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Optimal Relay Coordination with Hybrid Time–Current–Voltage Characteristics for an Active Distribution Network Using Alpha Harris Hawks Optimization †

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Abstract: The miscoordination and malfunctioning of directional overcurrent relays (DOCR) may occur due to a significant change in the fault current level (FCL) and a change in the network topology, from a radial to ring topology, caused by renewable energy resource-based distributed generation (RES-DG). In this paper, a hybrid time–current–voltage (TCV)-based protection scheme is proposed to eliminate the DOCR miscoordination and to reduce the overall operation time of DOCRs. The DOCR coordination problem is solved with alpha Harris Hawks optimization (α-HHO). Detailed numerical studies are carried out, and to show the performance of the proposed scheme, the results are compared with the existing protection schemes in the recent literature.

Keywords: RES-DGs; directional overcurrent relay; hybrid TCV; α-HHO; optimization

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1. Introduction

RES-DGs are becoming extensively integrated into conventional distribution networks. This is due to the developments in smart grid technologies and the environmentally friendly nature of RES-DGs [1]. Aside from the benefits, RES-DGs also create technical complexities from the perspective of operation and protection. Overcurrent relays (OCRs) can miscoordinate or malfunction, resulting in an interruption in the power supply system, or failures in the power infrastructure [2]. Researchers have proposed numerous strategies to deal with the protection issues [3–5].

In this paper, the efficiency of HHO, used in [6], is improved based on the performance of α-HHO, and the OCR-TCC is modified by including the fault voltage.

2. Methodology

2.1. Harris Hawks Optimization

Harris Hawks optimization (HHO) [6] comprises exploration and exploitation phases. HH can be divided into four categories based on their performance, i.e., α, β, δ, and ω. These HH has more knowledge about prey than other predators.

During the exploration phase, the HH can take positions based on the chance of attack (â′). If â′ is <0.5, the HH can take random positions. Mathematically, this is given by Equation (1), as follows:

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

On the other hand, for a chance of attack greater than 0.5, the HH take positions in collaboration with each other. During this, the HH position is updated by Equation (2), as follows:

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

The HH transfer from exploration to exploitation when the escape energy of the prey is less than one. The escape energy of the prey is calculated as follows:

$$E = 2 \times E_0 \times (1 - \frac{t}{t_{\max}}) \quad (3)$$

In the exploitation phase, the HH have four attacking strategies, based on the escape energy E and the escape probability (r) of the prey. These are given in Table 1.

Table 1. Attacking strategies during exploitation phase.

	Soft Seige (SS)	**Soft Siege with Progressive Rapid Dives (SSPRD)**	**Hard Siege (HS)**	**Hard Siege with Progressive Rapid Dive (HSPRD)**
Escape Energy (E)	E ≥ 0.5	E ≥ 0.5	E < 0.5	E < 0.5
Escape Probability (r)	r ≥ 0.5	r < 0.5	r ≥ 0.5	r < 0.5

During SS, SSPRD, HS, and HSPRD, the positions are updated using Equations (4)–(8), respectively.

$$P_{(t+1)} = \Delta P_{(t)} - E \left| J \times P_{best(t)} - P_{(t)} \right| \therefore \Delta P_{(t)} = P_{best(t)} - P_{(t)},\ J = 2(1 - r_5) \quad (4)$$

$$P_{(t+1)} = \begin{cases} C & if \quad Fit(c) < P_{(t)} \\ R & if \quad Fit(R) < P_{(t)} \end{cases} \therefore C = P - E \left| J \times P_{best(t)} - P_{(t)} \right|,\ R = C + S \times LF(D) \quad (5)$$

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

$$P_{(t+1)} = \begin{cases} C & if \quad Fit(c) < P_{(t)} \\ R & if \quad Fit(R) < P_{(t)} \end{cases} \therefore C = P_{best(t)} - E \left| J \times P_{best(t)} - P_{m(t)} \right|,\ P_{m(t)} = \frac{1}{N} \sum_{j=1}^{N} X_{i(t)} \quad (7)$$

2.2. α-Harris Hawks Optimization

The best HH is named α-HH. It can be supposed that the position vector of this HH is P_{best}. Similarly, the position vectors of the second and third best HHs are defined as $P_{best} - 1$ and $P_{best} - 2$, respectively, depending upon the performance efficiency of the new position vector P_{new} from the total number of HH. Therefore, the new position vector $P_{(n)}$, obtained by the selection–mutation of ith hawks, can be calculated as follows:

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

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

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

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

2.3. Hybrid Time–Current Voltage Characteristics

The conventional OCR TCC is based on the fault current only. Its characteristic equation is as follows:

$$t = \mathrm{TDS}\left[\frac{A}{\left(\frac{I}{I_P}\right)^B - 1} + C\right] \quad (11)$$

where t is the operation time of the relay, I is the fault current, 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 [7], which has a modulating effect on the TCC and reduces the relay operation time drastically. The modified TCC is given as follows:

$$t = \mathrm{TDS}\left[\frac{A}{\left(\frac{I}{I_P}\right)^B - 1} + C\right]\left(\frac{1}{e^{1-V_f}}\right)^K \quad (12)$$

where V_f is the fault voltage measured at the relay point and K is the relay constant. The objective function here is to minimize the overall relay operation time and eliminate miscoordination among the relays.

3. Results and Disscussion

The performance of the proposed scheme is evaluated on the standard IEEE-8 bus system, which is modified with the integration of two wind farms (WFs) at bus three and six. As we will compare the results with the HHO used in [6], the same system as used in [6] is used here. The one-line diagram of the IEEE-8 bus system is shown in Figure 1. The three-phase bolted faults are simulated at the mid-point of each line. There is a total of seven faults, represented as F1–F7. The system is protected with 14 DOCRs and there is a total of 20 primary/backup relay pairs. The coordination time interval (CTI) is kept as 0.3 s. The lower and upper limits for TDS are 0.05 and 1.1, whereas, for I_p, these are kept as 1.1*I_{load} and 1.5*I_{load}. The objective functions given is to minimize total relay time and is evaluated with HHO [6], and proposed α-HHO with DOCR-TCV. For both algorithms, the population size is 30 and the maximum iterations are 500. The relay settings obtained with HHO and α-HHO are reflected in Table 2. The operating time of the primary/backup relays of each pair is shown in Table 3. The overall operating time for the relays with HHO is 67.9 s, whereas, with α-HHO, it is 25.63 s, which is 62.25% less than HHO. Additionally, no CTI violation is recorded, which shows the better performance of α-HHO as compared to conventional HHO. Figure 2 reflects the convergence graph for both HHO and α-HHO.

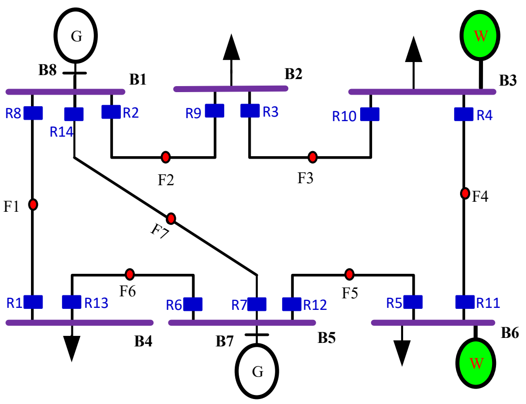

Figure 1. Standard IEEE-8 bus system.

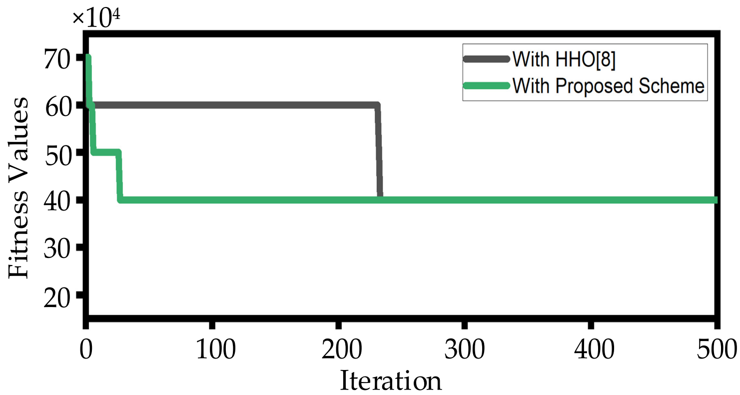

Figure 2. Convergence graph with HHO [6] and α-HHO.

Table 2. Optimal relay settings obtained with HHO and α-HHO.

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

Table 3. Primary/backup relay operation time for all pairs obtained using HHO and α-HHO.

Pair			TCC with HHO [6]		Hybrid TCV with α-HHO		Pair			TCC with HHO [6]		Hybrid TCV with α-HHO	
	PR	BR	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}		PR	BR	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}
1	1	6	1.753	2.054	0.448	0.788	11	5	4	1.510	2.331	0.617	0.956
2	8	7	1.415	2.373	0.135	1.158	12	12	13	0.109	1.869	0.538	0.865
3	8	9	1.415	1.731	0.229	0.797	13	12	14	0.109	1.605	0.506	0.836
4	2	1	1.552	2.628	0.304	1.014	14	6	5	1.664	2.064	0.556	0.915
5	2	7	1.552	2.366	0.301	1.121	15	6	14	1.664	2.220	0.551	1.129
6	9	10	1.278	1.582	0.195	0.739	16	13	8	1.359	1.667	0.617	0.938
7	3	2	1.256	1.686	0.303	0.625	17	7	5	1.369	2.005	0.619	0.919
8	10	11	1.443	1.795	0.135	0.472	18	7	13	1.357	2.218	0.612	0.994
9	4	3	2.026	2.532	0.149	0.759	19	14	1	1.097	2.539	0.559	0.916
10	11	12	1.455	2.496	0.300	0.601	20	14	9	1.097	1.689	0.557	0.860

4. Conclusions

In this paper, a novel protection coordination scheme is presented, which modifies the conventional TCC of OCR with a hybrid TCV. Further, the ORC problem was solved optimally with α-HHO, which is modeled by modifying the exploration phase of conventional HHO, based on α-HH selection and mutation processes. The scheme was evaluated on the standard IEEE-8 bus system. The results suggest that the highest reduction in overall relay operating time was achieved with zero miscoordination, which shows the effectiveness of the proposed scheme.

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