplating as linear one. In this manner, the relating *TDS* qualities can be found by finding the underlying foundations of the polynomial as in equation (6) by utilizing the ideal estimations of *PTDS* determined.

TABLE 3. Coefficients for equation (6).

a_0	a_1	a_2	a_3
1.86e-2	5.607e-2	3.0128e-3	1.234e-8

TABLE 4. Coefficients for equation (7).

b_0	b_1	b_2	b_3	b_4
0.92964	6.79213	14.03259	-8.43032	2.6798

TABLE 5. TDS outcomes of 6-bus system and comparison with the references.

Relay No	FA	IFA	MPSO [16]	GA [32]	TLBO [33]	PSO-DE [34]	PSO [35]
1	0.1002	0.1000	1.1794	0.55647	0.3780	0.4064	0.2602
2	0.1002	0.1000	0.5	0.5	0.3443	0.7506	0.4739
3	0.1006	0.1296	0.5562	0.5	0.2553	0.3872	0.2406
4	0.1102	0.1050	0.5	0.50004	0.3346	0.4031	0.2711
5	0.1000	0.1007	0.5	0.50002	0.1005	0.2005	0.1268
6	0.4070	0.3880	0.5	0.5	0.2376	0.2011	0.1264
7	0.1092	0.1016	0.5	0.51584	0.3	0.2003	0.1265
8	0.1000	0.1000	0.5	0.5	0.4720	0.2133	0.1265
9	0.1175	0.1128	0.5002	0.50003	0.0414	0.2006	0.1268
10	0.2860	0.1001	0.5	0.5	0.3323	0.2265	0.1424
11	0.1439	0.1143	0.5	0.5	0.2518	0.2610	0.1647
12	0.3404	0.2138	0.5	0.59127	0.2704	0.2039	0.1401
13	0.1063	0.1899	0.5	0.5	0.1735	0.2002	0.1265
14	0.4070	0.2881	0.5	0.52268	0.2817	0.2837	0.1779
OF (Sec.)	***7.6866***	***6.4050***	***NR****	***NR****	***23.787***	***9.2671***	***8.1245***

*NR** Not specified in the literature

III. FIREFLY ALGORITHM

Firefly algorithm (FA) nature-inspired optimization technique used for evaluating the complex and highly non-linear constrained issues and FA is not implemented for optimization of DOCR settings using IEEE 30-bus systems till date presented in this article. FA has been implemented in this paper to solve the problem of DOCR settings and the simulated results are compared with other optimization techniques. Yang [41], introduced the firefly algorithm first and it simulates the flashing mechanism of fireflies. For the application of the prescribed idea, the following predictions are assumed [42]. The gender

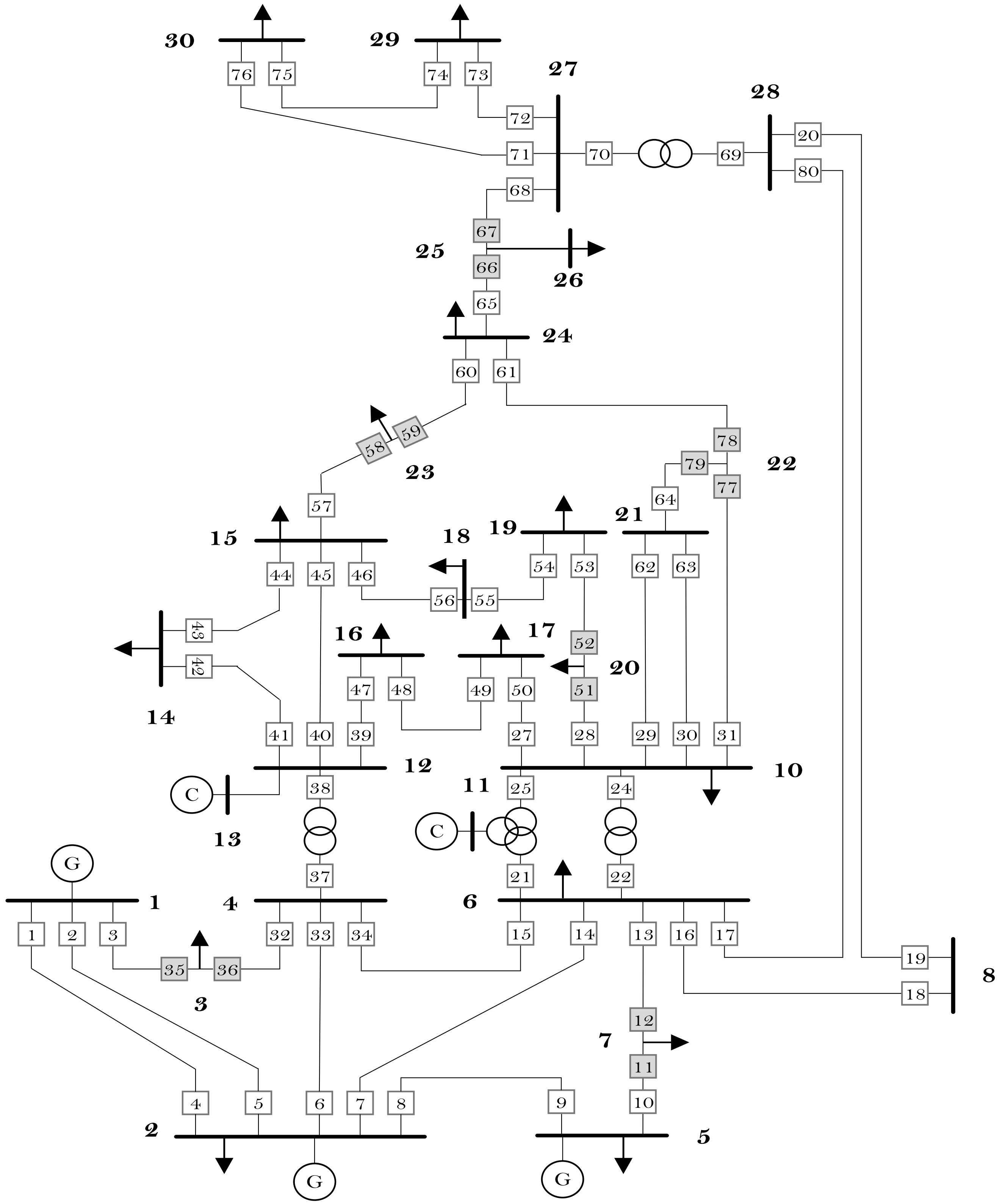

FIGURE 5. IEEE 30-bus system.

of all the fireflies are same. The attraction to brighter fireflies attract more than the lesser brightness. With the increase in distance the attraction among the fireflies will decline. The fireflies will move randomly if either of the fireflies shows brightness. Figure 2 shows the arrangement of fireflies.

TABLE 6. TDS outcomes of IEEE 30-bus and comparison with references.

Relay No	FA	IFA	ILP [13]	ILP [36]	Relay No	FA	IFA	ILP [13]	ILP [36]
1	0.1175	0.1175	0.1124	0.1461	39	0.3241	0.2342	0.3657	0.4441
2	0.1007	0.1006	0.1467	0.2047	40	0.2110	0.1500	0.2992	0.4238
3	0.1128	0.1102	0.1281	0.1942	41	0.1900	0.1635	0.1875	0.2341
4	0.1102	0.1056	0.0615	0.0749	42	0.1120	0.1010	0.2877	0.3877
5	0.2134	0.1134	0.1869	0.2601	43	0.1402	0.1395	0.3722	0.4822
6	0.1210	0.1145	0.1172	0.1757	44	0.1120	0.1010	0.1312	0.1845
7	0.1070	0.1030	0.0838	0.1286	45	0.1006	0.1000	0.3638	0.4077
8	0.1100	0.1000	0.1189	0.1635	46	0.1651	0.1263	0.2302	0.2779
9	0.1200	0.1063	0.1079	0.1293	47	0.3120	0.1523	0.4461	0.5253
10	0.0410	0.0102	0.0656	0.0878	48	0.1000	0.1010	0.0831	0.1169
11	0.1340	0.1222	0.1171	0.2253	49	0.1000	0.1411	0.2835	0.4771
12	0.1210	0.1134	0.1322	0.1901	50	0.1410	0.1312	0.1582	0.3357
13	0.1610	0.1535	0.1892	0.2314	51	0.1000	0.1100	0.3513	0.4263
14	0.1410	0.1355	0.2413	0.2660	52	0.0500	0.1290	0.1485	0.1840
15	0.1007	0.1000	0.1997	0.2400	53	0.0599	0.1144	0.3179	0.5338
16	0.1007	0.1000	0.1018	0.1141	54	0.1005	0.1001	0.2935	0.3547
17	0.1200	0.1334	0.1239	0.1327	55	0.3468	0.1189	0.4326	0.5456
18	0.1006	0.1001	0.0830	0.0972	56	0.1712	0.1500	0.2001	0.3848
19	0.2110	0.1255	0.2845	0.3081	57	0.2101	0.1353	0.2259	0.4440
20	0.1710	0.1388	0.3177	0.3534	58	0.3310	0.1209	0.3801	0.4583
21	0.1340	0.1222	0.2582	0.3144	59	0.1006	0.1135	0.2424	0.2427
22	0.1050	0.0192	0.0779	0.1405	60	0.1006	0.1000	0.2756	0.4326
23	0.1710	0.1513	0.2466	0.2695	61	0.0500	0.1591	0.0500	0.0500
24	0.1309	0.1309	0.1309	0.1787	62	0.0500	0.1000	0.0500	0.0500
25	0.2210	0.1189	0.2582	0.0500	63	0.2101	0.1400	0.1648	0.1650
26	0.1000	0.9998	0.0779	0.0500	64	0.1930	0.1444	0.3623	0.4994
27	0.2010	0.1806	0.2689	0.2861	65	0.1900	0.1310	0.2075	0.2562
28	0.1061	0.1052	0.0802	0.1156	66	0.1820	0.1475	0.0518	0.0606
29	0.1721	0.1412	0.3873	0.4689	67	0.1512	0.1439	0.1618	0.1732
30	0.1007	0.1000	0.1771	0.2156	68	0.1007	0.1005	0.0500	0.0500
31	0.1007	0.1001	0.4096	0.4446	69	0.1200	0.1040	0.1490	0.1676
32	0.1710	0.1435	0.1864	0.2236	70	0.0150	0.0999	0.0500	0.0500
33	0.2123	0.1732	0.2732	0.3159	71	0.0150	0.0999	0.0952	0.0941
34	0.1000	0.1006	0.1530	0.1841	72	0.1729	0.1658	0.0899	0.0902
35	0.3210	0.1479	0.4359	0.4853	73	0.1981	0.1367	0.2194	0.2505
36	0.3100	0.1356	0.3561	0.4008	74	0.1601	0.1323	0.1400	0.1886
37	0.1006	0.1006	0.4637	0.5524	75	0.2101	0.1280	0.3481	0.4068
38	0.1072	0.1367	0.2167	0.3433	76	0.2101	0.1141	0.1218	0.1428
Objective Function (sec)						***30.454***	***32.224***	***42.367***	***NR****

*NR** means not specified in the literature.

A. SELF-ADAPTIVE WEIGHT

In the flashing mechanism of FA, it is normal that the fireflies must reach to the promising territory of flashing, and afterwards, the local search in promising area must be implemented to filter the quality of fireflies. To get rid of this, a weight displayed in Eq. (15) is acquainted with

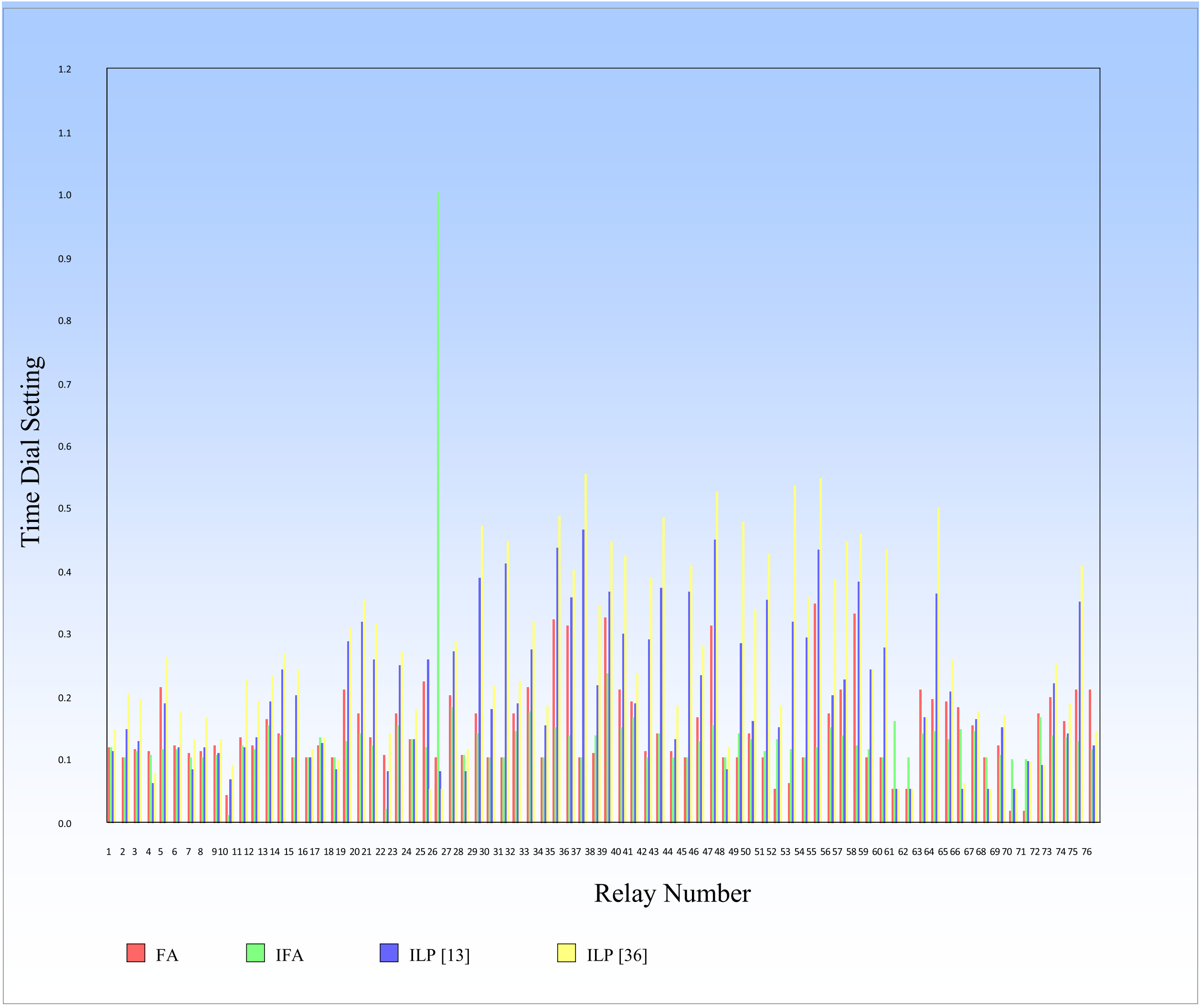

FIGURE 6. Graphical representation of the TDS for 6-bus system with literature.

alter the level of moving toward the more splendor of the fireflies.

$$w = \begin{cases} \left(\dfrac{f(x_{best})}{f(x_{worst})}\right)^2, & if\ f(x_{worst}) \neq 0 \\ 1, & otherwise \end{cases} \quad (15)$$

where *f(xbest)* and *f(xworst)* are the objective function outcomes of the brighter firefly and lesser firefly. As seen in the Eq. (15) the presented weight is self-adaptive and slightly improves its value, since the distinction of capacity values between the best and worst solutions is getting to be littler as the flashing mechanism. The weight w is resolved naturally, and in this manner no extra parameter should be tuned is presented.

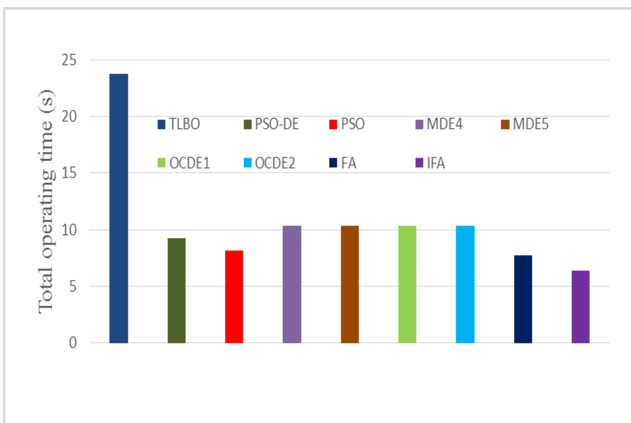

FIGURE 7. Graphical illustration of optimized total operating time of the proposed IFA with the literature.

B. EXPERIENCE-BASED LEARNING STRATEGY

In FA optimizer, the firefly flashing phenomena is refreshed by taking the best solution and worst solution simultaneously, this technique can improve the convergence rate and enhances the exploitation ability of the algorithm. Moreover, the flashing diversity and the exploration ability of the algorithm may be disintegrated with the brief convergence rate. Hence,

TABLE 7. Comparison results of IEEE 6-bus models: In terms of objective, function values.

Method	Objective Function
TLBO [33]	23.787
PSO-DE [34]	9.2671
PSO [35]	8.1245
MDE4 [23]	10.3812
MDE5 [23]	10.3514
OCDE1 [22]	10.3479
OCDE2 [22]	10.3286
FA	7.6866
IFA	6.4050

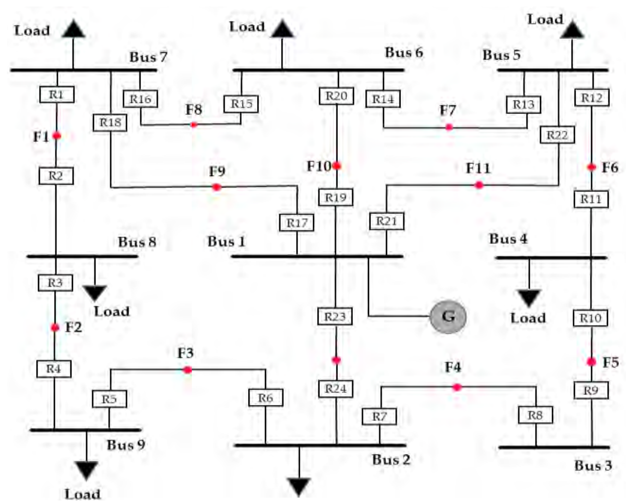

FIGURE 8. IEEE 9-bus system.

a learning strategy based on the experience of other solutions is developed to improve the flashing mechanism and thus increase the exploration ability. To be explicit, other two individual's x_k and x_l are randomly selected from the population, at that point the potential search direction controlled by them is used to refresh the present individual *xi,* as appeared in Eq. (16).

$$x'_{ij} = \{x_{ij} + rand \cdot (x_{kj} - x_{ij}), \quad iff \ (x_k) < f\,(x_l)$$
$$x'_{ij} = \{x_{ij} + rand \cdot (x_{kj} - x_{ij}), \quad otherwise \qquad (16)$$

where x_{kj}, and x_{lj}, are the outcomes of the j^{th} variable for the k and l individuals ($k \neq l \neq i$), respectively. '*rand*' is a random value in between [0, 1]. So as to adjust the exploration and exploitation abilities of flashing process, the above experience-based learning strategy Eq. (16) and the introduced weight Eq. (15) are employed randomly for each firefly in this study.

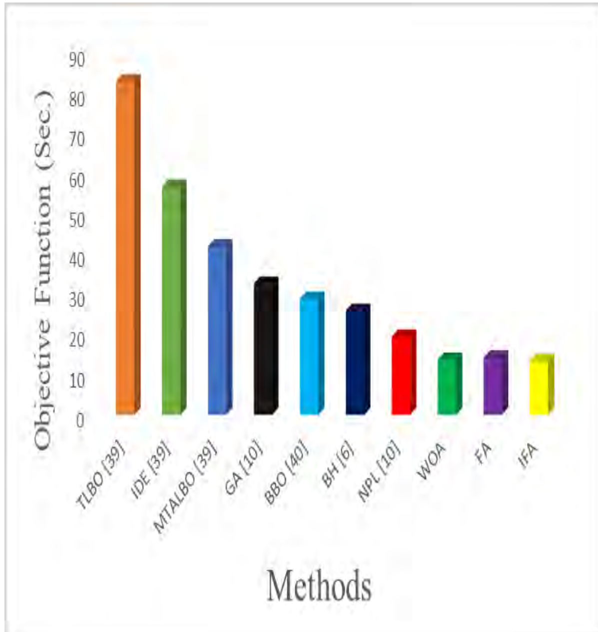

FIGURE 9. Graphical illustration of objective function of the proposed IFA with the literature.

IV. RESULTS AND DISCUSSION

The Firefly (FA) and improved firefly algorithm (IFA) has been implemented using MATALB software for IEEE 6 and 30-bus system respectively and explained in the next section. The IEEE 9-bus system has been tested for numerical DOCRs using proposed algorithm and result is further validated using a nature inspired whale optimization algorithm just in case of Numerical DOCRs. The result obtained for numerical DOCRs by the proposed algorithm has been compared with WOA and other optimization techniques.

A. IEEE 6-BUS SYSTEM

Fig. 3 depicts the single line layout of IEEE 6-bus network. The single line chart comprises of 7 lines, 4 power generators and 14 DOCRs. The point of the proposed calculation for this situation is to arrange the settings of 14 relays and the primary target is to look out the ideal TDS values.

At the close end of each relay (close in faults) three phase faults are connected. Table 1 shows the primary/backup relay (P/B) relay pairs and the close in fault currents. The pickup tabs and the CT ratios of the relays as presented in Table 2. Table 3 and Table 4 respectively show the coefficients of the equations (6) and (7). The transient variations in the system topology have not been considered and a CTI of 0.2 is accepted.

The TDS values after getting from the simulation results has been depicted in table 5. Table 5 shows the optimized values of TDS obtained from firefly optimization simulation and on comparing with other techniques, it shows that the results have been optimized to the minimum. This table also shows the effectiveness and efficiency of the proposed algorithm for the 6-bus system.

TABLE 8. Primary/Backup and the close in fault currents.

Primary Relay		Backup Relay	
Relay No.	Fault Current (A)	Relay No.	Fault Current (A)
1	4863.6	15	1168.3
1	4863.6	17	1293.9
2	1634.4	4	1044.2
3	2811.4	1	1361.6
4	2610.5	6	1226
5	1778	3	1124.4
6	4378.5	8	711.2
6	4378.5	23	1345.5
7	4378.5	5	711.2
7	4378.5	23	1345.5
8	1778	10	1124.4
9	2610.5	7	1226
10	2811.4	12	787.2
11	1634.4	9	1044.2
12	2811.4	14	1168.3
12	2811.4	21	1293.9
13	3684.5	11	653.6
13	3684.5	21	1293.9
14	4172.5	16	1031.7
14	4172.5	19	1264.1
15	4172.5	13	1031.7
15	4172.5	19	1264.1
16	3684.5	2	653.6
16	3684.5	17	1293.9
17	7611.2	-	0
18	2271.7	2	653.6
18	2271.7	15	1168.3
19	7435.8	-	0
20	2624.2	13	1031.7
20	2624.2	16	1031.7
21	7611.2	-	0
22	2271.7	11	653.6
22	2271.7	14	1168.3
23	7914.7	-	0
24	1665.5	5	711.2
24	1665.5	8	711.2

B. IEEE 30-BUS SYSTEM

The second case study implemented is IEEE 30-bus system that consists of 76 overcurrent relays as shown in figure 5 [36].

Algorithm Pseudo Code for the Proposed Algorithm

1. Set parameters for objective function f(x), $x = (x_1, \ldots\ldots, x_d)^T$
2. Initialize population of fireflies x_i, $(i = 1, 2, 3, \ldots, n)$
3. Calculate the light intensity Ii at xi by $f(xi)$
4. Define light intensity coefficient γ
5. **While (t<MaxIteration)**
6. **For** $i, j = 1$: n all particles
7. Update weight of the fireflies
$$w = \begin{cases} \left(\dfrac{f\,(x_{best})}{f\,(x_{worst})}\right)^2, & if\ f\ (x_{worst})\ is\ non\ zero \\ 1, & otherwise \end{cases}$$
8. Update *Xbest* population
9. If attractiveness varies with distance then
10. Move firefly i towards firefly j in all the directions
11. Update the experience based learning strategy using Eq. (16)
12. **End if**
13. Evaluate new solution and update the intensity of light
14. **End for i**
15. **End for j**
16. Find the best solution
17. Accept the new solution if it is better than old one
18. **End for**
19. **End while**

The streamlined TDS values are appeared table 6 and the result has been compared with the literature. Table 6 demonstrates the optimized TDS estimations of 30-bus system and the results had been compared with the literature. This demonstrates the legitimacy of the proposed optimizer in relays coordination.

Figure 3 and 5 shows the graphical representation of optimized *TDS* values with the literature for IEEE 6 and 30-bus system respectively. The graphical representations shows that the time dial settings had been optimized to the minimum. Table 7 is the comparative analysis of the objective function (OF) values and from the table the OF values shows that the IFA has improved results. Figure 7 shows the graphical representation of the optimized total operating time in seconds for the proposed IFA with the literature.

C. COORDINATION SCHEME USING NUMERICAL DIRECTIONAL RELAYS IEEE 9-BUS SYSTEM.

The third case study used in the proposed algorithm for relay coordination employing numerical relays is IEEE 9- bus system [28]. This test case has also been implemented for whale optimization algorithm (WOA). The WOA is a nature inspired meta-heuristic optimizer that uses the social behavior of humpback whales by utilizing the bubble-net mechanism [43]. The populace is 30 whales with maximum 500 iterations have been utilized in this algorithm.

TABLE 9. Optimal TDS for IEEE 9-Bus system.

Relay No.	TDS (FA)	PS (FA)	TDS (IFA)	PS (IFA)	TDS(WOA)	PS(WOA)
1	1.0850	1.8150	0.9788	1.6079	0.1039	0.5196
2	1.0654	1.2988	0.7945	0.3692	0.5934	1.3962
3	0.5560	1.4980	0.1309	0.9686	0.6080	0.6714
4	0.4492	1.3920	0.3740	0.3262	0.1000	0.5000
5	0.7472	0.9480	0.3880	0.4523	0.1000	0.5000
6	1.0764	1.6430	0.6056	1.5864	1.1000	2.0000
7	0.9764	1.6430	0.6240	1.3431	0.3927	0.7141
8	1.0472	0.9480	1.0285	0.2088	1.1000	2.0000
9	1.0492	1.3920	0.5377	0.4618	0.1000	0.5000
10	0.8557	1.4980	0.7623	0.8566	0.1000	0.5000
11	0.7305	1.1369	0.2139	1.1585	1.1000	2.0000
12	0.9802	1.8150	0.5964	1.7203	0.2313	0.8336
13	1.0492	1.3740	0.9327	0.9274	0.5111	0.5283
14	1.0637	1.5560	0.7761	0.6999	0.1000	0.5000
15	1.0908	1.5560	0.6309	0.5456	0.1000	0.5000
16	1.0593	0.9639	1.0295	0.9873	0.8753	1.2390
17	0.9420	1.7200	0.2740	1.3869	0.1005	0.5129
18	1.0295	1.6347	0.6019	1.9435	0.1005	0.5028
19	1.0572	1.6800	0.7807	1.2390	0.1121	0.5000
20	0.3245	0.8006	0.2164	0.7110	0.2180	1.6530
21	0.5918	1.7200	0.3072	1.6203	0.1000	0.5000
22	0.6747	0.7000	0.4921	0.5859	0.1000	0.5000
23	0.6609	1.7900	0.1011	1.4038	0.1005	0.5025
24	0.9041	0.7441	0.4305	0.7467	0.1000	0.5000
OF (Sec.)	***14.2216***		***13.3409***		***13.7000***	

TABLE 10. Objective function of IEEE-9 bus system comparison with literature.

Method	Objective function (OF)
TLBO [39]	82.9012
IDE [39]	56.6471
MTALBO [39]	41.901
GA [10]	32.6058
BBO [40]	28.8348
BH [6]	25.884
NPL [10]	19.4041
WOA	**13.7000**
FA	**14.2216**
IFA	**13.3409**

The IEEE 9-bus system is associated with 24 numerical DOCRs, 9 buses, 12 lines and is having a generator attached at bus 1 shown in Fig 8. In this system, there are 56 combinations of primary-backup relay pairs among 24 numerical DOCRs [40] shown in table 8. The upper and lower range of time dial settings (TDS) are between 0.1 to 1.1 and respectively for plug setting (PS) from 0.5 to 2.0. Table 9 shows the optimized TDS values for numerical DOCRs and the results shows that the IFA achieves minimum values as compared to the whale optimization algorithm. Table 10 illustrates the comparative analysis for obtained objective function with the other techniques mentioned in the literature. Figure 9 shows the graphical representation of the objective function values.

V. CONCLUSION

The work presented in this article shows the optimal coordination of directional overcurrent relay (DOCR) considering improved firefly algorithm (IFA). In IFA, a self-adaptive weight is presented to get the best solution and removing the worst solution during the course of simulation procedure. In an electrical power network the problem of relay coordination is hard with many constraints. The coordination of DOCRs needs suitable and robust techniques to trace out the main issue. In this work the goal to be achieved was to minimal the time dial setting (TDS) of the relays implemented successfully on IEEE 6 and 30-bus system. The proposed algorithm has also been test for IEEE 9-bus system for numerical DOCRs and using WOA for this test case.

The results in table 9 shows that the IFA with WOA proves better for the problem formulation. The obtained results had been compared with the other algorithms depicted in the references. The results obtained shows that the proposed algorithm is efficient and robust as compared with the other techniques.

In future, the optimizer can be enhanced to tackle directional overcurrent relay issues of complicated and higher buses power systems and will be tested on dual setting relays. The complicated cases will cover clashing objective functions of electrical network that might be coordinated with the environmentally friendly power vitality sources and FACTS devices.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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