Alpha Harris Hawks Optimization based Overcurrent Relay Coordination with Hybrid Time-Current-Voltage Characteristics Considering the Grid-Connected Distributed Generation

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Mian Rizwan[1,2], Lucheng Hong[1*], Safdar Rasool[2,3], Yuan Gu[1], Minghe Wu[1] and Sara Bilal[4]

1 Jiangsu Provincial Key Laboratory of Smart Grid Technology and Equipment, Southeast University, Nanjing 210000, China.

2 Department of Electrical Engineering, University of Gujrat, Gujrat 50700, Pakistan.

3 School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, New South Wales, Australia.

4 Department of Management Science and Engineering, Southeast University, Nanjing 210000, China .

* Correspondence: rizwan.nazeer26@uog.edu.pk

ABSTRACT

The conventional protection schemes may lead towards the inadvertent operation of the protection devices with the increased penetration of renewable energy sources based distributed generation (RES-DG) in distribution networks (DN). The miscoordination and the malfunctioning of directional overcurrent relays (DOCR) may occur due to significant change in the fault current level (FCL) and the change in the network topology form the radial to ring topology caused by the RES-DG. Optimization algorithms (OA) and modification in relay characteristics were mostly used to tackle the DOCR miscoordination problem. However, in this paper, a fast and an accurate protection coordination scheme is proposed to eliminate the DOCR miscoordination and to reduce the overall operation time of DOCRs by employing an advance optimization algorithm along with an innovative modification in the relay characteristics. In the first step, time-current characteristics (TCC) of the conventional DOCR are modified to a hybrid time-current-voltage (TCV) characteristics by including the effect of the fault voltage in the relay characteristics equation. Thereafter, the performance of conventional Harris Hawk's optimization (HHO) is enhanced with an improvement in the exploration strength of the HHO by an adaptive mutation-selection of the alpha hawks during each iteration named as alpha-HHO (α-HHO). The protection coordination problem is formulated as a non-linear constrained optimization problem. The proposed protection scheme is evaluated on the IEEE-8 bus meshed DN. The standard IEEE-8 bus test system is modified by integrating multiple squirrel cage induction generators and PV-based RES-DGs at optimal bus locations. Detailed numerical studies are carried out with the help of simulations to show the performance of the proposed scheme. The results are compared with the existing protection schemes reported in recent literature. The investigation results show that the highest reduction in overall relay operating time with zero mis-coordination is achieved with the proposed scheme.

Keywords: RES-DGs, Directional Overcurrent Relay, Hybrid TCV, α-HHO, Optimization.

INTRODUCTION

The renewable energy sources based distributed generations (RES-DGs) are being extensively integrated into the conventional distribution network. This is due to massive developments in smart grid technologies, low operation and maintenance costs, and environment friendly nature of RES-DGs (Rizwan et al., 2021, Rizwan et al., 2021). These benefits are subjected to optimal allocation and scheduling of RES-DG (Yu Tao et al., 2021) Along with the benefits of RES-DGs, it also creates technical complexities from the operation and the protection point of view. This transforms the passive nature of DN to an active nature, and the radial configuration to the ring configuration. This results into bidirectional power flows, and the change in fault current level for the DN. Due to these limitations, overcurrent relays (OCRs) can cause miscoordination or malfunctioning which leads to interruption in the power supply or damage of the equipment (Nassif, 2018). Numerous research efforts are made to tackle this protection problem and for a safe integration of RES-DGs into the DN.

The recloser fast curve is modified in (Rizwan et al., 2019) to restore the much influenced fuse-recloser coordination for fuse saving scheme, due to RES-DGs integration. Authors has evaluated the fuse-recloser coordination scheme by simulating real distribution system named as Rajewala-Pakistan 40 bus feeder. In (Dadkhah et al., 2020), the authors further modified the recloser fast curve equation by adding a correction factor, which take into account the difference in the fuse and the recloser's curve slope. A new time current characteristics (TCC) is developed in (Amin Yazdaninejadi et al., 2018) by adding an off time factors in the TCC of OCR. Which has a modulating effect on the relay operating time to reduce the overall relay operation time. A simple cost-effective logic was added in TCC for increasing fault currents virtually for fast clearance of faults (Yazdaninejadi, et al., 2020). Authors have also resolved the protection coordination problem with optimization algorithms. The time dial settings (TDS) and pickup current (Ip) of the OCR was optimally sorted with hybrid slap-swarm algorithm and linear programming (SSA-LP) in (Usama et al., 2021) for both the pre contingency and the post contingency fault scenarios to settle the protection coordination (PC) problem in both grid-connected and islanded mode of operation. The setting group algorithm was proposed by (Samadi et al., 2020), based on integer liner programing and particle swarm optimization to specify the proper setting group to activate for each relay in each network state, in order to minimize the total operation time of OCRs. Authors in (Rizwan et al., 2020), used Harris hawks optimization (HHO) algorithm to achieve the minimum operating time with the zero miscoordination. The algorithm was evaluated on IEEE-8 bus system for OCP.

In this paper, the efficiency of HHO used in (Rizwan et al., 2020) is improved based on performance of α-hawks and OCR-TCC is modified by including the fault voltage. The key contributions of the paper can be summarized as follows:

1. Improvement in the efficiency of optimization algorithm by mutating the best particles in each iteration.
2. Reduction in overall relay operation time by including the effect of fault voltage into

conventional TCC and modifying it to the hybrid TCV characteristics.

3. Rehabilitation of protection coordination scheme which could be disturbed due to the integration of the distributed generation.
4. The potential transformer already installed with DOCR is utilized to measure fault voltage, So, it becomes a cost-effective protection scheme.
5. Zero miscoordination of overcurrent relay is achieved with the least operation time.

METHODOLOGY

Harris Hawks Optimization

HHO is a population based algorithm developed by mimicking the hunting behavior of Harris hawks (HH) (Heidari et al., 2019). These are also called the wolves of the air. The HH can be divided into four categories based on their performance i.e. α, β, δ and ω. α HH has more knowledge about prey than others. It comprises mainly on three phases as follows

i. Exploration phase
ii. Transferal from exploration to exploitation
iii. Exploitation phase.

During the exploration phase, the HH can take positions based on chance of attack(ấ). If ấ is <0.5, the HH can take random positions. Mathematically, it is given by Equation 1,

$$\mathbf{P_{(t+1)} = P_{best(t)} - P_{avg(t)} - r_1[LL + r_2(UL - LL)]} \quad (1)$$

In Equation 1, $P_{(t+1)}$ is the position vector of HH at iteration (t+1), $P_{avg(t)}$ is the average position of HH. $P_{rand(t)}$ average position of randomly selected HH from current population. P(best) is the prey position, LL and UL are lower and upper limits of the position variables, r1 and r2 are random values selected in the range of [0, 1].

Whereas, when chance of attack is greater than 0.5, the HH takes positions in collaboration with each other. During this the HH position is updated by in each Equation 2.

$$\mathbf{P_{(t+1)} = P_{rand(t)} - r_3\left|P_{rand(t)} - 2 \times r_4 \times P_{(t)}\right|} \quad (2)$$

The HH keeps exploring the search space as long as the prey energy is greater than one. However, transfer from exploration to exploitation, when the escape energy of prey is less than one. The escape energy of prey is calculated as follows:

$$\mathbf{E = 2 \times 2 \times E_0 \times \left(1 - \frac{t}{t_{max}}\right)} \tag{3}$$

where E and E_0 are the current and initial escape energy of prey. t and t_{max} are the current iteration and total iterations respectively. In the exploitation phase, the HH have four attacking strategies based on the escape energy E and escape probabilty (r) of prey. These are given in Table 1.

Table 1. Attacking strategies of Harris hawks during exploitation phase.

	Soft Siege (SS)	**Soft siege with Progressive rapid dives (SSPRD)**	**Hard Siege (HS)**	**Hard siege with progressive rapid dive (HSPRD)**
Escape Energy (E)	$E \geq 0.5$	$E \geq 0.5$	$E < 0.5$	$E < 0.5$
Escape Probability(r)	$r \geq 0.5$	$r < 0.5$	$r \geq 0.5$	$r < 0.5$

During SS, SSPRD, HS and HSPRD the positions are updated using Equations 4-7 respectively.

$$P_{(t+1)} = \Delta P_{(t)} - E\left|J \times P_{best(t)} - P_{(t)}\right| \tag{4}$$

$$\therefore \Delta P_{(t)} = P_{bset(t)} - P_{(t)}$$

$$\therefore J = 2(1 - r_5)$$

$$P_{(t+1)} = \begin{cases} C & \text{if } \text{Fit}(c) < P_{(t)} \\ R & \text{if } \text{Fit}(R) < P_{(t)} \end{cases} \tag{5}$$

$$\therefore C = P_{best(t)} - E\left|J \times P_{best(t)} - P_{(t)}\right|$$

$$\therefore R = C + S \times LF(D)$$

$$P_{(t+1)} = P_{best(t)} - E\left|\Delta P_{(t)}\right| \tag{6}$$

$$P_{(t+1)} = \begin{cases} C & \text{if } \text{Fit}(c) < P_{(t)} \\ R & \text{if } \text{Fit}(R) < P_{(t)} \end{cases} \tag{7}$$

$$\therefore C = P_{best(t)} - E\left|J \times P_{best(t)} - P_{m(t)}\right|$$

$$\therefore P_{m(t)} = \frac{1}{N}\sum_{j=1}^{N} X_{i(t)}$$

where C and R are the values of current movements and rapid dives, LF is levy flight, $P_{m(t)}$ is the average position of hawks, N is the total number of hawks, and $\Delta P(t)$ is the difference between the position.

α-Harris hawks Optimization

During the exploration phase of HHO, the best hawks is named as α-HH. Suppose, the position vector of this HH is $P_{best.}$ Similarly, the position vectors of second and third best HH are defined as P_{best-1} **,** P_{best-2} , depending upon the performance efficiency of the new position vector P_{new} from total number of HH. So, the new position vector $P_{(n)}$ obtained by selection-mutation of i^{th} hawks can be calculated as

$$P_{i(m)} = P_{i(n)} + 2*(1-{}^{t}\!/_{t_{max}})*(2*r-1)(2*P_{best} - (P_{best}-1+P_{best}-2)+(2*r-1)(P_{best}-P_{i(n)}) \tag{8}$$

Where r is a number randomly selected from the range [0, 1].

For the next generation, the position vectors $P_{i(t+1)}$ can be calculated by the selective process as given in Equation 9 and for prey as in Equation 10.

$$P_{i(t+1)} = \begin{cases} P_{i(m)} & f(P_{i(m)}) < f(P_{i(n)}) \\ P_{i(n)} & f(P_{i(m)}) \geq f(P_{i(n)}) \end{cases} \tag{9}$$

$$P_{prey} = \begin{cases} P_{i(m)} & f(P_{i(m)}) < f(P_{prey}) \\ P_{i(n)} & f(P_{i(n)}) < f(P_{prey}) \end{cases} \tag{10}$$

Hybrid Time-Current Voltage Characteristics

The conventional OCR time current characteristics curve is based on the fault current only. Its characteristic eqution is as follows:

$$T_{OP} = TDS\left[\frac{A}{M^{B}-1} + C\right] \tag{11}$$

$$\therefore M = \frac{I}{I_P}$$

Where T_{OP} is the operation time of the relay, TDS is the time dial setting of relay, M is the multiple of pickup current, I is the fault current, I_P is the pickup current of relay. A denotes the constant for relay TCCs, and B denotes the inverse time type. The conventional TCC is modified by including the effect of fault voltage (Hong et al., 2021) which put the modulating effect on TCC and reduce the relay operation time drastically. The modified TCC is given as follow:

$$T_{OP} = TDS\left[\frac{A}{M^B - 1} + C\right]\left(\frac{1}{e^{1-V_f}}\right)^K \tag{12}$$

where V_f is the fault voltage measured at the relay point and K is a relay constant parameter that can have different values for different relays. When the value of K is set zero, the modified equation is converted into the conventional TCC. When a bolted fault occurs at the relay terminals, the voltage may reduce to zero. Therefore, the relay operation time does not approach to zero, the V_f is added as an exponential term and the exponential term is used in reciprocal to make the time of operation faster as the fault approaches near the relay and voltages approaches to zero. The effect of fault voltage on the relay operation time is shown in Figure 1. The value of K is set equal to 2. The red color thick line represents the relay operation time without considering fault voltage. Figure 1 shows that the relay operation time decreases as the fault voltage decrease.

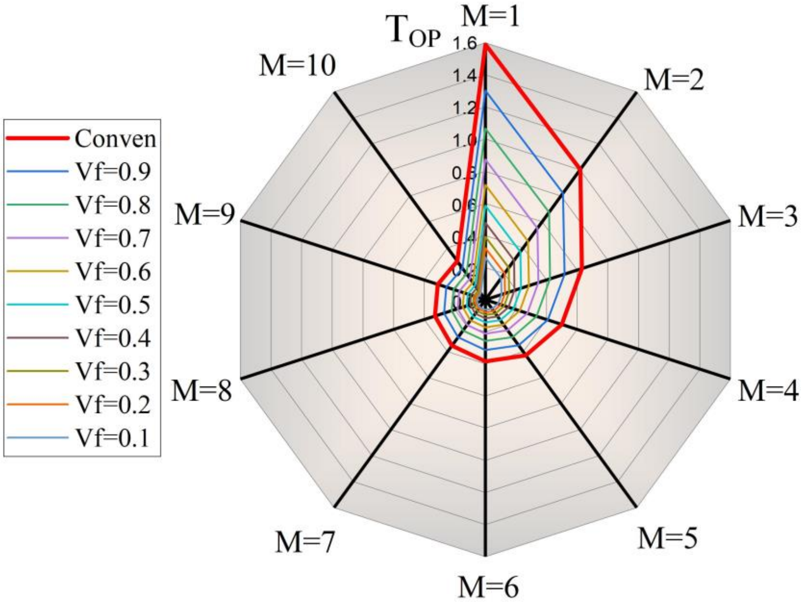

Figure 1. Effect of fault voltage on the relay operation time with modified relay TCV curves.

The objective here is to reduce overall relay operation times for primary-backup relays for all fault locations with zero miscoordination, So, the objective can be defined as follows;

$$\text{Objective Function} = \text{ Min } T_{OT} = \sum_{f=1}^{F}\left[\sum_{i=1}^{I}\left[t_{if}^{p} + \sum_{j=1}^{J} t_{ijf}^{b}\right]\right] \tag{13}$$

where T_{OT} is the overall operation time of relays for fault isolation, $\mathbf{t_{if}^{p}}$ and $\mathbf{t_{ijf}^{b}}$ represent the operation time of the i^{th} primary relay and j^{th} backup relay, respectively, for a fault at location f, and F, I, and J denote the set of fault points, the total primary relays, and the backup relays, respectively**.**

RESULTS AND DISSCUSSION

The performance of proposed scheme is evaluated on the standard IEEE-8 bus meshed distribution network sytem modifed with the integration of two wind farms (WFs) at bus 3 and bus 6. As the results are compared with the HHO used in (Rizwan et al., 2020), therefore, the same system specification as used in (Rizwan et al., 2020) are used here for a fair comparison. The line and load data for IEEE-8 bus system and WF information is availble in (Rizwan et al., 2020). The one line diagram of IEEE-8 bus system is shown in Figure 2. The faults are simulated at the mid point of each line. There are total seven faults represented as F1 to F7. The system is protected with 14 Directional OCR (DOCR). There are total 20 primary-backup relays pairs for all seven faults reflected in Table 2. Figure 3 shows the variation in fault current through primary and backup relays with and without RES-DGs. This variationin fault current due to RES-DG casues the miscoordinatin problem which is takcled and eradicated here.

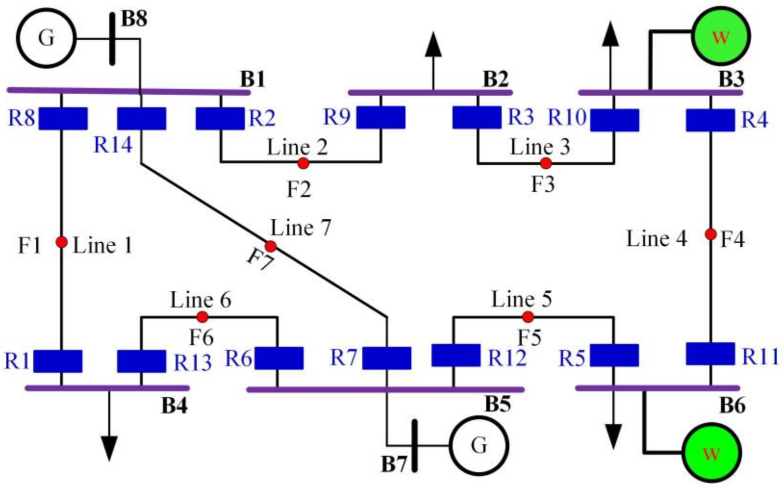

Figure 2. Standard IEEE-8 bus system modified by integrating two wind farms.

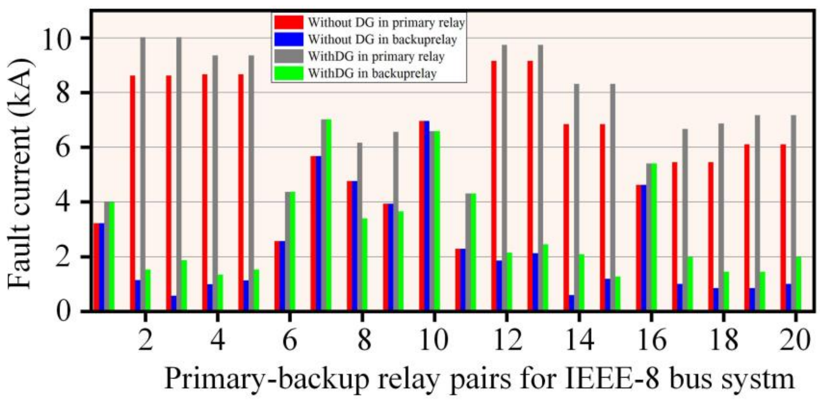

Figure 3. Fault currents through primary-backup relays with/without RES-DGs.

Table 2. Primary-Backup relays pairs for IEEE-8 bus system

Fault	Relay Pair	PR	BR	Fault	Relay Pair	PR	BR
F1	1	1	6	F5	11	5	4
	2	8	7		12	12	13
	3	8	9		13	12	14
F2	4	2	1	F6	14	6	5
	5	2	7		15	6	14
	6	9	10		16	13	8

F3	7	3	2	F7	17	7	5
	8	10	11		18	7	13
F4	9	4	3		19	14	1
	10	11	12		20	14	9

Whenever, there is fault, the primary relay should operate first to clear the fault and backup relay should wait for a specific time interval to operate if the fault is not cleared by primary relay. This is called coordination time interval (CTI). It this research work the CTI is kept 0.3 s. The TDS and I_p are also bound with limits, Lower and upper limits for TDS are 0.05 and 1.1, whereas for Ip these are kept $1.1\times I_{Load}$ and $1.5\times I_{Load}$ respectively. The value of K can be taken from 0 to 4, however , in this study, The value of K is set equal to 2 for hybrid time-current voltage characeristics equatio. The objective functions given in Equation 13 is evaluated with HHO (Rizwan et al., 2020) and propsed α-HHO with DOCR-TCV. For both algorithms the population size is 30 and maximum iterations are fixed to 500. The simulations were carried out in MATLAB.

Table 3. Optimal relay settings obtained with HHO and α-HHO

Relay	HHO		Proposed α-HHO	
	TMS	Ip (kA)	TMS	Ip (kA)
1	0.672	0.120	0.670	0.151
2	0.641	0.189	0.710	0.234
3	0.103	0.144	0.381	0.180
4	0.851	0.207	0.075	0.254
5	0.681	0.145	0.838	0.182
6	0.858	0.130	0.943	0.161
7	0.518	0.162	0.866	0.202
8	0.840	0.125	0.707	0.157
9	0.678	0.135	0.843	0.172
10	0.412	0.092	0.846	0.113
11	0.682	0.155	0.903	0.190
12	0.873	0.140	0.079	0.176
13	0.877	0.144	0.739	0.179
14	0.663	0.191	0.648	0.240

The computer used for the simulations had the following specifications: HP- processor Intel(R) Core(TM) i5-4210 CPU @ 1.70GHz 2.4 GHz, RAM of 8.0 GB with 64-bit operating system. The relay settings obtained with HHO and α-HHO are presented in Table 3. The operating time of primary-backup relays of each pair is shown in Table 4. The overall relays operating time with HHO is 67.9 sec, whereas with α-HHO, it is 25.63 sec. Which is 62.25% less than the HHO. This shows the better performance of α-HHO as compared to the conventional HHO. To show the effectivenes of the proposed scheme, both the TCC and the hybrid TCV are solved with HHO and α-HHO, and results are provided in Table 4. Table 4 shows that the highest reduction with proposed hybrid TCV with α-HHO is achieved. Also, no miscoordination is recorded among the primary-backup relays. The CTI between primary-backup relays for both HHO and α-HHO with TCC and hybrid TCV are depicted in Figure 4. Figure 5 shows the convergence graph of HHO and α-HHO. Therefore, a better performance is achieved with proposed scheme as compared to the conventional HHO.

Table 4. Primary/Backup relay operation time for all pairs obtained using HHO and α-HHO.

Pair	**TCC with HHO**		**TCC with α-HHO**		**Hybrid-TCV with HHO**		**Hybrid TCV with α-HHO**	
	TOP_{PR}	**TOP_{BR}**	**TOP_{PR}**	**TOP_{BR}**	**TOP_{PR}**	**TOP_{BR}**	**TOP_{PR}**	**TOP_{BR}**
1	1.753	2.054	1.296	1.694	0.666	0.974	0.448	0.788
2	1.415	2.373	1.184	1.582	0.511	1.315	0.135	1.158
3	1.415	1.731	1.284	1.758	0.422	0.891	0.229	0.797
4	1.552	2.628	1.107	1.902	0.569	0.919	0.304	1.014
5	1.552	2.366	1.107	1.578	0.565	1.274	0.301	1.121
6	1.278	1.582	0.419	0.720	0.767	1.078	0.195	0.739
7	1.256	1.686	0.179	1.198	0.304	0.611	0.303	0.625
8	1.443	1.795	0.658	1.499	0.611	0.914	0.135	0.472
9	2.026	2.532	0.265	0.576	0.066	0.366	0.149	0.759
10	1.455	2.496	1.227	1.546	0.732	1.163	0.300	0.601
11	1.510	2.331	1.356	1.903	0.761	1.076	0.617	0.956
12	0.109	1.869	1.379	2.211	0.106	0.858	0.538	0.865
13	0.109	1.605	1.379	1.774	0.106	0.802	0.506	0.836
14	1.664	2.064	1.385	1.736	0.672	0.980	0.556	0.915
15	1.664	2.220	1.385	2.400	0.666	1.105	0.551	1.129
16	1.359	1.667	1.132	1.503	0.605	0.957	0.617	0.938
17	1.369	2.005	0.940	1.770	0.688	1.084	0.619	0.919
18	1.357	2.218	0.932	2.597	0.680	0.993	0.612	0.994
19	1.097	2.539	1.236	1.841	0.529	0.829	0.559	0.916
20	1.097	1.689	1.236	1.718	0.527	0.959	0.557	0.860
Tot.	67.929 sec		54.591 sec		29.698 sec		25.6328 sec	

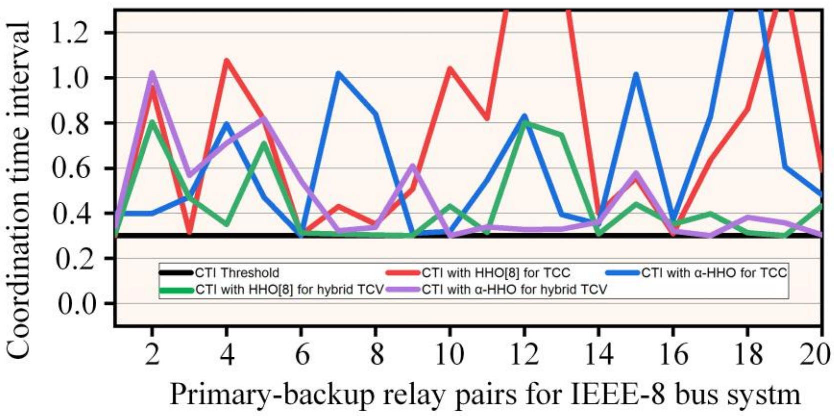

Figure 4. CTI between primary-backup relays for all pairs.

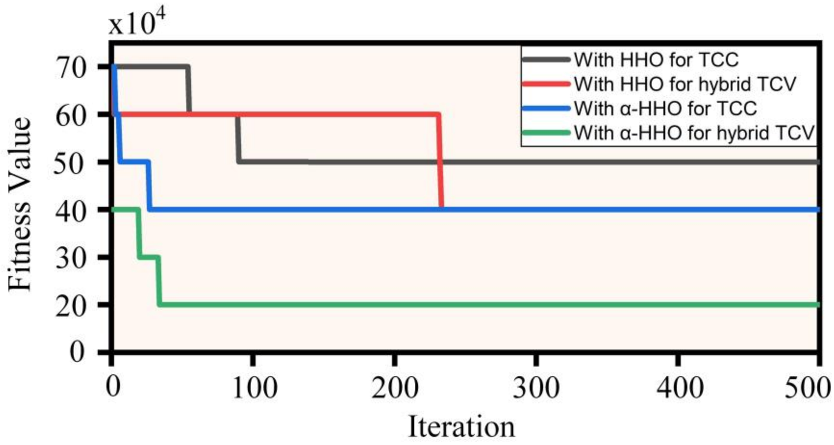

Figure 5. Convergence graph for IEEE-8 bus system with HHO and α-HHO for both curves.

CONCLUSION

In this paper, a novel protection coordination scheme is presented. In the proposed scheme, the conventional TCC of OCR is replaced with a hybrid TCV by including the effect of fault voltage. Moreover, the PC problem was solved optimally with α-HHO. The proposed scheme is modeled by modifying the exploration phase of conventional HHO based on α-HH selection and mutation process. The scheme was evaluated on IEEE-8 bus meshed distributio netwrok system modified by integrating two wind farms. The simulation results were compared with the conventional TCC and HHO. It is seen that the highest reduction in overall relay operating time was achieved with proposed scheme with zero miscoordination, which show the effectiveness of the proposed scheme.

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