Yanbu Journal of Engineering and Science

Volume 20 | Issue 1 Article 5

2023

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Recommended Citation

Ali, E. (2023), Harris Hawks Approach for Distinct Economic Dispatch Problems, *Yanbu Journal of Engineering and Science*: Vol. 20: Iss. 1, 32-50.
DOI: https://doi.org/10.53370/001c.75397
Available at: https://yjes.researchcommons.org/yjes/vol20/iss1/5

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Research article

Harris Hawks Approach for Distinct Economic Dispatch Problems

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Keywords: Harris Hawks Approach, Economic Dispatch, Prohibited Zones

https://doi.org/10.53370/001c.75397

Yanbu Journal of Engineering and Science

Vol. 20, Issue 1, 2023 Submitted: 06 DEC 2022 Revised: 31 DEC 2023 Accepted: 31 DEC 2022

In this article, a nature inspired optimization approach is suggested, which is named Harris Hawks Approach (HHA). The prime inspiration of HHA is the mutual attitude and chasing way of Harris' hawks in kind named surprise swoop. In this brilliant drawing, diverse hawks swoop victim cooperatively from distinct ways in an endeavor to startle it. Harris hawks can detect a sort of chasing paradigms rely on the spirited nature of scenarios and escaping styles of the victim. HHA is developed for handling the Economic Dispatch (ED) process. Since the ED is a non-linear, complex and obliged optimization process, its prime target is to lower the net generation cost while achieving the inequality and equality restrictions of the studied system. To prove the capabilities of the developed HHA, several test systems including 6, 13, 40 and 10 units have been implemented and tested for solving various ED problems. The simulation results clarify the potency of the HHA compared with other approaches illustrated recently in literature.

1. INTRODUCTION

Thermal units have proven their mantle for multiple decades and the recent grids are designed to work around them. As the renewable energy future is still in progress, the need of the hour is to handle thermal unit sources such that one can extract extreme power from them at reduced cost and emissions.[1] The act of managing thermal units for a fixed load demand under considerable operational and physical limits is a famous power system operation problem termed as ED.[2] ED is a single objective optimization process with the aim to achieve power dispatch at minimum possible cost without violating any limits. The addition of an emission objective switches ED into a multi-objective task aiming minimization of both cost and emission for a power demand without violating any limits. This multi-objective process is termed as combined economic emission dispatch (CEED) task.[3]

ED is a non-linear, complex and computational intensive power system operational problem. This mathematical complexity makes it an ideal candidate for optimization algorithms to tackle and prove their mantle. Many modern population based meta-heuristic and nature inspired techniques have been used to resolve this process. Several of the famous optimizations algorithms that attempted this problem include: Genetic Algorithm(GA),[4] Simulated Annealing(SA),[5,6] Differential Evolution(DE),[7,8] Moth Swarm Optimization Algorithm(MSA),[9] Spider Monkey Optimization(SMO),[10] Grey Wolf Optimizer(GWO),[11] Fire Fly Algorithm(FFA),[12,13] Harmony Search Algorithm(HSA),[14,15] Spiral Optimization Algorithm(SOA),[16] Artificial Bee Colony(ABC),[17,18] Bacterial Foraging Algorithm (BFA),[19] Particle swarm Optimization(PSO),[20,21] β-hill climbing optimization,[22] Mine Blast Algorithm(MBA),[23] Flower Pollination Algorithm(FPA),[24] Chaotic Turbulent Flow of Water Based Optimization Algorithm(CTFWO),[25] and Coyote Optimization Algorithm(COA).[26] Table 1 addresses the contributions of.[4–26] All these algorithms are population-based strategies having fixed population and they locate the optimum solution within a search space using two distinct stages of search namely local and global search. All these algorithms were successful in achieving the solution of the desired problem with varying degree of precision and time.

In this article, HHA is introduced to solve various ED problems. HHA has been developed in[27,28] depend on the hunting technique of the Harris hawks. The major merits of the HHA are its simplicity and have a few exploratory and exploitative mechanisms. HHA has been employed in many optimization problems as parameter identification for the fuel cell module,[29] photovoltaic cell module[30] and others in.[31–33] Also, it showed remarkable results compared with literature. This success of HHA in solving of various problems and the opportunity to improve its mechanism are the main inspiration behind this research.

This article is organized as follows, portion 2 introduces the overview of ED problems, portion 3 provides summary and mathematical formulations of HHA, portion 4 presents the simulation results along with statistical analysis, finally portion 5 shows the conclusion.

Nomenclature

F_t	The net fuel charge of unit in $,
$F_i(P_i)$	The function of fuel charge i^{th} unit in $,
$\gamma_i, \beta_i, \alpha_i$	The coefficients of charge for i^{th} unit in $/MW,[1] $/MW and $ respectively,
P_i	The generation active power of ith unit in MW,
d	The value of units connected in the system,
P_D	The net load of the network in MW,
P_L	The transmission losses of the network in MW,
P_i,P_j	The active power injections at i^{th} and j^{th} nodes respectively,
B_{ij}, B_{0i}, B_{00}	The coefficients of transmission loss equation,
$P_i^{\min}, P_i^{\max}$	The lower and upper values of active power at unit i,
e_i, f_i	The coefficients of ith unit for valve effect in $ and MW^{-1} respectively,
F	The optimum cost of net emission and generation,
$F_i(P_i)$,$E_i(P_i)$	The net emission and fuel charge of units respectively,
a, b, c	The coefficients for emission of units in Kg/MW,[2] Kg/MW and Kg respectively,
η_i, δ_i	The coefficients for emission of ith unit in Ton and MW^{-1} respectively,
h	The value of price penalty agent in $/Kg,

2. PROCESS FORMATION

The CEED process is to lower two calculating objective functions together, emission and fuel cost, while achieving distinct inequality and equality limits. Commonly the process is shaped as follows.

2.1. COST FUNCTION OF ED

For thermal units, the charge of fuel per unit output power significantly changes with the product power of the generator. Fuel charges are shaped as a quadratic function of product power,[34] as displayed in equation (1).

$$F(P) = \gamma P^2 + \beta P + \alpha \tag{1}$$

Minimize

$$F_t = \sum_{i=1}^{d} F_i(P_i) = \sum_{i=1}^{d} \left(\gamma_i P_i^2 + \beta_i P_i + \alpha_i\right) \tag{2}$$

The reduction is executed according to the equality restriction that the net generation should emulate to the load plus the loss so:

$$\sum_{i=1}^{d} P_i = P_D + P_L \tag{3}$$

The net transmission loss using Kron's loss form can be modeled by equation (4)

$$P_L = \sum_{i=1}^{d}\sum_{j=1}^{d} (P_i B_{ij} P_j) + \sum_{i=1}^{d} B_{0i} P_i + B_{00} \tag{4}$$

It is supposed that these parameters are constant. Depend on the upper and lower power constraints of units the inequality limit is

$$P_i^{\min} \le P_i \le P_i^{\max} i = 1, 2, \ldots\ldots, d \tag{5}$$

2.2. EFFECT OF VALVE POINT

The valve effect is considered in the charge function of units. The intense raise in losses due to the wire drawing effects which happen like every steam admission valve begins to unlock results in the nonlinear rippled curve[35] as displayed in Fig. 1. Based on the rippled curve, the charge function is more precise modeling. Thus, the fuel charge function of every fossil fuel unit is considered as the sum of a sinusoidal and a quadratic function.[36]

$$\begin{aligned} F_t &= \sum_{i=1}^{d} F_i(P_i) \\ &= \sum_{i=1}^{d} \left(\gamma_i P_i^2 + \beta_i P_i + \alpha_i + e_i * \sin\left(f_i * \left(P_i^{\min} - P_i\right)\right)\right) \end{aligned} \tag{6}$$

2.3. OBJECTIVE FUNCTION OF CEED

The aerial pollutants like carbon dioxide, sulfur oxides, and nitrogen oxides caused by fossil fuel fired units can be shaped independently.[37–39] However, for comparison purposes, the net emission of these pollutants can be given as[40]:

$$\begin{aligned} E_t &= \sum_{i=1}^{d} E_i(P_i) \\ &= \sum_{i=1}^{d} \left(a_i P_i^2 + b_i P_i + c_i + \eta_i * \exp\left(\delta_i * P_i\right)\right) \mathrm{Kg} \end{aligned} \tag{7}$$

Optimization of unit cost has been modeled based on imitative ED with emission and line flow restrictions as given in.[40]

$$\text{Minimize } F = \sum_{i=1}^{d} \{F_i(P_i), E_i(P_i)\} \tag{8}$$

The smallest amount of the above cost function has to be discovered according to inequality and equality limits modeled by equations (3) and (5). The dual-objective CEED process is switched into a unique optimization process by introducing a price penalty factor h as follows.[41]

$$\text{Minimize } F = F_t + h \times E_t \tag{9}$$

Subject to limits obtained by equations (3) and (5). The charge penalty agent h which is the ratio between the upper fuel charge and upper emission of corresponding generators in $/Kg,[33,40] blends the emission with fuel charge then F is the net working charge in $.

$$h_i = \frac{F_t\left(P_i^{\max}\right)}{E_t\left(P_i^{\max}\right)}, \mathrm{i} = 1, 2, \ldots\ldots\ldots\ldots, \mathrm{d} \tag{10}$$

2.4. PROHIBITED ZONES

There are many restrictions on the generators operation level as physical restriction of steam valve, component, oscillations in shaft mounting etc., taking into account the

List of abbreviations

CEED	Combined Economic Emission Dispatch
GA	Genetic Algorithm
SA	Simulated Annealing
DE	Differential Evolution
MSA	Moth Swarm Optimization Algorithm
SMO	Spider Monkey Optimization
FFA	Fire Fly Algorithm
HSA	Harmony Search Algorithm
SOA	Spiral Optimization Algorithm
ABC	Artificial Bee Colony
BFA	Bacterial Foraging Algorithm
GWO	Grey Wolf Optimizer
PSO	Particle Swarm Optimization
MBA	Mine Blast Algorithm
FPA	Flower Pollination Algorithm
NGWO	Novel Grey Wolf Optimizer
TS	Tabu Search
MTS	Multiple Tabu Search
NPSO	New Particle Swarm Optimization
RDPSO	Random Drift Particle Swarm Optimization
CLPSO	Comprehensive Learning Particle Swarm Optimization
SLPSO	Self-Learning Particle Swarm Optimization
IRDPSO	Improved Random Drift Particle Swarm Optimization
ST-IRDPSO	Self-Adaption Improved Random Drift Particle Swarm Optimization
MABC	Modified Artificial Bee Colony
HCRO-DE	Hybrid Chemical Reaction Optimization- Differential Evolution
NPSO-LRS	New Particle Swarm Optimization-Local Random Search
GAAPI	Genetic Algorithm with specific type of Ant Colony Optimization
CBA	Chaotic Bat Algorithm
UHGA	Hybrid technique integrating the Uniform design with Genetic Algorithm
NGHS	Natural Global-worst Harmony Search
NPHS	Natural Proportional Harmony Search
NTHS	Natural Tournament Harmony Search
NRHS	Natural Rank Harmony Search
HGWO	Hybrid Grey Wolf Optimizer
QOPO	Quasi-Oppositional Search based Political Optimizer
HSSA	Hybrid Salp Swarm Algorithm
COA	Coyote Optimization Algorithm
CTFWO	Chaotic Turbulent Flow of Water-Based Optimization Algorithm
NA	Not Available
IGA	Improved Genetic Algorithm
MODE	Multiobjective Differential Evolution
NSGA	Non dominated Sorting Genetic Algorithm
PDE	Pareto Differential Evolution
SPEA	Strength Pareto Evolutionary Algorithm
GSA	Gravitational Search Algorithm
TLBO	Teaching Learning based Optimization

Table 1. Summary of literature survey

Paper	Year	Algorithm	Contribution	Application
[4]	1994	GA	ED Problem with valve point loading	72 units
[5]	1994	SA	ED Problem with valve point loading and ramping characteristics	13 units
[6]	2008		CEED	
[7]	2016	DE	Combined heat and power economic dispatch also, valve-point loading, and POZ have been considered.	3 units
[8]	2010		Emission constrained economic power dispatch problem	IEEE 30-bus
[9]	2017	MSA	CEED	3 and 6 units
[10]	2020	SMO	CEED	6 units
[11]	2016	GWO	ED process with valve point loading and POZ	10, 40, 80, and 140 units
[12]	2015	FFA	ED process with valve point loading	3, 13 and 40 units
[13]	2014		ED process with valve point loading	IEEE 30-bus
[14]	2018	HSA	ED process with valve point loading	3, 13 and 40 units
[15]	2019		ED process with valve point loading and losses	6, 10, 13, 14, 40, and 140 units
[16]	2014	SOA	CEED and valve point loading	3, 6, and 40 units
[17]	2014	ABC	CEED	IEEE 30-and 40 units
[18]	2017		ED process with valve point loading	6, and 40 units
[19]	2017	BFA	CEED and considering transmission losses	IEEE 30-bus, 6-generator
[20]	2009	PSO	CEED	IEEE 30-bus
[21]	2003	PSO	ED with ramp rate limits, POZ, and non-smooth cost functions are considered	three different systems
[22]	2018	Hill β Climbing	ED with valve point loading	3,13, and 40 units
[23]	2018	MBA	CEED with valve point loading	6, 10, and 13 units
[24]	2016	FPA	CEED with valve point loading	3, 10, and 40 units
[25]	2022	CTFWO	Optimum reactive power dispatch	IEEE 30 and 57-bus
[26]	2023	COA	ED and unit commitment	4, and 10 units

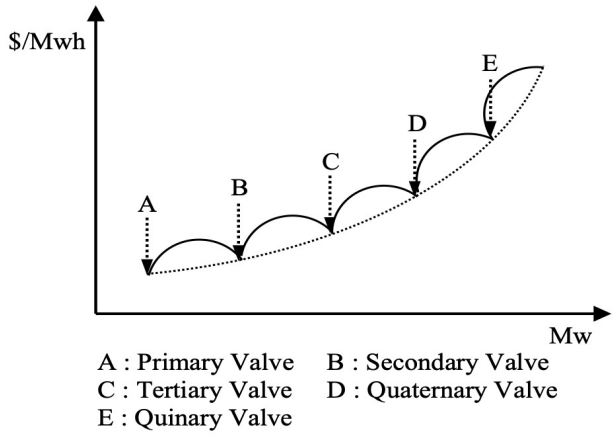

Fig. 1. Valve point effect

Prohibited Operating Zone (POZ) generates a cease in the curve of fuel cost as following[42]:

$$P_i \in \begin{cases} P_{i\,min} \le P_i \le P^l_{i,1} \\ P^u_{i,k-1} \le P_i \le P^l_{i,k} \\ P^u_{i,z_i} \le P_i \le P_{i\,max} \end{cases} \quad (11)$$

$$k = 2, 3, \ldots\ldots\ldots, z_i \text{ and } i = 1, 2, \ldots\ldots\ldots, N$$

Where, $P^u_{i,k}$ and $P^l_{i,k}$ are the upper and lower limits of k_{th} POZ index of $i_t h$ unit, and z_i is the POZ numbering as shown in Fig. 2.

3. THE HARRIS HAWKS APPROACH

In this paper, Harris Hawks Approach (HHA) is employed to solve ED problems. The prime inspiration of HHA is the mutual attitude and chasing sort of Harris' hawks in nature named shock pounce. In this brilliant planning, distinct hawks pounce a victim cooperatively from several ways in an effort to shock it.[27,28]

Harris hawks can expose a set of chasing paradigms based on the dynamic nature of scenarios and escaping styles of the victim. This study simulates mathematically as

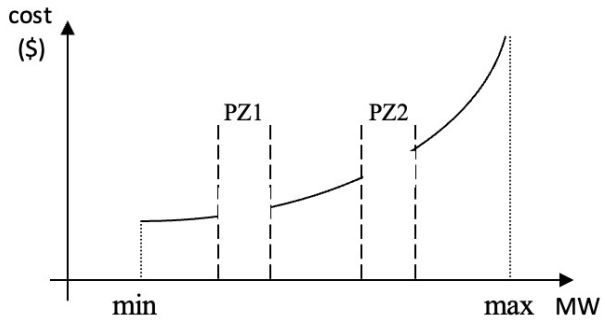

Fig. 2. Cost function with prohibited operating zones



Fig. 3. Harris's hawk and their behaviors.

dynamic styles and behaviors to promote an optimization approach. The comparisons and statistical results illustrate that the HHA gives very hopeful and occasionally competitive results compared with well-settled metaheuristic approaches.The behaviors of these birds can be shown in nature, as shown in Fig. 3.

HHA is a population-based seeking approach, which draws on three prime steps as seen in Figure 4 and are discussed as follows:

3.1. EXPLORATION LEVEL

In this level, it is planned to wait mathematically, seek, and detect the required hunt. The iter + 1 (the Harris hawks location) is mathematically modeled as follows:

$$X(iter+1) = \begin{cases} X_{\text{rand}}(iter) - r_1 \mid X_{rand}(iter) - 2X_r(iter) \\ \quad \ldots\ldots\ldots\ if\ q \geq 0.5 \\ X_{\text{rabit}}(iter) - X_m(iter) - r_3\,(LB + r_4(UB - LB) \\ \quad \ldots\ldots\ldots\ if\ q < 0.5 \end{cases} \tag{12}$$

Where

X_{rabit} shows for the rabbit location, $iter$ stands the local iteration,

X_{rand} is the elected hawk randomly among the obtainable population r_i,

$i = 1, 2, 3, \ldots\ldots, q$ are random numbers varying in [0, 1],

$\mathrm{X_m}$ gives the mean location for hawks and is counted as follows:

$$\mathrm{X_m(iter)} = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} X_i(iter)$$

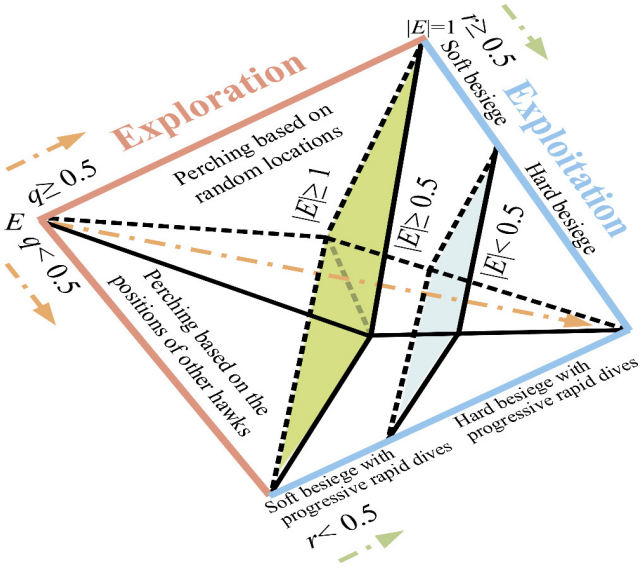

Fig. 4. Different levels of Harris hawks optimization.

which X_i displays the location of the hawks and N introduces the hawk size.

3.2. TRANSITION FROM EXPLORATION TO EXPLOITATION

Considering T as the upper size of the repetitions $\mathrm{E_0} = \varepsilon(-1, 1)$ as the premier energy during every step, HHA counts the escaping energy of rabbit (E) by Eq. (13). Regarding this amount, exploration and exploitation can be varied.

$$\mathrm{E} = 2\mathrm{E_0}\left(1 - \frac{iter}{T}\right) \tag{13}$$

In this sense, $|\mathrm{E}| \geq 1$ the exploration level gets initiated; furthermore, the neighborhood of the resolutions is pointed to be exploited.

3.3. EXPLOITATION LEVEL

Depending on the residual energy of the victim, the hawks can consider a soft or hard besiege for stalking it from diverse ways. A so-named coefficient "r". is defined to size the escaping opportunity of the victim. Accordingly, $r < 0.05$ represents a felicitous escape. Furthermore, when $|\mathrm{E}| \geq 0.5$ HHA makes soft surrounding and when $|\mathrm{E}| < 0.5$ hard surround is implemented. It is precious noting that even if the victim is capable to escape (i.e., $|\mathrm{E}| \geq 0.5$), its success also relies on r. The attack process is affected by the escaping and pursuing way of the victim and hawks' respectively. In this sense, four main steps are investigated which are discussed broadly in.[27,28]

A) SOFT BESIEGE

Rabbit still has adequate vigor when $r \geq 0.5$ and $|\mathrm{E}| \geq 0.5$, by some erratic deceitful jumps rabbit has an endeavor to flee but lastly it cannot. Harris hawks secure easily over these attempts to make the rabbit more worn out, then pro-

ceed with the surprise pounce. This attitude can be modeled by the equations below.

$$X(t+1) = \Delta X(t) - E\,|JX_{rabbit}(t) - X(t)| \quad (14)$$

$$\Delta X(t) = X_{rabbit}(t) - X(t) \quad (15)$$

Where $\Delta X(t)$ shows the dissimilarity among the current location in iteration t, and vector of the rabbit, r_5 is an arbitrary number in $(0,1)$, and $J = 2(1-r_5)$ explains the unsystematic dive power of rabbit all through the busting procedure. J alters in each repetition to grow the activity manner of rabbit.

B) HARD BESIEGE

The sacrifice is worn out and it has a weak escaping might when $r \geq 0.5$ and $|E| < 0.5$ then, the Harris hawks trap the prey to lastly execute the amazement dive. Furthermore, the fresh use of Eq. (16) modernized this status.

$$X(t+1) = X_{rabbit}(t) - E|\Delta X(t)| \quad (16)$$

C) SOFT BESIEGE

With advanced rapid dives, the rabbit has appropriate might to abscond effectively when still $|\mathrm{E}| \geq 0.5\,|$ but $r < 0.5$ and still earlier the amazement dive, a soft besiege is created. This procedure is more intelligent than pretending. In the HHA, the levy flight notion is executed. To fully grow the escaping styles of the prey and the leap frog movement. From the rule in the Eq. (17) it is confirmed that the hawks can administer their subsequent steps to proceed a soft besiege.

$$Y = X_{rabbit}(t) - E\,|JX_{rabbit}(t) - X(t)| \quad (17)$$

They estimate the probable outcome of the preceding jump to comprehend that whether it is good or not. Also, they start to do uneven, abrupt, and brisk dives if it is not logical, when approaching the prey. It is believed that LF-based styles used by following equation:

$$Z = Y + S \times LF(D) \quad (18)$$

The Levy flight function is LF and S is an arbitrary size $1 \times D$ and D is the dimension of the problem. Eq. (17) can execute the positions of hawks in the soft besiege level.

$$X(t+1) = \begin{cases} Y & \text{if } F(Y) < F(X(t)) \\ Z & \text{if } F(Z) < F(X(t)) \end{cases} \quad (19)$$

D) HARD BESIEGE

With progressive rapid dives the rabbit has no appropriate power to get away and hard besiege is done ahead of the astonishment dive to kill the sufferer. When $|\mathrm{E}| < 0.5$ and $R < 0.5$, the circumstances of the victim side are like the soft besiege, but at the time, the busting sufferer lowered the mean distance position of hawks. Accordingly, the hard besiege condition is modeled by (19).

Where Eq. (17) and (18) obtain Y and Z.

4. RESULTS AND DISCUSSION

To explain the applicability of HHA to solve various ED problems, the performance of the HHA are evaluated on the following ED cases:

Case 1. A 6-units for a demand of 1263 MW with a quadratic charge function, POZs and transmission loss.

Case 2. A 13 units with 1800 MW demand.

Case 3. A 40-units for a demand of 10500 MW, and valve effect is involved.

Case 4. A 10 units with 2000 MW, emission, and valve-point effect is considered.

4.1. TEST SYSTEM 1

This is a small network comprising of 6 units with a load demand of 1263MW and involves transmission loss, POZ, and ramp-rate limits. The system data are taken from.[43] Table 2 introduces the optimum generation values and fuel cost obtained by diverse algorithms. The gained optimal cost is 15443.07$/hr. It can be seen that the generation values reach the generation limit constraints and do not fall in the POZs. Table 3 displays the comparison of the statistical results of different algorithms. In this table, the results given by HHA are compared with JAYA,[44] GWO,[45] NGWO,[45] SA,[46] PSO,[46] NPSO,[47] GA,[48] MTS,[49] TS,[49] RDPSO,[50] IRDPSO,[50] ST-IRDPSO,[50] MABC,[51] HCRO-DE,[52] NPSO-LRS,[53] GAAPI,[54] DE,[55] CBA,[56] CLPSO,[57] SLPSO,[57] BLPSO,[57] and HHO.[58]

4.2. TEST SYSTEM 2

The test system has 13 units in this case with the expected net demand of 1800MW. The detailed data of these units is given in.[58] The best solution obtained by running the developed HHA to resolve the ED process is recorded in Table 4. In this table, the net demand of the best solution, mean of the results, and the best results are also mentioned. The results in Table 4 show that the behavior of the developed HHA is better than the performance of NGHS,[14] NPHS,[14] NTHS,[14] NRHS,[14] HHO,[58] HSSA,[59] GWO,[60] QOPO,[60] UHGA,[61] and HGWO[62] with the lowest net demand of (17960.366$/h). Moreover, the best result obtained by the developed HHA (17960.366$/h) is very close to the mean result (17960.64$/h). Also, the developed algorithm is better than the others. This demonstrates that the developed algorithm is proved to be the best algorithm amongst all the approaches.

4.3. TEST CASE 3

This test system consists has 40 units with emission and non-smooth fuel cost functions. Loss parameters and unit data have been found in.[24] Table (5) displays the results of solving CEED for 10500 MW demand using HHA and comparing with NGHS,[14] NPHS,[14] NRHS,[14] NTHS,[14] NGWO,[45] NPSO,[45] IGA,[45] CJAYA,[45] HHO,[58] QPSO,[59] UHGA,[61] and HGWO.[62] The result of the developed approach leads to a lower fuel charge than other approaches as given in Table (5) while reaching the limits of units. Thus, these approaches have stuck in local lower solutions. Moreover, the supremacy of the developed HHA in achieving the global lower charge is noted. Thus, HHA executes better than these approaches in terms of fuel cost even for a large level power network with valve loading effect. Also, Table

Table 2. Results of various algorithms for 6 units

Power(MW)	JAYA[44]	GWO[45]	SA[46]	PSO[46]	NPSO[47]	GA[48]	MTS[49]	HHA
P1(MW)	457.9858	446.6281	478.1258	447.5823	447.4734	462.0444	448.1277	447.3997
P2(MW)	176.8785	171.7686	163.0249	172.8387	173.1012	189.4456	172.8082	173.2392
P3(MW)	250.0717	264.671	261.7146	261.330	262.6804	254.8535	262.5932	263.3163
P4(MW)	129.3748	141.3356	125.7665	138.6812	139.4156	127.4296	136.9605	138.0006
P5(MW)	172.8886	166.5389	153.7056	169.6781	165.3002	151.5388	168.2031	165.4104
P6(MW)	88.4618	85.00	93.7965	85.8963	87.9761	90.715	87.3304	87.0798
Ptotal(MW)	1275.6611	1276.3156	1276.1339	1276.0066	1275.96	1276.027	1276.0232	1275.46
Ploss(MW)	12.6665	13.3099	13.1317	13.0066	12.947	13.0268	13.0205	12.46
Fbest($/h)	15447.09	15450.07	15461.1	15450.14	15450	15457.96	15450.06	15443.07

Table 3. Statistical results of 6 units.

Algorithm	Year	Best	Worst	Mean
JAYA[44]	2018	15477.09	15622.16	15500.11
GWO[45]	2019	15450.07	15487.14	15453.41
NGWO[45]	2019	15449.17	15460.1	15449.86
SA[46]	2004	15461.1	15545.5	15488.98
PSO[46]	2004	15450.14	15491.71	15465.83
NPSO[47]	2007	15450.0	15454.0	15452.0
GA[48]	1999	15457.96	15524.69	15477.71
MTS[49]	2008	15450.06	15453.64	15451.17
TS[49]	2008	15454.89	15472.56	15454.89
RDPSO[50]	2017	15449.89	NA	15458.01
IRDPSO[50]	2017	15449.89	NA	15456.55
ST-IRDPSO[50]	2017	15449.89	NA	15450.7
MABC[51]	2015	15449.8995	15449.8995	15449.8995
HCRO-DE[52]	2014	15443.075	15443.916	15443.327
NPSO-LRS[53]	2007	15450	15454	15452
GAAPI[54]	2012	15449.78	15449.85	15449.81
DE[55]	2015	15449.5826	15449.6508	15449.62
CBA[56]	2016	15450.2381	15454.76	15518.6588
CLPSO[57]	2018	15447.72	15452.88	15449.83
SLPSO[57]	2018	15447.34	15447.62	15447.46
BLPSO[57]	2018	15447.34	15447.67	15447.45
HHO[58]	2022	15499.78	NA	15488.41
Proposed	-	15443.07	15443.3	15443.14

Table 4. Comparison of various algorithms for 13 units.

Power(MW)	NGHS[14]	NPHS[14]	NTHS[14]	NRHS[14]	HHO[58]	HSSA[59]	GWO[60]	QOPO[60]	UHGA[61]	HGWO[62]	**HHA**
P1(MW)	538.5587	628.3185	628.3185	628.3185	628.3185	628.3185	807.1247	628.3183	628.21	628.3185	**628.3185**
P2(MW)	224.4003	224.3982	149.5986	149.5983	149.5971	149.5951	144.869	298.1864	223.94	149.5898	**149.5996**
P3(MW)	150.4400	147.9527	222.7515	222.7526	222.7712	222.7696	297.9434	223.7622	149.3	222.7756	**222.7491**
P4(MW)	109.8668	109.8664	109.8662	109.8662	60.00	60.00	60.00	60.00008	109.71	109.8663	**109.8665**
P5(MW)	109.8668	109.8661	60.0000	109.8662	109.8628	109.8662	60.00	60.00	109.71	60.00	**109.8665**
P6(MW)	109.8667	109.8665	109.8662	109.8658	109.8663	109.8619	60.00	60.00	109.71	109.8660	**109.8665**
P7(MW)	109.8669	60.00	109.8664	109.8659	109.8628	109.8633	60.00	159.7331	109.71	109.8869	**109.8665**
P8(MW)	109.8667	109.8664	109.8665	60.0000	109.8609	109.8659	60.00	60.00	60.00	109.8453	**109.8665**
P9(MW)	109.8666	109.8650	109.866	109.8663	109.8603	109.8595	60.0362	60.00	109.71	109.8516	**60.00**
P10(MW)	77.4005	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	**40.00**
P11(MW)	40.00	40.00	40.00	40.00	40.00	40.00	40.0267	40.00	40.00	40.00	**40.00**
P12(MW)	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	**55.00**
P13(MW)	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00001	55.00	55.00	**55.00**
Ptotal(MW)	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	**1800**
Fmean($/h)	17982.23	17986.51	17987.37	17988.65	17966.37	17970.78	NA	NA	17992.92	17960.63	**17960.64**
Fbest($/h)	17967.19	17960.51	17960.37	17960.38	17960.43	17960.43	18051.11	17988.99	17964.81	17960.38	**17960.366**

(6) illustrates the statistical results of HHA compared with NGHS,[14] NPHS,[14] NTHS,[14] NRHS,[14] HHO,[58] UHGA,[61] GWO,[62] ARCGA,[63] TSAGA,[64] CCPSO,[65] CDE_SQP,[66] EDA/DE,[67] BBO,[68] SOMA,[68] CSOMA,[68] DE/BBO,[69] DHS,[70] EP,[71] EP-SQP,[71] PSO,[71] PSO-SQP,[71] GA-PS SQP,[72] CPSO,[73] CPSO–SQP,[73] NPSO_LRS,[74] APSO,[75] DE,[76] CDEMD,[77] HMAPSO,[78] and FAPSO-NM.[79]

4.4. TEST CASE 4

This case studies 10 units with valve effect. Table 7 displays the results of handling CEED for 2000 MW demand via HHA and comparing with other approaches.[3,40,80,81] The developed HHA yields a smaller cost than FPA, GSA, MODE, NSGA, SPEA, PDE, MOGA and TLBO while achieving the constraints of network. Moreover, its emission is smaller than the others. Thus, HHA succeeds in reaching the global minimum solution. Hence, HHA outlasts others in reducing the net cost.

5. CONCLUSIONS

In this article, HHA has been evolved to handle ED processes in power networks. The execution of the HHA was examined for distinct test cases and compared with the mentioned in fresh literatures. The supremacy of HHA over other approaches for settlement ED and CEED processes even for wide-level power network with POZ, and valve effect is assured. Thus, HHA optimization is a hopeful approach for treating sophisticated tasks. Implementations of the developed algorithm to multi-area power network integrated with renewable sources are the outlook scope of this work.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

Table 5. Comparison of various algorithms for 40 units.

Outputs	NGHS[14]	NPHS[14]	NTHS[14]	NRHS[14]	NPSO[45]	NGWO[45]	IGA[45]	CJAYA[45]	HHO[58]	QPSO[59]	UHGA[61]	HGWO[62]	**HHA**
P1 (MW)	114.00	111.102	110.812	110.801	113.9891	111.3177	110.97	114.00	110.8005	113.7611	110.8056	110.8001	**72.481**
P2 (MW)	113.459	112.107	110.80	110.80	113.6344	112.7551	110.88	111.6651	110.8209	113.9886	110.80	110.8218	**103.0314**
P3 (MW)	97.398	97.402	97.40	97.40	97.55	118.6377	98.17	119.9876	97.4	119.9993	97.4052	97.3934	**83.2726**
P4 (MW)	179.752	179.73	179.733	179.733	180.0059	183.3649	178.85	188.2606	179.7331	189.8949	179.7314	179.7318	**182.3106**
P5 (MW)	96.975	88.668	87.80	87.80	97.00	91.8097	87.78	96.9763	92.5934	97.00	87.8939	92.6135	**76.1669**
P6 (MW)	140.00	140.00	140.001	140.00	140.00	104.3697	140.00	139.9488	140.00	139.9986	140.00	140.00	**126.1346**
P7 (MW)	259.603	259.596	259.60	259.60	300.00	297.6533	260.37	264.0949	259.6006	300	259.6016	259.6065	**258.8452**
P8 (MW)	284.61	284.604	284.60	284.60	300.00	289.4349	286.83	299.9814	284.6025	299.9992	284.6084	284.6012	**297.1636**
P9 (MW)	284.61	284.615	284.60	284.60	284.5797	298.4044	285.14	284.9042	284.6029	299.997	284.6046	284.5997	**290.8899**
P10 (MW)	130.00	130.00	130.00	130.00	130.0517	129.35	204.86	130.0908	130.0008	130.00	130.00	130.00	**274.8232**
P11 (MW)	168.799	94.00	94.00	94.00	243.7131	241.9702	165.98	94.0011	168.7998	94.0001	94.00	168.7992	**356.9806**
P12 (MW)	168.798	168.80	94.00	94.00	169.0104	166.9113	167.75	94.00	168.7998	94.35996	168.8002	168.7930	**124.4054**
P13 (MW)	214.76	214.76	214.76	214.76	125.00	214.849	214.31	125.1028	214.7603	125.1963	214.7600	214.7614	**493.3764**
P14 (MW)	304.52	304.519	394.279	394.279	393.9662	215.669	305.65	394.2529	394.2794	304.5059	304.5239	394.2808	**344.9029**
P15 (MW)	304.519	394.279	394.279	394.279	304.7586	305.6922	393.66	484.1262	304.5202	394.4782	394.2796	394.2809	**372.3864**
P16 (MW)	394.278	394.28	394.279	394.279	304.512	394.6479	394.6	304.595	394.2794	394.2599	394.279	304.5237	**345.4624**
P17 (MW)	489.280	489.28	489.268	489.279	489.6024	494.7618	489.22	490.8265	489.2792	489.331	489.282	489.2802	**422.6378**
P18 (MW)	489.278	489.281	489.279	489.279	489.6087	493.1559	489.25	489.3438	489.2807	489.4125	489.2799	489.2846	**434.4065**
P19 (MW)	511.281	511.277	511.279	511.289	511.7903	512.7416	511.23	511.3775	511.2870	511.2939	511.2804	511.271	**461.3107**
P20 (MW)	511.28	511.281	511.279	511.269	511.2624	520.8929	510.69	512.1395	511.2791	511.4796	511.2803	511.2782	**434.3828**
P21 (MW)	523.284	523.279	523.279	523.279	523.3274	526.1137	524.74	523.6621	523.2793	525.461	523.2789	523.2798	**545.2846**
P22 (MW)	523.276	523.281	523.281	523.282	523.2196	532.1443	525.52	523.3534	523.2794	523.6933	523.2799	523.2807	**490.3572**
P23 (MW)	523.285	523.288	523.279	523.279	523.4707	536.8421	522.98	524.9677	523.2794	526.5896	523.2799	523.2798	**506.0639**
P24 (MW)	523.291	523.281	523.279	523.279	523.0661	524.4669	522.22	524.2850	523.2803	524.3047	523.2832	523.2795	**467.3109**
P25 (MW)	523.279	523.276	523.279	523.279	523.3978	525.2461	523.26	522.9279	523.2801	524.7312	523.2823	523.2811	**488.1203**
P26 (MW)	523.28	523.28	523.279	523.279	523.2897	529.3289	523.32	523.2298	523.2827	523.5606	523.2884	523.2766	**486.9019**
P27 (MW)	10.006	10.001	10.00	10.00	10.0208	9.95	10.00	10.00	10.0007	10.00	10.00	10.00	**16.8002**
P28 (MW)	10.00	10.00	10.00	10.00	10.0927	9.95	10.00	10.0047	10.00	10.22341	10.00	10.00	**39.3475**
P29 (MW)	10.00	10.001	10.00	10.00	10.0621	9.95	10.00	10.00	10.0026	10.08921	10.00	10.00	**23.6359**
P30 (MW)	97.00	94.38	87.80	87.80	88.8456	88.4106	88.86	97.00	87.9154	97.0000	97.00	87.8779	**86.3295**
P31 (MW)	189.998	190.00	190.00	189.999	189.9951	188.9088	162.30	190.00	190.00	190.0000	190.00	190.00	**165.9924**

Outputs	NGHS[14]	NPHS[14]	NTHS[14]	NRHS[14]	NPSO[45]	NGWO[45]	IGA[45]	CJAYA[45]	HHO[58]	QPSO[59]	UHGA[61]	HGWO[62]	**HHA**
P32 (MW)	190.00	190.00	190.00	190.00	190.00	188.8126	177.94	189.9503	190.00	189.9998	190.00	190.00	**174.5707**
P33 (MW)	190.00	190.00	190.00	190.00	190.00	186.9624	160.18	190.0000	190.00	190.00	190.00	190.00	**184.057**
P34 (MW)	164.815	165.068	164.801	164.801	165.9825	195.0897	166.54	169.8860	164.8004	200.00	164.8113	164.8134	**193.6668**
P35 (MW)	200.00	200.00	194.393	194.393	172.4153	171.5047	164.80	199.8549	164.7998	200.00	200.00	164.8051	**191.6152**
P36 (MW)	200.00	200.00	200.00	200.00	191.2978	176.1085	170.68	199.9896	164.7999	199.9999	200.00	164.8105	**196.1763**
P37 (MW)	110.00	110.00	110.00	110.00	109.9893	89.5297	108.17	109.9712	110.00	109.9804	110.00	110.00	**90.0101**
P38 (MW)	110.00	110.00	110.00	110.00	109.9521	89.3589	100.68	109.9977	110.00	110.00	110.00	110.00	**37.5421**
P39 (MW)	110.00	110.00	110.00	110.00	109.8733	109.3222	109.34	109.9871	110.00	110.00	110.00	110.00	**89.4239**
P40 (MW)	511.286	511.282	511.279	511.279	511.5671	512.5412	511.28	511.255	511.2802	511.4108	511.2803	511.2946	**471.4405**
Fuel cost $*10^5$$	**1.2146779**	**1.2142881**	**1.2141273**	**1.214128**	**1.2170473**	**1.2188181**	**1.2191593**	**1.217998**	**1.2141483**	**1.217896**	**1.2142448**	**1.2141509**	**1.210745**

Table 6. Comparison between HHA and various algorithms.

Algorithm	Best cost [$]	Mean cost[$]	Worst cost[$]	Time (Sec)
UHGA[61]	121424.48	121602.81	NA	333.68
NGHS[14]	121467.79	121543.42	NA	NA
NPHS[14]	121428.81	121550.62	NA	NA
NTHS[14]	121412.74	121549.95	NA	NA
NRHS[14]	121412.80	121542.08	NA	NA
HGWO[62]	121412	121419	NA	NA
HHO[58]	121414.83	121468.74	NA	NA
ARCGA[63]	121410.1038	121462.1502	121536.8745	15.67
TSAGA[64]	121463.07	122928.31	124296.54	696.01
CCPSO[65]	121403.5362	121445.3269	121535.4934	19.3
CDE_SQP[66]	121741.979	122295.128	122839.294	14.260
EDA/DE[67]	121412.50	121460.70	121517.8	NA
BBO[68]	121426.6	121508.03	121688.66	NA
SOMA[68]	121418.785	121449.879	121508.376	NA
CSOMA[68]	121414.698	121415.048	121417.804	NA
DE/BBO[69]	121420.890	121420.90	121420.90	60.0
DHS[70]	121403.535	121410.597	121417.227	1.320
EP[71]	122624.35	123382	125740	1167.35
EP-SQP[71]	122323.970	122379.630	NA	997.730
PSO[71]	123930.450	124154.490	NA	933.390
PSO-SQP[71]	122094.67	122245.250	NA	733.970
GA-PS-SQP[72]	121458	122039	NA	46.980
CPSO[73]	121865.2	122100.87	NA	114.650
CPSO–SQP[73]	121458.5	122028.16	NA	98.490
NPSO_LRS[74]	121664.431	122209.318	122981.591	16.810
APSO[75]	121663.522	122153.673	122912.396	5.05
DE[76]	121416.29	121422.72	121431.47	NA
CDEMD[77]	121423.401	121526.733	121696.987	44.30
HMAPSO[78]	121586.90	121586.9	21586.9	NA
FAPSO-NM[79]	121418.30	121418.80	121419.8	40.0
HHA	**121074.50**	**121195.78**	**121396.63**	**0.88**

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Table 7. Results of 10 units for demand of 2000 MW

Power (MW)	FPA[3]	GSA [40]	MODE [80]	NSGA[80]	SPEA[80]	PDE[80]	MOGA [80]	TLBO [81]	**HHA**
P1(MW)	53.188	54.9992	54.9487	51.9515	52.9761	54.9853	54.1807	55	**54.9987**
P2(MW)	79.975	79.9586	74.5821	67.2584	72.813	79.3803	78.4981	80	**77.5591**
P3(MW)	78.105	79.4341	79.4294	73.6879	78.1128	83.9842	84.7653	83.9202	**77.0918**
P4(MW)	97.119	85	80.6875	91.3554	83.6088	86.5942	81.3502	82.8342	**77.2572**
P5(MW)	152.74	142.106	136.855	134.052	137.243	144.439	138.0526	132.013	**160**
P6(MW)	163.08	166.567	172.639	174.95	172.919	165.776	166.2667	173.988	**240**
P7(MW)	258.61	292.875	283.823	289.435	287.202	283.212	295.466	299.71	**274.3019**
P8(MW)	302.22	313.239	316.341	314.056	326.402	312.771	326.7642	317.968	**276.8507**
P9(MW)	433.21	441.178	448.592	455.698	448.881	440.114	428.9338	427.017	**380.9511**
P10(MW)	466.07	428.631	436.429	431.805	423.903	432.678	429.6309	431.396	**381.7419**
Fbest($/h)	113370	113490	113480	113540	113520	113510	113422.34	113471	**111892.4**
Emission	3997.7	4111.4	4124.9	4130.2	4109.1	4111.4	4120.5204	4113.5	**3653.343**

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