Optimal Coordination of Numerical and Directional Over Current Relays using Hybrid Enhanced Grey Wolf Harris Hawk Optimization Algorithm

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Abstract:- Growing demand as a result of the present trend in the world's energy crises is increasingly causing the distribution system to take mesh appearance. As a result, directional overcurrent relays (DOCRs) have become widely used for network coordination, protection and control in both distribution and transmission networks. Efficient and reliable network operation and control, requires optimal coordination of the DOCRs such that the overall operational time is minimized. However, the relay parameter settings must be carefully and optimally chosen (for example, Time Dial settings is bounded between 0.05s to 1s) such that any fault occurrence can be cleared as fast as possible, while still ensuring that void network topologies are avoided. As a result, setting the DOCR parameters is a challenging problem and attempt has been made through nonlinear optimization schemes to resolve this problem but poor convergence, misdetection, higher coordination time and complexity of solution became serious limitation to the effective operation of DOCR most especially when the network becomes large and complex. A quick convergent hybrid meta-heuristic optimization approach is suggested. The standard Grey-wolf optimizer (GWO) and Harris-hawk optimizer (HHO) were both improved, and a hybrid enhanced Grey-wolf Harris-hawk optimizer (HEGWHHO) algorithm was created. The effectiveness of the created HEGWHHO and its derivatives—conventional GWO, conventional HHO, hybrid GWO and HHO (HGWHHO), enhance GWO, and enhanced HHO were examined and contrasted with that of other pertinent algorithms in the literature. Including the IEEE 8 and 30 Bus networks, three DOCR coordination test systems, where utilized to test the developed algorithm's performance. In terms of DOCR setting optimization, all six algorithms that were taken into consideration in this work were successful. The created HEGWHHO has, nevertheless, been able to further minimize the DOCR optimization goal function in the IEEE test system by 4.51% and 8.84% lower than the best performing methods in literature. Furthermore, the overall order of decreasing performance of the six algorithms investigated in this work have been found to be HEGWHHO > HGWHHO > EGWO > EHHO > GWO > HHO.

Keywords:- *Directional Overcurrent Relay, Grey Wolf Optimizer, Harris Hawk Optimizer, Hybrid Enhanced Grey Wolf Harris Hawk Optimizer.*

I. INTRODUCTION

The electrical power system network is susceptible to failure because of system fault which are stochastic in nature. Long-distance lines and distant locations are more likely to experience faults. Thus, having a strong protection system is one of the most crucial components of the power system. By preventing disruptions in the energy supply and shielding pricey equipment from damage, such as generators, transformers, switchgear, and conductors therefore, Persuasive protection system are usually employed to help businesses avoid income loss. The isolation of the problematic area with sufficient margins and the avoidance of needless time delays are requirements for proper coordination of the protective relays for the power system. (Birla, Maheshwari & Gupta, 2006).

To achieve a minimum overall primary and backup relay operating time while guaranteeing selectivity and delivering reliable service, DOCR's operation involves coordinating primary and backup relays. Both of these relays have two types of settings: pickup tap setting (PTS) and time dial setting (TDS). In order for the primary relay nearest to the fault to respond quickly for operation before all end-to-end relays, the PTS and TDS are set up in this manner (i.e., backup relays). As a result, the coordination of the DOCRs entails optimization problems, the resolution of which involves the best modification of each relay's TDS and PTS under certain limitations that depend on the features of the relays. The directional over current relay (DOCRs) coordination problem, on the other hand, becomes a very complex mixed integer in a large-scale, bidirectional, and interconnected (multi mesh) power system. To reduce the overall operational time, one must adopt selectivity criteria between the primary and backup relay while adhering to operational constraints.

To prevent the healthy part of the system from being affected by the fault, the DOCR relay system is designed to detect a fault occurrence and quickly isolate the problematic area of a network. To obtain the best value and the shortest operation time, TDS and PS are chosen as the two variables. The optimal TDS and PS settings will reduce the total working time of relays (Alee & Amree 2021). The coordination issue at DOCR was initially resolved by trial and error. Therefore, more iterations are required to arrive at the ideal relay configuration.

To prevent wasteful trips, over current relays must be able to distinguish between and respond sequentially to faults in the protected zone. The settings of the over current relays can be determined using a variety of techniques, including trial and error, the conventional approach, and the deterministic approach, among others. The over current protection relay settings are calculated using the traditional way. The traditional approach to configuring protection over current relays needs a lot of inputs and does not always result in the optimal coordination. The computation method gets considerably more difficult and time-consuming when there are several sources. The directional over current relay coordination problem has been solved using deterministic approaches, however the outcomes were subpar. Deterministic approaches have the drawback of being computationally expensive and ineffectual because the findings are reliant on an initial guess of the principal relays.

In this paper, it is suggested to enhance the computed over current protection relay settings by using the Hybrid Enhanced Grey Wolf Harris Hawk Optimization (HEGWHHO) method, being a relatively new stochastic search technique.

- *Problem Formulation*

The growth in electricity demand has brought out an increase in network size and complexity, this result in more fault occurrences which increases the frequency and severity of fault on the network and hence higher maintenance cost. To secure networks, numerical and directional over current relays are used in network protection coordination and control. The conventional relay protection coordination methods are mainly used in the industry for offline calculation of the protective over current relay settings (Maheswari & Gupta 2005). However, network operation requires real-time relay settings for efficient and reliable protection and control, Literatures have made attempt to improve the coordination problem. In this regard, researchers including (Panida & Peerapol, 2020), designed a dual-directional overcurrent relay quaternary protection system (dual-DOCR).

In general, complexity and lack of flexibility are some of the setbacks of most of the other works. This research work is set to develop a flexible approach for optimal DOCR coordination, an algorithm with higher rate of convergence to global minimal and to provide a better strategy for network protection coordination that will minimize cost.

II. METHODOLOGY

Operationally, DOCR can be divided into primary and backup relay systems. The DOCR coordination problem, which is typically placed closest to the location of fault occurrence, involves determining the best Time-Dial Setting (TDS) and Peak-up current Setting (PS) of these relay types. Other relays can use any primary relay as a backup, and vice versa. The close-in and the far-bus fault coordination of primary relays are frequently subclassified. This is often used in literature to model a suitable relay coordination objective function as will be seen later in this work. However, this imposes constraint that, a Primary relay must always operate before its corresponding Back-up counterpart. Due to the non-convexity of DOCR problem a hybrid enhanced Grey Wolf Harris Hawk optimizer (HEGWHHO) is developed for optimal DOCR setting for reliable network protection coordination.

DOCR starts to function when the input current exceeds the sum of the plug settings PS and the current transformation ratio (CTR) in a predetermined direction. The current transformer in a DOCR allows the same kind of DOCR to be used to protect different parts of a network with current transformers of various sizes. Inverse definite minimum time (IDMT) DOCRs are the most typical. The International Electro-Technical Commission (IEC) proposed Eqn. (1) for calculating the operational time of DOCR with IDMT characteristic (Amraee *et. al.* 2012).

$$T_{i,j} = \frac{0.14 \times TDS_i}{\left(\left(\frac{I_{SC,j}}{CTR_i \times PS_i}\right)^{0.02} - 1\right)} \tag{1}$$

Furthermore, the short circuit current and the current transformation ratio in Eqn. (1) are usually represented by other user defined variables in most literatures

The DOCR objective function (OF) is often designed to reduce the total operating time of the group of primary relays. In this work, an objective function that takes into account both the operational times of the near (primary) and far (backup) relay is also taken into account. DOCRs are expected to operate as fast as possible to prevent the effect of a phenomenon called “built-up current”, while still ensuring constraints satisfaction. The two objective functions (Type-1 and Type-2) considered in this work, are repressed by Eqns. (2) and (3) respectively. To compare the proposed DOCR coordination technique to the current ones, the most recent literature that took these aims into account is used. Depending on the network and fault data that are available, the Type-1 or Type-2 goal can be used. The Type-1 objective function is shown in Eqn. (2) (Amraee *et. al.*, 2012).

$$OF^{Type-1} = \sum_{j \in M_{fault}} \left(\sum_{i=1}^{N_{DOCR}} T_{i,j}^{pri.}\right) \tag{2}$$

Where, ?? denotes the operating period of the ith main relay when it guards the network against the jth fault and denotes the total number of DOCR in the network. is a collection of every network problem that has occurred. Although equation also includes the Type-2 objective function of Eqn. (3) (Thangaraj *et. al.*, 2010).

$$OF^{Type-2} = \sum_{j \in M_{fault}} \left(\sum_{i=1}^{N_{cl}} T_{i,j}^{pri\_cl\_in.} + \sum_{k=1}^{N_{far}} T_{k,j}^{pri\_far\_bus.} \right) \tag{3}$$

Where N is the total number of relays reacting to close-in and far-bus faults, $T_{i,j}$ and $T_{k,j}$ the operational time of the ith primary relay during a jth close-in fault, and is the operational time of the kth primary during a jth far-bus fault, relay. It cannot be measured via an equation (3), $T_{i,j}^{pri\_cl\_in.}$ and $T_{k,j}^{pri\_far\_bus.}$ are evaluated using Eqns. (4) and (5) respectively (Thangaraj *et. al.*, 2010).

$$T_{i,j}^{pri\_cl\_in.} = \frac{0.14 \times TDS_i}{\left(\frac{a_i}{PS_i \times b_i} - 1 \right)} \tag{4}$$

And

$$T_{k,j}^{pri\_far\_bus.} = \frac{0.14 \times TDS_k}{\left(\frac{c_k}{PS_k \times d_k} - 1 \right)} \tag{5}$$

Where, a_i, b_i, c_k, and d_k represents the ***i***th and ***k***th primary close-in and far-bus relay tripping coefficients respectively.

The aforementioned objective functions are usually minimized in an attempt to optimize the DOCR settings to achieve optimal network protection coordination. However, optimum DOCR coordination cannot be achieved without satisfying a set of predefined constraints in the following subsection, a basic explanation of the DOCR optimization constraint is provided. The proposed DOCR optimization was designed to satisfy 4 major constraints: Operational time constraint, Time Dial Setting (TDS) Constraints, Peak-up Setting (PS) Constraint and Coordination Time Interval Constraint.

III. OPTIMIZATION TECHNIQUE

To optimize the DOCR optimization problem formulated so far in the immediate sub-section above, an enhanced heuristic approach with high rate of convergence to the global optimum solution is required due to its complexity and higher dimensionality. In this regard, a hybrid enhanced Grey wolf and Harris hawk optimizer (HEGWHHO) is proposed. The HEGWHHO is formed by the hybridization of enhanced versions of the existing Harris hawk and Grey wolf optimizers.

❖ *Proposed Enhanced Harris Hawk Optimizer (EHHO)*

The proposed EHHO has three major modifications to the existing HHO. This modification can be summarized using steps A, B, and C.

A. In EHHO, each hawk (representing candidate solution), in the population of Harris hawks is represented by normalized values instead of the actual values used in HHO. In this manner, solutions are further guided and the search space are narrowed. This can also aid solution manipulation as can be observed in step C. Let X_{hh} represent a candidate solution in HHO. Then X_{hh} can be represented by Eqn. (18), in which the number of unknown/optimization variables is equal to 2***N***$_{DOCR}$

$$X_{hh} = [TDS_1, TDS_2\ TDS_3, \ldots TDS_{N_{DOCR}}, PS_1, PS_2\ PS_3, \ldots PS_{N_{DOCR}}] \tag{6}$$

On the other hand, in EHHO, each variable is represented by its normalized equivalent, as represented by Eqn. (3.20).

$$X_{ehh} = [TDS_1^{norm}, TDS_2^{norm}\ TDS_3^{norm}, \ldots TDS_{N_{DOCR}}^{norm}, PS_1^{norm}, PS_2^{norm}\ PS_3^{norm}, \ldots PS_{N_{DOCR}}^{norm}] \tag{7}$$

Where,

$$TDS_k^{norm} = \frac{TDS_k - TDS^{Min}}{TDS^{Max} - TDS^{Min}} \tag{8}$$

And

$$PS_k^{norm} = \frac{PS_k - PS^{Min}}{PS^{Max} - PS^{Min}} \tag{9}$$

Furthermore, in EHHO, upon objective function evaluation, each normalized parameter in a solution, must be initially decoded back to its actual equivalent value using Eqn. (22) or (23).

$$TDS_k = TDS^{Min} + (TDS^{Max} - TDS^{Min}) \times TDS_k^{norm} \tag{10}$$

And

$$PS_k = PS^{Min} + \left(PS^{Max} - PS^{Min}\right) \times PS_k^{norm} \qquad (11)$$

B. The preying behavior of the Alpha wolf in the existing GWO was incorporated into EHHO to form an additional exploitation step, to boost its rate of convergence. The step can be described using the following pseudo code.

➢ *Algorithm 1: Alpha Preying*

```
• Input : $\boldsymbol{t}$, $\boldsymbol{T}$, $\boldsymbol{X^t_{ehh}}$ and $\boldsymbol{X^t_{ehh,best}}$
• $\boldsymbol{X^t_{ehh,Alpha}} = \boldsymbol{X^t_{ehh,best}}$
• if escape energy < 0
• for each element of $X^t_{ehh}$ % at trial t
• $r_1$=rand(.);  % r1 is a random number in the range [0,1]
• $r_2$=rand(.);  % r2 is a random number in the range [0,1]
• $\tau$ =2× (1-(t/T))  % at trial t out of T
• A=2× $\tau$ ×$r_1$-$\tau$;  %  coefficient of a prey attack
• C=2×$r_2$;  % coefficient of closeness to a prey
• $X^{t+1}_{ehh} = X^t_{ehh,Alpha} - A \times \left|C \times X^t_{ehh,Alpha} - X^t_{ehh}\right|$  % $X^t_{ehh,Alpha}$ is the best solution
• end
• end
• Output : $X^{t+1}_{ehh}$
```

C. The last modification step in the EHHO is referred to as enhanced exploitation. This was is similar to the linear interpolation method. The enhanced exploitation can be represented using the following pseudo code.

➢ *Algorithm 2: Enhanced Exploitation*

```
• Input : $\boldsymbol{X^t_{ehh}}$, $\boldsymbol{X^t_{ehh,best}}$
• Decode $\boldsymbol{X^t_{ehh}}$, $\boldsymbol{X^t_{ehh,best}}$ to obtain $\boldsymbol{X^t_{hh}}$, $\boldsymbol{X^t_{hh,best}}$using (3.23) and (3.24)
• $f^t_{ehh} = OF(X^t_{hh})$  % evaluate the objective function/fitness of $X^t_{ehh}$
• $f^t_{ehh,best} = OF\left(X^t_{hh,best}\right)$  % evaluate the objective function/fitness of $X^t_{ehh,Alpha}$
• $f^t = \left(\frac{f^t_{ehh} \times f^t_{ehh,best}}{f^t_{ehh} + f^t_{ehh,best}}\right)$ % evaluate the total position uncertainty coefficient
• $X^{t+1}_{ehh} = \left(\frac{X^t_{ehh}}{f^t_{ehh}} + \frac{X^t_{ehh,best}}{f^t_{ehh,best}}\right) \times f$ % predict the most probable position of prey
• Output : $X^{t+1}_{ehh}$
```

Finally, the proposed EHHO can be described using Algorithm 3. In the EHHO each candidate solution $X^t_{ehh}$is upgraded to a new solutionX^{t+1}_{ehh}, which is further upgraded to anotherX^{t+1*}_{ehh}, updating the best solution from $X^t_{ehh,best}$to $X^{t+1}_{ehh,best}$and then to $X^{t+1*}_{ehh,best}$.

➢ *Algorithm 3: EHHO*

```
• Input: $\boldsymbol{T}$
• Initialize $X^t_{ehh}$
• Set $X^t_{ehh,best}$= $X^t_{ehh}$
• While $\boldsymbol{t}$ is less than $\boldsymbol{T}$
• Perform the HHO Exploration and Exploitation steps
• Update $X^t_{ehh}$ and $X^t_{ehh,best}$
• Perform Alpha Preying
• Update $X^t_{ehh}$ and $X^t_{ehh,best}$
• Perform Enhanced Exploitation
• Update $X^t_{ehh}$ and $X^t_{ehh,best}$
• t=t+1;
• end
```

```
Output : $X^{t}_{ehh,best}$
```

Optimization Algorithms Enhancement

The proposed EGWO has two major modifications to the existing GWO. The first modification is similar to that of the proposed EHHO, where by, each wolf is represented by its normalized equivalent, denoted byX^{t}_{egw}. Unlike the Enhanced Exploitation used by EHHO, the EGWO uses Enhanced Preying to interpolate the next possible position. This new solution search step can be describe using the pseudocodes presented in (Sani, 2023).

Algorithm 4: Enhanced Preying

```
Input: $X^{t}_{egw}$, $X^{t}_{egw,Alpha}$, $X^{t}_{egw,Beta}$ and$X^{t}_{egw,Delta}$
Execute Algorithm 2, using $X^{t}_{egw}$and $X^{t}_{egw,Alpha}$ to evaluate $X^{t+1}_{egw,Alpha}$
Execute Algorithm 2, using $X^{t}_{egw}$and $X^{t}_{egw,Beta}$ to evaluate $X^{t+1}_{egw,Alpha}$
Execute Algorithm 2, using $X^{t}_{egw}$and $X^{t}_{egw,Delta}$ to evaluate $X^{t+1}_{egw,Delta}$
$X^{t+1}_{egw}= (X^{t+1}_{egw,Alpha}+X^{t+1}_{egw,Alpha}+X^{t+1}_{egw,Delta})/3$
Output : $X^{t+1}_{egw}$
```

Similarly, like the EHHO, the proposed EGWO is achieved by initially performing the existing GWO steps on a set of normalized solution candidates while still performing Enhanced Preying on each solution. The EGWO algorithm can be further described using Algorithm 5.

Algorithm 5: EGWO

```
Input: T
Initialize $X^{t}_{egw}$
Set $X^{t}_{egw,Alpha}= X^{t}_{egw}$
Set $X^{t}_{egw,Beta}= X^{t}_{egw}$
Set $X^{t}_{egw,Delta}= X^{t}_{egw}$
While t is less than T
Perform the GWO Preying steps
Update $X^{t}_{egw}$, $X^{t}_{egw,Alpha}$, $X^{t}_{egw,Beta}$and $X^{t}_{egw,Delta}$
Perform Enhanced Preying
Update  $X^{t}_{egw}$, $X^{t}_{egw,Alpha}$, $X^{t}_{egw,Beta}$and $X^{t}_{egw,Delta}$
t=t+1;
End
```

Proposed Hybridized Enhanced Harris Hawk & Grey Wolf Optimizer (HEGWHHO)

As mentioned earlier, the proposed HEGWHHO is formed by the hybridization of the developed EHHO and EGWO. Algorithm 6 presents the suggested HEGWHHO's pseudo code. Six different optimizer variants are generally taken into account in this study, three of which are constructed in this chapter and another three of which are already known from the literature. The optimizers include: HHO, EHHO, GWO, EGWO, HGWHHO and HEGWHHO. The resulting performance of this optimizers are compared with one another and with best result so far in literature, via 3 IEEE test system for network protection coordination. These test systems include: the IEEE 8, 15, and 30 bus networks. MATLAB codes for the EHHO, EGWO and HEGWHHO are presented in Appendix A, B, and C respectively.

Algorithm 6: HEHHGWO

```
Input: T , k
Initialize $X^{t}_{egw}$ and set $X^{t}_{egw,Alpha}$, $X^{t}_{egw,Beta}$ and $X^{t}_{egw,Delta}$ = $X^{t}_{egw}$.
While t is less than T
r=rand(.);  % r is a random number in the range [0,1]
If  r < 0.5
Update  $X^{t}_{egw}$, $X^{t}_{egw,Alpha}$using EHHO over k trials
Perform Enhanced Exploitation
Update  $X^{t}_{egw}$, $X^{t}_{egw,Alpha}$
Else
```

- Update X_{egw}^{t}, $X_{egw,Alpha}^{t}$, $X_{egw,Beta}^{t}$ *and* $X_{egw,Delta}^{t}$ using EGWO over ***k*** trials
- Perform Enhanced Preying
- Update X_{egw}^{t}, $X_{egw,Alpha}^{t}$, $X_{egw,Beta}^{t}$ *and* $X_{egw,Delta}^{t}$
- End
- *t=t+1;*
- **end**
- Output : $X^{t}_{egw,Alpha}$

IV. RESULTS AND DISCUSSION

A. *Testing on IEEE Buses*

Here, the results for the simulation scenario for DOCR coordination optimization are collated, examined and contrasted with the ones found in the literature. Two (2) IEEE test system networks (Bus 8 and 30) and their corresponding data were used for simulation. Six (6) optimizer variants (HHO, EHHO, GWO, EGWO, HGWHHO, and HEGWHHO) were compared to demonstrate the order of increasing performance and effectiveness.

Table 4.1: The Optimization Parameter Settings & Scenario (Cases 1 to 3) Setups

Case No.	**Number of IEEE Network Buses**	**No. of Wolves / Hawks**	**No. of Trials (T)**	**DOCR Exponent (n)**	N_{DOCR}	**HEHH GWO (*k*)**	ε_{slack}	**Number (P/B) Relay Pair**	**Operational Time Equation**
1	8	28	100	1	14	14	0	20	(3.1)
2	30	136	100	1	68	68	0	122	(3.1)

- ➢ *Case 1: IEEE 8-Bus network*

Another medium scale DOCR optimization problem is simulated using the IEEE 8-Bus network which has 14 DOCRs and 20 P/B pair constraints. The TDS, PS, and $\boldsymbol{T}_{ij}$ optimization results are presented in Table 4.2(a), whereas, those of the P/B pair constraints are presented in Table 4.2(b). Furthermore, the comparative analysis results for the 8-Bus network are also presented in Table 4.3.

Table 4.2(a): The DOCR TDS, PS, and T_{ij} for IEEE 8-Bus Network (HEGWHHO)

DOCR No.	**DOCR Settings**		$\boldsymbol{T}_{i,j}$
	TDS	**PS**	
1	0.1078	2	0.388187431
2	0.248	2.5	0.740904894
3	0.2164	2.5	0.678257779
4	0.1563	2.5	0.583312036
5	0.1	2.5	0.497823931
6	0.1635	2.5	0.481837341
7	0.2301	2.5	0.610917918
8	0.1655	2.5	0.488296095
9	0.1382	2.5	0.520363839
10	0.1648	2.5	0.606281977
11	0.1752	2.5	0.6612686
12	0.2494	2.5	0.746497864
13	0.1	2.5	0.428785394
14	0.2311	2.5	0.614703302

Table 4.2(b): P/B Relay Pair Constraints for IEEE 8-Bus Network (HEGWHHO)

S/No	**P/B Pair**		**CTI**
	Primary	**Backup**	
1	1	6	0.300093197
2	2	1	0.305321107
3	2	7	0.300313829
4	3	2	0.300060986
5	4	3	0.300000742
6	5	4	0.300274873
7	6	5	0.544725477
8	6	14	0.56955385

9	7	5	0.415644899
10	7	13	0.808449342
11	8	7	0.552922629
12	8	9	0.427012277
13	9	10	0.300151286
14	10	11	0.301497953
15	11	12	0.30005782
16	12	13	0.672869397
17	12	14	0.304893327
18	13	8	0.300854433
19	14	1	0.431522699
20	14	9	0.300605069

Table 4.3: Comparison of the IEEE 8-Bus Result

Method/ Reference	**OF(s)**	**% Performance**	**NFE**	**TDS, PS, & $T_{i,j}$**	**CTI**
				Result Table.	**Result Table.**
MPSO [Zeineldin et.al. 2006]	17.33	0.00	-	-	-
GA [Noghabi et.al. 2009]	11.001	36.52			
GA-LP [Noghabi et.al. 2009]	10.949	36.82	-	-	-
BBO-LP [Albasri et.al. 2015]	8.7556	49.48	-	-	-
BIP [Correa et.al. 2015]	8.6944	49.83	-	-	-
SOA [Amraee et.al. 2012]	8.4271	51.37	-	-	-
SA-LP [Alexandre et.al. 2020]	8.4271	51.37	-	-	-
HEGWHHO	**8.0474384**	**53.56**	**396800**	4.8(a)	4.8(b)
HGWHHO	8.43689889	51.32	1097531	1/G1	1/G1
EGWO	10.8830656	37.20	4808401	2/G2	2/G2
GWO	13.6106797	21.46	3500724	3/G3	3/G3
EHHO	11.9518272	31.03	4209857	4/G4	4/G4
HHO	16.6196382	4.10	2007187	5/G5	5/G5

In just 396800 function evaluations, the HEGWHHO was able to minimize the DOCR total operational time to 8.0474384s, which is 53.56% lower than that obtained using the MPSO [Zeineldin et.al. 2006]. HEGWHHO was also found to supersede the best performing algorithm in literature (SA-LP [Alexandre et.al. 2020]) by more than 2% reduction in objective function value. The results of this scenario shows that the DOCRs have a district TDS setting, unlike those of case 3. The algorithm was not restricted by the boundary conditions of TDS. However, most of the PSs are the same (bounded by the upper limit of the PS constraints). These results depict a slowly varying operational time that ranges between 0.407s and 0.796s, which is due to the constant PS values.

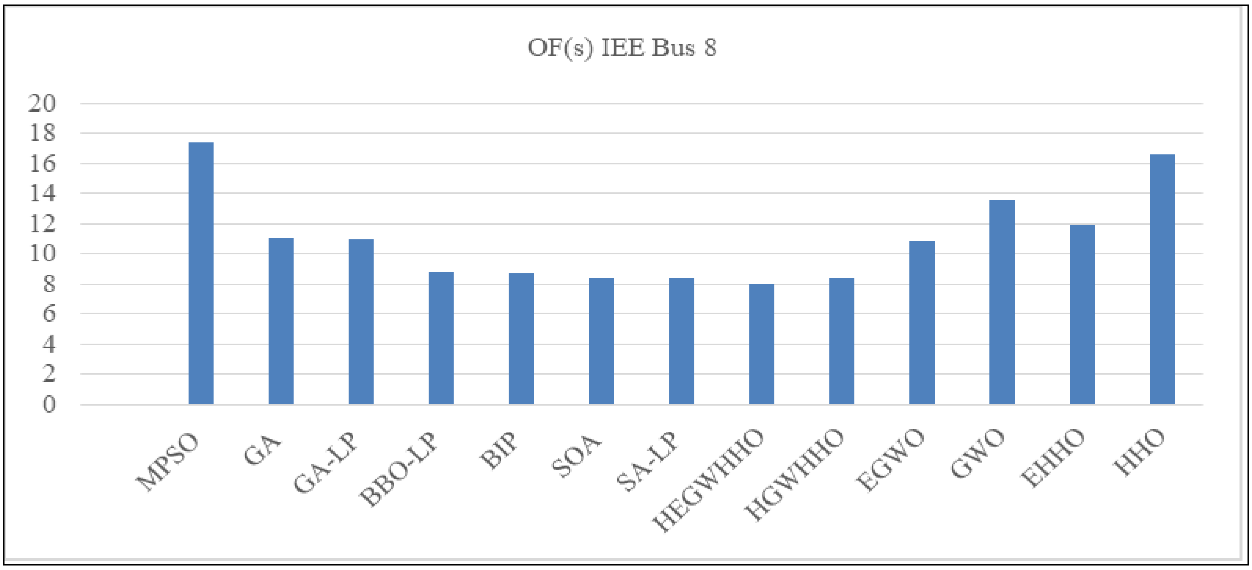

Fig 4.1a: Comparison of the IEEE 8-Bus Results

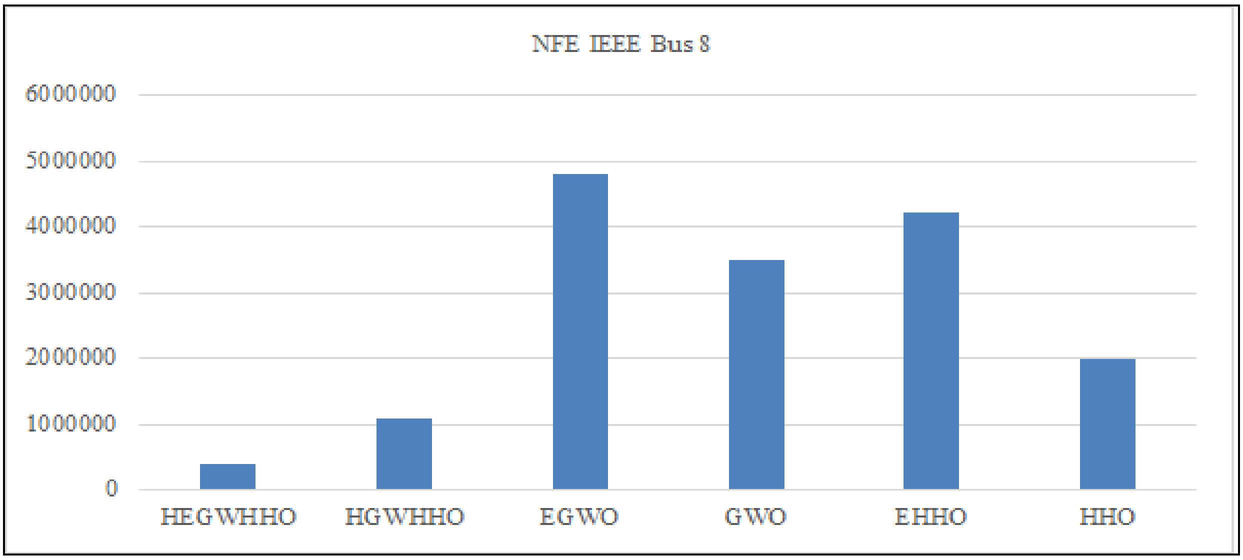

Fig 4.1b: Comparison of NFE IEEE 8-Bus Result

The comparative analysis results for the 8-Bus network of the objective function and that of number of function evaluation are also presented using bar chat as shown in Figure 4.1a and 4.1b.

- *Case 2: IEEE 30-Bus network*

The network has 68 DOCRs with 122 P/B relay pair coordination time constraints. The data used in this case are as presented in (Alexandre *et. al.*, 2020).

Table 4.4: TDS, PS & $T_{i,j}$ Results for the IEEE 30-Bus Network (HEGWHHO)

n_{docr}	**DOCR Settings**		$T_{i,j}$	n_{docr}	**DOCR Settings**		$T_{i,j}$
	TDS	**PS**			**TDS**	**PS**	
1	0.3388	2	0.4293	35	0.2447	1.5	0.27688
2	0.3392	2	0.3395	36	0.4113	2.5	0.48896
3	0.3166	1.5	0.3385	37	0.2838	1.5	0.32924
4	0.3167	1.5	0.337	38	0.4125	1.5	0.50094
5	0.1453	1.5	0.1699	39	0.4365	2.5	0.5387
6	0.2798	1.5	0.2939	40	0.1612	1.5	0.18329
7	0.4266	1.5	0.4494	41	0.3233	1.5	0.3386
8	0.3525	1.5	0.387	42	0.5526	2.5	0.58619
9	0.3173	1.5	0.3201	43	0.4652	2	0.50104
10	0.199	1.5	0.2205	44	0.5024	2	0.5287
11	0.2921	1.5	0.2944	45	0.2193	1.5	0.24142
12	0.1	2	0.129	46	0.3152	2.5	0.37806
13	0.2277	1.5	0.2573	47	0.1034	2	0.17363
14	0.1988	1.5	0.2195	48	0.1343	1.5	0.15926
15	0.5259	1.5	0.5388	49	0.4592	1.5	0.45019
16	0.5619	1.5	0.5739	50	0.2517	1.5	0.259
17	0.156	1.5	0.1934	51	0.3146	1.5	0.32439
18	0.397	1.5	0.4271	52	0.6028	1.5	0.6162
19	0.1016	1.5	0.1227	53	0.1473	1.5	0.17295
20	0.3713	1.5	0.3902	54	0.344	2	0.39532
21	0.2712	1.5	0.2938	55	0.4677	1.5	0.5161
22	0.1129	1.5	0.1439	56	0.1012	1.5	0.1264
23	0.1038	1.5	0.1965	57	0.2933	1.5	0.32842
24	0.103	1.5	0.2103	58	0.3786	2.5	0.48223
25	0.422	2.5	0.4723	59	0.1	1.5	0.1252
26	0.4124	1.5	0.4091	60	0.4881	1.5	0.05
27	0.1475	1.5	0.161	61	0.2766	1.5	0.31893
28	0.475	1.5	0.5776	62	0.1	1.5	0.1225
29	0.2379	1.5	0.244	63	0.1897	1.5	0.20042
30	0.5321	2.5	0.5619	64	0.1002	1.5	0.11463

31	0.1	1.5	0.1168	65	0.1	1.5	0.1148
32	0.1	1.5	0.1166	66	0.1001	1.5	0.11632
33	0.2568	2	0.3328	67	0.279	1.5	0.30701
34	0.1437	1.5	0.1691	68	0.1	1.5	0.1184

Table 4.5: Optimal P/B DOCR pair CTI Results for the IEEE 30-Bus Network (HEGWHHO)

P/B Pair		**CTI**	**P/B Pair**		**CTI**	**P/B Pair**		**CTI**
Primary	**Backup**		**Primary**	**Backup**		**Primary**	**Backup**	
1	4	0.300021	19	18	0.5681305	41	35	0.5654121
2	6	0.4421001	20	24	0.3001691	41	39	0.5742391
2	8	0.3001435	21	9	0.3000042	41	44	0.5382576
2	10	0.4391356	21	13	0.3001467	42	48	0.3003987
3	2	0.3000764	21	18	0.3000758	43	35	0.300251
4	12	0.4891843	21	20	0.3001033	43	39	0.300026
5	1	0.8091396	22	23	0.3002888	43	42	0.3001114
5	8	0.6151799	23	19	0.3004642	44	56	0.3003079
5	10	0.7378824	24	21	0.3000969	45	37	0.3001395
6	11	0.3000767	25	28	0.3000076	46	25	0.3000471
6	14	0.3002279	25	30	0.3000706	47	41	0.3000286
7	1	0.3001335	25	32	0.8910224	48	50	0.3000672
7	6	0.3000241	26	45	0.300319	49	47	0.3000952
7	10	0.3002395	27	26	0.4339309	50	27	0.3000063
8	16	0.3000264	27	30	0.7232908	51	29	0.3001539
9	1	0.494364	27	32	1.4696405	52	31	0.3708571
9	6	0.4814591	28	49	0.3001172	52	54	0.3001488
9	8	0.3301173	29	26	0.300041	53	31	1.1557561
10	13	0.4321278	29	28	0.6882493	53	51	0.3000034
10	18	0.4318952	29	32	1.308214	54	55	0.3000595
10	20	0.4312461	30	52	0.3000476	54	58	0.3001239
10	22	0.3254564	31	26	0.5083779	55	43	0.3000776
11	3	0.3001701	31	28	0.8974566	56	53	0.3469507
12	5	0.3353224	31	30	0.8024285	56	58	0.7590489
12	14	0.5700197	32	51	0.3557989	57	53	0.300219
13	5	0.3002038	32	54	0.4831772	57	55	0.4107261
13	11	0.3566063	33	36	0.3001292	58	62	0.3103581
14	9	0.4290763	33	38	0.3001515	59	57	0.3002888
14	18	0.4145557	34	40	0.300001	59	62	0.3001002
14	20	0.4141009	35	34	0.3754174	61	57	0.3001847
14	22	0.3588299	35	38	0.3957461	62	64	0.3004572
15	7	0.3001003	36	39	0.3293317	62	66	0.3006087
16	17	0.300466	36	42	0.3313347	63	61	0.3000379
17	9	0.5079218	36	44	0.300053	63	66	0.3003526
17	13	0.4873758	37	34	0.3001412	64	68	0.6368427
17	20	0.4860731	37	36	0.301742	65	61	0.3002996
17	22	0.3003148	38	46	0.3001672	65	64	0.3003992
18	15	0.3000564	39	33	0.300256	66	67	0.30003
19	22	0.3525479	40	35	0.8129264	67	63	0.3002993
19	9	0.5907718	40	42	0.8773834	68	65	0.4305853
19	13	0.5683416	40	44	0.813353	-	-	-

This coordination problem can be considered as a large DOCR optimization problem. Conventionally, 8 of the P/B relay pair constraints are usually relaxed (Alexandre *et. al.*, 2020), for simplicity. However, none of the constraints is relaxed in this work. Table 4.6 presents the results for optimum TDS and PS setting of the IEEE 30-bus network.

Table 4.6: Comparison of the IEEE 30-Bus Result

Method/ Reference	**OF(s)**	**% Performance**	**NFE**	**TDS, PS, & $T_{i,j}$ Result Table**	**CTI Result Table**
SA-LP [Alexandre et.al. 2020]	22.3936	34.70	-	-	-
HEGWHHO	**20.4143872**	**40.47**	**1176680**	1/I1	2/I2
HEGWHHO	20.92156442	38.99	1031680	4.12	4.13
HGWHHO	21.71341551	36.68	6226180	3/I3	4/D4
EGWO	22.14644165	35.42	7172680	5/I5	6/I6
GWO	30.21781075	11.89	8171180	7/I7	8/I8
EHHO	22.3855537	34.72	8834610	9/I9	10/I10
HHO	34.29678479	0	9296680	11/I11	12/I12

In this scenario, the HEGWHHO outperformed all other techniques with a total operational time of 20.4143872 (over 1176680 function evaluations), and 20.92156442 (over 1031680 function evaluations). All constraints were satisfied by its solution. Table 4.8 presents the optimum CTI obtained by the developed HEGWHHO with $\varepsilon_{slack}= 0$. The optimization results obtained by the other optimizers have also been presented Appendix D. In Table 4.8, all except HHO and GWO optimizers, outperformed the existing best algorithm in literature. Even though the P/B pair constraints are not relaxed in this work, the proposed optimizers performed better that the best existing strategy presented by SA-LP (Alexandre *et. al.*, 2020). The order of decreasing performance achieved by the optimizers/method can be represented as HEGWHHO > HGWHHO > EGWO > EHHO > SA-LP (Alexandre *et. al.*, 2020) > GWO >HHO. Generally, in this work, the HEGWHHO algorithm have demonstrated superiority over its counterparts, with an outstanding performance of 40.47% over the existing worse algorithm (HHO). It has further minimized the objective function by 5% lower as compared to the best existing method in literature, SA-LP (Alexandre *et. al.*, 2020).

The comparative analysis results for the 30-Bus network of the objective function and that of number of function evaluation are also presented using bar chat as shown in Figure 4.2a and 4.2b.

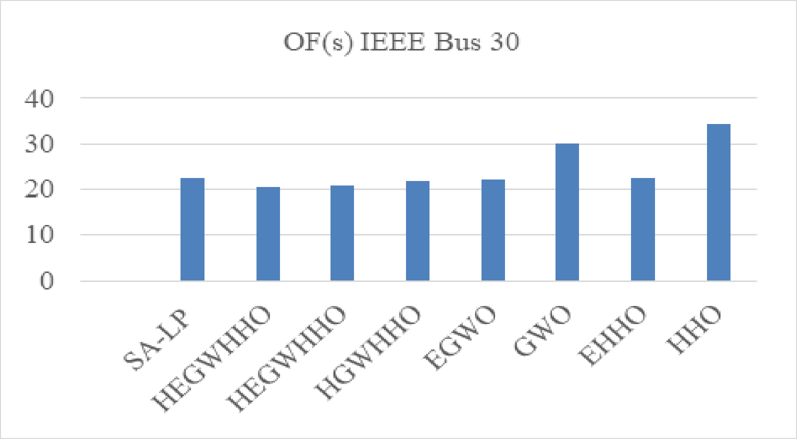

Fig 4.2a Comparison of the IEEE 30-Bus Result

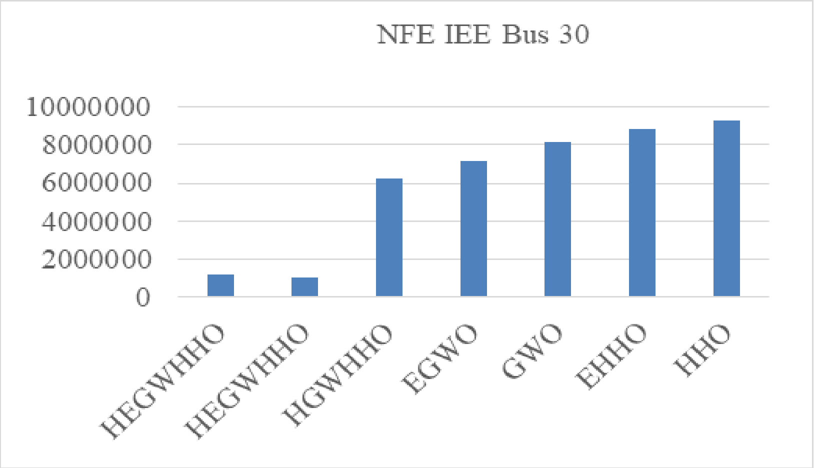

Fig 4.2b: Comparison of the IEEE 30-Bus Result

B. Performance Analysis of the HEGWHHO Algorithm

As described earlier, the HEGWHHO and its 5 variants including the HHO, EHHO, GWO, EGWO, and HGWHHO, have been presented in this work. However, HEGWHHO have demonstrated an outstanding performance over all of the algorithms, and other similar once presented in literature. Table 4.9 presents a summary of the results for the six simulation cases, and the best objective function values reported in relevant literatures.

Table 4.7: Result Summary of the Simulation Scenarios and Comparison

Case No.	**Number of Buses**	**N_{DOCR}**	**CPU Time (s)**	**NFE**	**OF (s) HEGWHHO**	**Best OF in Literature**
1	8	14	0.0685	396800	8.0474	8.4271s SA-LP (Alexandre *et. al.*, 2020)
2	30	68	0.9899	1176680	20.4144	22.3936s SA-LP (Alexandre *et. al.*, 2020)

V. CONCLUSION

The developed HEGWHHO algorithm has demonstrated a guaranteed convergence rate over a considerably low simulation time, as such, the proposed models can be readily deployed in real-time network protection scenarios. In general, the developed HEGWHHO was able to further minimize the DOCR optimization objective function of the test systems by 4.51%, and 8.84%, lower than the best performing methods in literature. This proves that our proposed approach could go a long way in proving reliable solution to DOCR setting problems. It also demonstrates the possibility of using the HEGWHHO as a tool for real time protection coordination application.

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