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Economic/Environmental Dispatch Optimization using an Improved ABC Algorithm

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Abstract

This paper presents an improved artificial bee colony (ABC) based technique for solving the dynamic economic emission dispatch (DEED) problem. Ramp rate limits (RRL), valve-point loading effects (VPLE) and prohibited operating zones (POZs) have been considered. The proposed technique integrates Cauchy operator and the grenade explosion method in the original ABC approach to avoid the random search mechanism. However, the DEED is a multiobjective optimization problem with two conflicting criteria which need to be minimized simultaneously. Thus, it is recommended to provide the best solution obtained by decision-makers. A Shannon's entropy based-method is used for the first time within the context of the on-line planning of generator outputs to extract the better solution compromise among the Pareto set. The robustness of the proposed technique is verified on 10-unit system test with POZs. Simulation Results proved that the proposed algorithm gives better optimum solutions in comparison with other meta-heuristic techniques.

Keywords- Artificial bee colony; Dynamic dispatch; Prohibited operating zones; Shannon's entropy; Cauchy operator; Valve-point loading effects.

1. INTRODUCTION

Along with economic dispatch, the allocation of emissions has become a key issue under several conditions. It consists to minimize CO, CO2, NOx and SO2 [1 - 2]. However, due to the dynamic nature of the today network loads, it's required to schedule the thermal unit outputs power in real time according to the variation of demand power during a certain time period [3]. To solve this modified EED problem known as dynamic economic emission dispatch (DEED), several mathematical formulations have been suggested in the literature [3 - 8]. In the most references, the DEED dispatch is taken in consideration as dynamic problem of optimization having the same objectives as static optimization problem EED over a time period of one day, subdivided on definite intervals time of one hour with respecting the constraints imposed by generator ramp-rate limits (RRL) [3]. Therefore, at an hour, the operational decision may be influenced by that taken at a previous hour.

Other constraints such as prohibited operating zones (POZ) and valve-point loading effects (VPLE) have been considered in some few works [10 - 12]. However, incorporating VPLE in the fuel cost function makes it with ripples and the problem will be with multiple minima. On the other hand, POZ constraints due to physical operation limitation such as vibrations in the shaft bearing [13 - 14] create discontinuities in the objective functions. Therefore, the DEED problem becomes highly nonlinear with non-convex and discontinuous fitness functions.

A considerable amount of research works has been suggested for solving this kind of problems. Classical methods like DP [15], LP [16], LI [17 and interior point [18] methods have been used to solve the static EED. However, several criticisms have been addressed to these techniques as they are iterative and require an initialization step. That can cause the convergence property for the search process into optimum local. Moreover, they may fail to solve the dynamic case including above constraints.

Currently, metaheuristics search algorithms are classified on different groups in terms on methodology of optimization, view the high efficiency and good performance in solving complex optimization problems. Swarm intelligence based in EA were assumed that they are the most used algorithms.

Among metaheuristic-based optimization techniques, genetic algorithm [3 - 19], PSO [11], SA [20 - 21], artificial bee colony (ABC) [14], tabu search [22], DE [6] and bacterial foraging [7] have been suggested for solving the EED problem.

Traditional algorithms, they are criticized in later works [23]. Whereas their efficiencies are sensitive to the form of problem constraints and the number of units.

Most of above research works presented in the literature have concentrated only about static EED problem except a few of them, where the DEED multi-objective problem is taken into consideration. In addition, RRL and POZ constraints were not considered during transition from the last hour of the current day to the first hour of the next day.

Recently, ABC algorithms have attracted much attention for EED problem [14]. ABC algorithm introduced in [24] simulates research behavior, based on population like GA and PSO. This algorithm is easy to execute, but it has a low rate of convergence [23]. Thus, many improved techniques have been proposed to further enhance the ABC performance [23, 25].

Grenade explosion method (GEM) [26] is incorporated in order to increase ABC's exploitation ability. The GEM is an optimization method used by Ahrary [27] in 2010. The effectiveness of this modified version of ABC symbolized by GABC is verified on a set of standard reference functions.

In [23], the Cauchy operator is embedded into the scout bees' phase of the ABC for increasing the exploration ability, and symbolized by GCABC. Thus, a new method exploiting the advantages of GEM and Cauchy operator has been used in this study, to solve the DEED problem with respect to the all above constraints. This optimization symbolized by GCABC integrates the GEM and Cauchy operator into the ABC technique. On the other hand, new decision making method based on Shannon's entropy, called extended entropy-weighted reference (EEWR) approach, is developed and incorporated in the GCABC algorithm to select the suitable solution among all non-dominated solution provided by the optimization algorithm. Unlike other techniques such as those based on graph theory [27], Z-transformation [28] and fuzzy sets [1], the EEWR is characterized by uncomplicated mathematics [30].

The main contributions of this work are summarized as follows:

- A new optimization technique called GCABC for scheduling power production of thermal units according to the expected load variations is proposed. To the best of our knowledge, this article is the first attempt to solve the EED problem using the GCABC algorithm. In addition, a new EEWR-based technique is proposed for the decision making. This technique has not been used in any field of power systems.
- All above constraints were considered simultaneously in the DEED problem.
- The RRL constraints have been taken into account during transition from the last hour of the one day to the first hour of the next day.

The rest of this paper lies in six sections. In section two, a mathematical formulation of the DEED problem is presented. Section three illustrates an overview for original ABC approach. The proposed optimization algorithm is described in section four. Section five presents the extended entropy-weighted reference approach. Section six is devoted to the validation of the proposed algorithm. The last section is consecrated to the conclusion. Problem Formulation

2. MATERIALS AND METHODS

Problem Formulation

In the literature, the DEED problem was considered as multi-objective optimization problem (MOP). It aims to minimize simultaneously the total emission and total fuel cost function by finding the power production of thermal plants according to the predicted power of load demands. The resolution of the DEED problem can be accomplished by solving the static EED (SEED) problem over a certain period of time. In this study, DEED problem objectives and constraints are described as below.

Objective Functions

Thermal units with multi-steam admission valves that work sequentially to cover ever-increasing generation, make the total fuel cost with higher order nonlinearity due to the VPLE, as illustrated in Figure 1. Unfortunately, neglecting the VPLE that is required when using classical methods, causes some inaccuracy in the solution of the DEED problem. Taking into account the VPLE constraints, a sinusoidal form will be taken on total non-smooth cost function expressed in ($/h), as given in equation (1). The second objective corresponding to the total emission in (ton/h) is described by equation (2).

$$C_T = \sum_{t=1}^{T}\sum_{i=1}^{N} a_i + b_i P_i^t + c_i \left(P_i^t\right)^2 + \left| d_i \sin\left\{ e_i \left(P_i^{\min} - P_i^t\right)\right\}\right| \quad (1)$$

$$E_T = \sum_{t=1}^{T}\sum_{i=1}^{N} \alpha_i + \beta_i P_i^t + \gamma_i \left(P_i^t\right)^2 + \eta_i \exp\left(\lambda_i P_i^t\right) \quad (2)$$

Where,

a_i, b_i, c_i, d_i and e_i are the cost coefficients of the *i*-th unit.

While, α_i, β_i, γ_i, η_i and λ_i are the emission coefficients.

P_i^t is the output power in MW at the *t*-th interval. T is the hours number. In our work, $T = 24$.

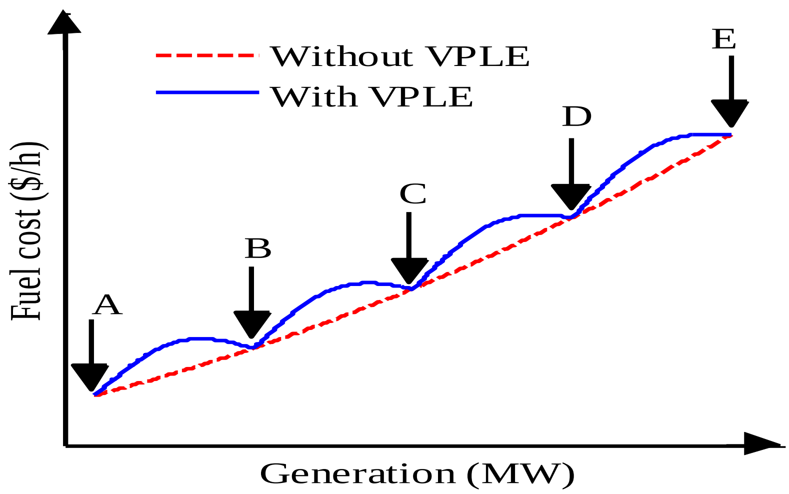

Figure 1. Fuel Cost Function with Five Valves (A, B, C, D, E)

The bi-objective DEED problem can be converted into mono-objective optimization problem [30]. The price penalty factor (PPF)-based approach is used. Equation (3) represents combined economic-emission objective function FT:

$$F_T = \mu C_T + (1-\mu)\lambda E_T \tag{3}$$

Where, $\mu = rand(0,1)$. As shown in equation (4), the PPF of the i-th unit is the ratio between its fuel cost and its emission for maximum generation capacity.

$$PPF_i = \frac{C_{i_{\max}}}{E_{i_{\max}}} \tag{4}$$

Problem Constraints

The DEED problem will be solved by minimizing the function FT defined by equation (3) with respect to the following constraints.

- Generation capacity

Due to the unit design, the real power output of each unit *i* should be within its minimum limit $P_i^{\min}$ and maximum limit $P_i^{\max}$.

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

- Power balance constraints

Each time period *t*, the full power production must cover the full power of demand P_D^t plus the total power transmission line losses P_L^t. Thus, the power balance constraints can be described by the following equation.

$$\sum_{i=1}^{N} P_i^t - P_D^t - P_L^t = 0,\ t = 1,\ldots,T \tag{6}$$

Where P_L^t can be calculated using constant loss formula [31], as given below.

$$P_L^t = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i^t B_{ij} P_j^t + \sum_{i=1}^{N} B_{oi} P_i^t + B_{oo} \tag{7}$$

Where, B_{ij}, B_{oi}, B_{oo} are the loss parameters also called *B*-coefficients.

- Generating unit RRL

In practice, the power generation of each unit *i* during two consecutive time periods is confronted by its RRLs defined by equations (8) and (9).

$$P_i^{t-1} - P_i^t \le R_i^{down} \tag{8}$$

$$P_i^t - P_i^{t-1} \le R_i^{up} \tag{9}$$

Where, P_i^{t-1} is the previous output real power of the i-th machine. R_i^{down} and R_i^{up} are the down-ramp and up-ramp limits of the of the i-th unit in (MW/time period).

As one of contributions of this study, two constraints have been embedded in the problem formulation and they are described by equations (10) and (11).

$$P_i^{24} - P_i^1 \le R_i^{down} \tag{10}$$

$$P_i^1 - P_i^{24} \le R_i^{up} \tag{11}$$

- POZ constraints

The POZ constraints are described as follows.

$$P_i^t \in \begin{cases} P_i^{\min} \le P_i^t \le P_{i,1}^{down} \\ P_{i,k-1}^{up} \le P_i^t \le P_{i,k}^{down} & ,k = 2,\ldots,z_i \\ P_{i,z_i}^{up} \le P_i^t \le P_i^{\max} \end{cases} \tag{12}$$

Where, $P_{i,k}^{down}$ and $P_{i,k}^{up}$ are down and up bounds of POZ number *k*. z_i is the number of POZ for the *i*-th unit [26]. Figure 2 shows the fuel cost function for a typical thermal unit with POZ constraints.

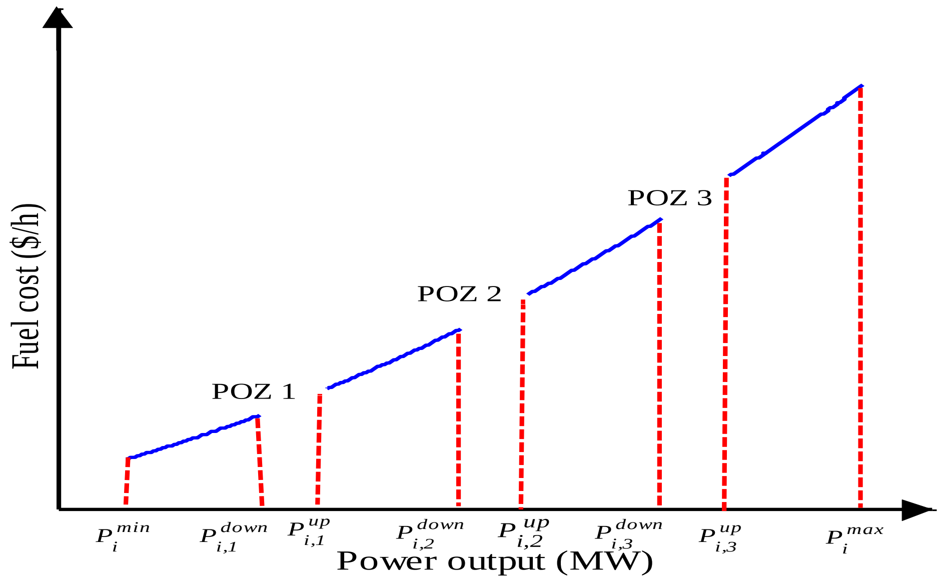

Figure 2. Cost function for a thermal unit with POZ constraints

By considering generation capacity, RRL and POZ constraints, the minimum and maximum limits of the power generation P_i^t of the *i*-th unit for the period *t* will be modified as below.

$$P_i^t \in \begin{cases} \max\left(P_i^{\min}, P_i^{t-1} - R_i^{down}\right) \le P_i^t \le \min\left(P_i^{\max}, P_i^{t-1} + R_i^{up}, P_{i,1}^{down}\right) \\ \max\left(P_i^{\min}, P_i^{t-1} - R_i^{down}, P_{i,k-1}^{up}\right) \le P_i^t \le \min\left(P_i^{\max}, P_i^{t-1} + R_i^{up}, P_{i,k}^{down}\right) \quad, k = 2,..., z_i \\ \max\left(P_i^{\min}, P_i^{t-1} - R_i^{down}, P_{i,z_i}^{up}\right) \le P_i^t \le \min\left(P_i^{\max}, P_i^{t-1} + R_i^{up}\right) \end{cases} \tag{13}$$

3. ORIGINAL ABC APPROACH OVERVIEW

In reference [24], ABC approach has been detailed. It is starting by random generated an initial population of *SN* solutions.

The equation (14), give the expression of fitness function evaluated at the solution X^i:

$$fit\left(X^i\right) = \begin{cases} \dfrac{1}{1+f\left(X^i\right)}, & f\left(X^i\right) \ge 0 \\ 1+\left|f\left(X^i\right)\right|, & f\left(X^i\right) < 0 \end{cases} \tag{14}$$

Where $f\left(X^i\right)$: objective function estimated at X^i.

The candidate solution X^i is chosen by the probability P_i expressed as follows.

$$p_i = \frac{fit\left(X^i\right)}{\sum_{n=1}^{SN} fit\left(X^n\right)} \tag{15}$$

The new solution V^i is generated by modifying only one parameter x_j^i of X^i as follows.

$$v_j^i = x_j^i + \varphi_j^i\left(x_j^i - x_j^k\right) \tag{16}$$

Where, indices k and j are chosen randomly respectively from $\{1,2,...,SN\}$ and $\{1,2,...,D\}$. The new solution randomly according to the following equation.

$$x_j^i = X_j^{\min} + rand(0,1)\left(X_j^{\max} - X_j^{\min}\right) \tag{17}$$

Where, $X_j^{\max}$ and $X_j^{\min}$ are bounds of the food source in dimension *j*.

4. PROPOSED OPTIMIZATION ALGORITHM

The classical ABC technique is improved to enhance its exploitation and exploration abilities. In references [25 - 26], the ABC algorithm has been criticized for the random selected for the j-the dimension. These pieces are thrown in all the dimensions t of the explosion. Equation (18) gives the old food source considered. The optimal search dimension (OSD) given by equation (19), when a new food sources is proposed.

$$v_t^i = x_t^i + \varphi_t^i\left(x_t^i - x_t^k\right) \tag{18}$$

Where, $k \in \{1,2,...,SN\}$: randomly chosen index , $k \ne i$ and $t \in \{1,2,...,D\}$. $\varphi_t^i \in [0,1]$: random number.

$$fit\left(V_{OSD}^i\right) = \max\left\{ fit\left(V_t^i\right) \mid t = 1,2,...,D\right\} \tag{19}$$

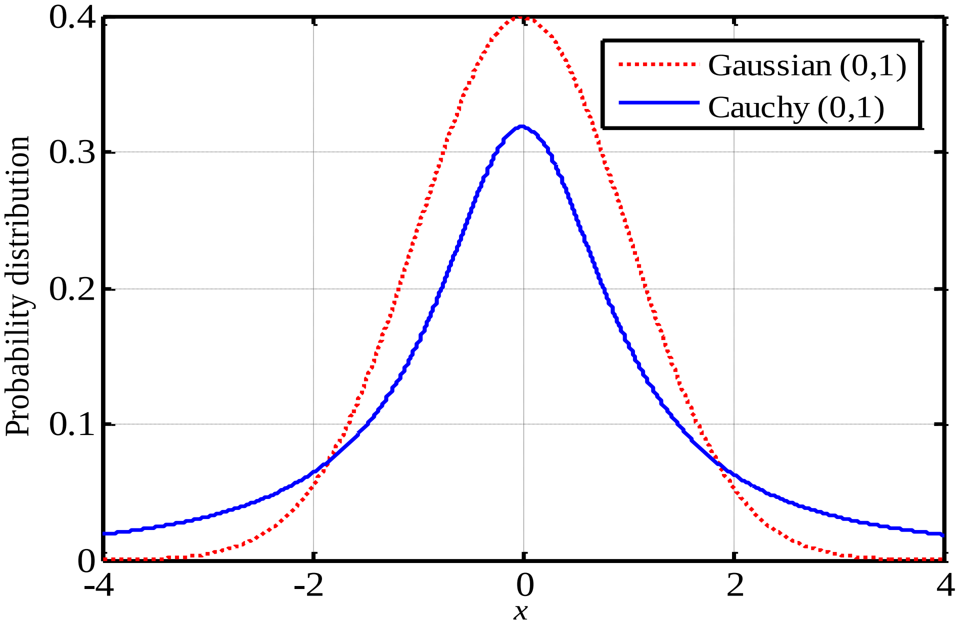

Figure 3. Standard Cauchy and Gaussian distributions

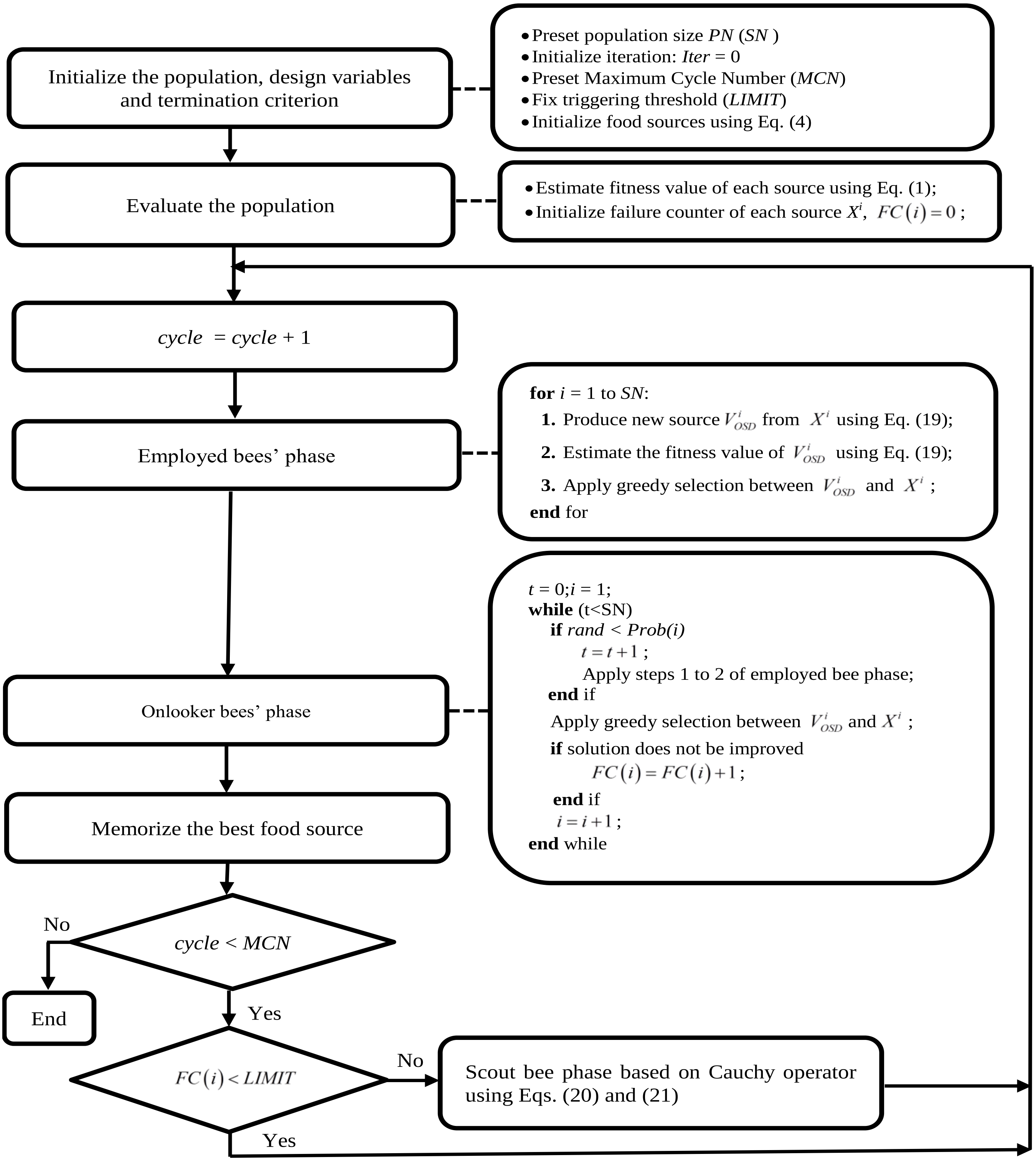

Figure 4. Flowchart of the GCABC algorithm.

A greedy selection between the new solution V^i and the old one X^i is applied [32]. The standard Gaussian function given in Figure 3. In this study, the new solution provided X^i will be obtained using equation (20) instead equation (17).

$$x_j^i = x_j^i CAUCHY(0,1) \tag{20}$$

Where,

$$CAUCHY(0,1) = \frac{1}{\pi\left(1+(x_j^i)^2\right)} \tag{21}$$

Figure 4 presents the flowchart of the modified ABC approach.

5. EXTENDED ENTROPY-WEIGHTED REFERENCE APPROACH

The bi-objective optimization DEED problem with contradictory functions. Pareto front is used in Results of simulations. Then, a decision makers (DM) is a required.

In this study, a Shannon's entropy-based multi-attribute decision-making (MADM) method is proposed to rank the obtained non-dominated solutions. The concept of Shannon's entropy is used in several scientific domains such as for materials selection [33] and single-sensor fault location [34]. This concept can be adopted for MOPs with n objective functions and m non-dominated solutions as follows.

Step 1: Construct the decision matrix $X = \left(x_{ij}\right)_{m\times n}$. Where x_{ij} called performance index.

Step 2: Normalize matrix *X* in order to have performance indices comparable and dimensionless [33].

$$x_{ij}^{*} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}^{2}} \tag{22}$$

Step 3: Calculate entropy h_j as follows.

$$E_j = -E_0 \sum_{i=1}^{m} x_{ij}^{*} \ln x_{ij}^{*},\; j = 1,...,n \tag{23}$$

Where, $E_0 = \dfrac{1}{\ln(m)}$ and $\ln x_{ij}^{*}$ is considered 0 for $x_{ij}^{*} = 0$.

Step 4: Compute the weight of each objective *j*.

$$w_j = \frac{1-E_j}{\sum_{j=1}^{n}\left(1-E_j\right)} \tag{24}$$

On the other hand, the decision maker can assign a degree of importance s_j for each objective function j called subjective weight. Thus, weights should be modified as follows.

$$w_j^{*} = \frac{s_j w_j}{\sum_{j=1}^{n} s_j w_j} \tag{25}$$

Step 5: Determine the i-th co-ordinate reference point (CRP) per objective function. It is defined as the highest performance index for maximization and the lowest performance for minimization [34]. However, the DEED is minimization problem. Thus, the CRP can be found as follows.

$$r_j = \min_{i} x_{ij}^{*} \tag{26}$$

Step 6: Calculate the deviation of each performance index from the CRP for each objective function. Then, determine the maximum deviation for each alternative respecting all objective functions using the following equation. Each non-dominated solution is considered as alternative.

$$z_i = \max_{j}\left|w_j^{*} r_j - w_j^{*} x_{ij}^{*}\right| \tag{27}$$

Step 7: Classify all alternatives according their maximum deviations. Then, select the alternative with rank one as the optimal alternative.

6. RESULTS AND DISCUSSION

Having been applied for the first time to solve one of the main power system problems which is the DEED problem, the GCABC will be tested in this section on three well-known benchmark power systems. In order to demonstrate the effectiveness of the proposed optimization technique, a comparison with ABC algorithm and more than ten metaheuristic-based techniques used for solving the power dispatch problem is presented. DEED problem for a ten-unit system with POZs has been considered. To compared, GCABC and ABC methods have been implemented with same parameters. Results have been obtained using MATLAB R2009a installed on a PC with i7-4510U CPU @ 2.60 GHz, 64 bit.

In this case, the ten-unit system is used to prove the feasibility of GCABC for solving the DEED problem including all operating constraints such as VPLE, RRL and POZ constraints. Thus, the problem becomes with high nonlinearity and more complicated. The B-loss matrix of the ten-unit system is given below.

$$B = 10^{-4}\begin{bmatrix} 0.49 & 0.14 & 0.15 & 0.15 & 0.16 & 0.17 & 0.17 & 0.18 & 0.19 & 0.20 \\ 0.14 & 0.45 & 0.16 & 0.16 & 0.17 & 0.15 & 0.15 & 0.16 & 0.18 & 0.18 \\ 0.15 & 0.16 & 0.39 & 0.10 & 0.12 & 0.12 & 0.14 & 0.14 & 0.16 & 0.16 \\ 0.15 & 0.16 & 0.10 & 0.40 & 0.14 & 0.10 & 0.11 & 0.12 & 0.14 & 0.15 \\ 0.16 & 0.17 & 0.12 & 0.14 & 0.35 & 0.11 & 0.13 & 0.13 & 0.15 & 0.16 \\ 0.17 & 0.15 & 0.12 & 0.10 & 0.11 & 0.36 & 0.12 & 0.12 & 0.14 & 0.15 \\ 0.17 & 0.15 & 0.14 & 0.11 & 0.13 & 0.12 & 0.38 & 0.16 & 0.16 & 0.18 \\ 0.18 & 0.16 & 0.14 & 0.12 & 0.13 & 0.12 & 0.16 & 0.40 & 0.15 & 0.16 \\ 0.19 & 0.18 & 0.16 & 0.14 & 0.15 & 0.14 & 0.16 & 0.15 & 0.42 & 0.19 \\ 0.20 & 0.18 & 0.16 & 0.15 & 0.16 & 0.15 & 0.18 & 0.16 & 0.19 & 0.44 \end{bmatrix} \tag{28}$$

Total cost and emission functions will be minimized individually and simultaneously according to the variation of the power demand P_D^t in MW over a time period of one day, subdivided on 24 intervals time of one hour. Unit data are taken from [3]. Results obtained using GCABC will be compared with other methods used recently in this field such as IBFA [30] and NSGAII [31]. Generation schedule in MW using GCABC algorithm for minimum emission, minimum cost and better compromise solution with POZ constraints are depicted respectively in Tables 1 to 3. In addition, it can be seen that when total cost in $/h is minimized, the total emission in ton/h is at its maximum value and vice versa.

The comparison results shown in Table 4 confirm that the proposed GCABC outperforms other recently optimization techniques in providing the optimum generation schedule for the DEED problem.

Table 1. Best cost solution of DEED for ten-unit system with POZs

Hour	P_D^t	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	1036	165.1722	135.0000	74.9911	60.0000	217.7918	123.0594	130.0000	120.0000	20.0000	10.0000
2	1110	167.6946	135.0000	73.0000	60.0000	225.5290	160.0000	130.0000	120.0000	50.0000	11.6151
3	1258	165.1467	135.0000	130.7068	109.4423	222.2158	159.6540	129.8626	119.9272	79.8127	34.9853
4	1406	166.1955	135.0000	204.6526	158.5269	243.0000	159.3404	129.9671	119.9999	80.0000	45.0290
5	1480	165.3037	135.0000	284.6526	180.6623	223.2852	159.0436	126.9919	119.2148	79.0341	46.5121
6	1628	165.0421	197.1578	300.0000	230.5442	242.0280	159.3173	129.9755	119.9726	79.7804	52.6939
7	1702	168.3524	218.3787	300.0000	280.5442	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
8	1776	223.7119	236.8584	300.0000	300.0000	243.0000	160.0000	128.3324	120.0000	74.9990	47.9167
9	1924	254.8130	312.0045	340.0000	300.0000	243.0000	160.0000	129.7417	120.0000	80.0000	55.0000
10	2022	281.6090	392.0045	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
11	2106	299.5729	466.5255	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
12	2150	344.5307	470.0000	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
13	2072	331.6120	396.8097	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
14	1924	251.6284	316.8097	340.0000	300.0000	242.3627	159.9721	129.6446	119.9888	79.9273	54.2544
15	1776	171.6509	236.8097	340.0000	300.0000	242.2374	159.9811	130.0000	119.9771	79.9411	53.8399
16	1554	165.5076	156.8097	306.4683	264.4758	219.6782	130.8916	130.0000	120.0000	55.0000	49.2722
17	1480	169.0883	135.0000	254.3244	214.4758	243.0000	160.0000	130.0000	112.0475	55.0000	46.6240
18	1628	165.6371	178.7215	310.0000	264.4758	242.8573	159.5210	129.4395	119.7081	53.4817	52.5369
19	1776	226.6454	235.2243	310.0000	300.0000	243.0000	160.0000	130.0000	120.0000	55.0000	55.0000
20	1972	303.6464	315.2243	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
21	1924	257.0288	309.5224	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
22	1628	177.2024	229.5228	287.8057	252.4559	222.4773	159.9822	129.8984	119.9953	52.1639	45.3427
23	1332	169.2690	149.5228	207.8057	202.4559	181.1936	147.9671	130.0000	120.0000	22.1639	33.6897
24	1184	165.0205	135.0000	154.9911	110.0000	231.1936	133.3121	130.0000	120.0000	20.0000	10.0000
Total cost ($)						2484750.6					
Total emission (ton)						329806.1					
Total losses (MW)						1294.63					

Table 2. Best emission solution of DEED for ten-unit system with POZs.

Hour	P_D^t	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**
1	1036	165.1973	135.5474	88.2981	85.5534	125.9366	134.0340	94.6226	91.6778	80.0000	55.0000
2	1110	165.3964	136.3397	96.6585	93.7655	140.9384	142.0490	104.4831	118.2801	79.8072	54.9385
3	1258	173.7384	161.4627	117.8362	118.1307	171.4666	160.0000	129.6612	119.7145	80.0000	55.0000
4	1406	201.8915	200.5469	144.4983	144.0740	206.8471	159.9450	129.8995	120.0000	79.9476	55.0000
5	1480	218.7299	218.6176	158.6131	159.7492	220.2930	160.0000	129.9589	119.9015	80.0000	55.0000
6	1628	256.6836	252.4014	190.6077	190.5288	243.0000	159.9955	129.9249	119.9618	80.0000	55.0000
7	1702	272.7968	274.3721	212.4622	209.6487	242.9502	160.0000	129.9697	119.9577	79.9904	54.9711
8	1776	294.8214	292.9359	228.0325	232.9494	242.7303	160.0000	130.0000	120.0000	80.0000	55.0000
9	1924	310.9404	305.3055	308.0325	282.9494	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
10	2022	348.6140	349.1063	316.2626	299.9912	243.0000	160.0000	130.0000	119.9743	79.9883	54.9963
11	2106	376.3353	389.5405	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
12	2150	406.4744	408.1671	340.0000	300.0000	243.0000	159.8472	130.0000	120.0000	80.0000	55.0000
13	2072	364.0815	365.0862	339.2999	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
14	1924	323.6511	329.6909	277.5422	277.0345	243.0000	160.0000	129.9013	119.9812	79.9687	55.0000
15	1776	292.7577	294.6125	230.8673	230.3903	242.8318	160.0000	130.0000	120.0000	80.0000	55.0000
16	1554	238.9812	239.7960	177.4273	180.3903	243.0000	159.8499	129.9341	120.0000	55.0000	55.0000
17	1480	223.2398	225.6792	162.3366	164.0039	226.1877	159.9309	129.6733	119.8937	55.0000	55.0000
18	1628	261.0968	261.2505	197.2309	195.7729	242.8841	159.9919	130.0000	120.0000	55.0000	54.9945
19	1776	299.1301	299.6726	237.7574	237.0560	242.9911	160.0000	129.9957	119.9963	55.0000	55.0000
20	1972	337.6117	337.3574	297.6844	287.0560	243.0000	160.0000	130.0000	119.9994	80.0000	54.9990
21	1924	323.8381	328.6764	274.1292	281.1486	243.0000	160.0000	130.0000	120.0000	79.9626	55.0000
22	1628	244.0025	250.1234	194.1392	231.1486	213.6108	160.0000	129.7954	120.0000	80.0000	55.0000
23	1332	175.3112	170.4698	120.1466	181.1486	172.4936	160.0000	129.8356	120.0000	80.0000	55.0000
24	1184	166.4041	153.1720	100.5170	131.1486	151.6960	149.4570	120.9247	101.3411	80.0000	55.0000
Total cost ($)						2593541.4					
Total emission (ton)						293651.3					
Total losses (MW)						1315.45					

Table 3. Best compromise solution of DEED for ten-unit system with POZs.

Hour	P_D^t	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
1	1036	165.2652	135.0000	81.3867	99.3317	129.5071	122.7783	93.2248	120.0000	63.0413	46.2773
2	1110	165.0583	135.6716	81.9721	115.0534	172.7545	122.6671	93.3115	119.3316	79.1533	47.6930
3	1258	165.2240	135.0142	140.8731	123.1665	186.0199	159.8130	123.2239	120.0000	78.7596	54.6022
4	1406	171.1921	157.7587	175.8106	169.6648	223.2948	159.6843	129.9203	120.0000	80.0000	54.5440
5	1480	166.9725	202.4911	186.5923	180.6429	241.1341	158.7487	129.8949	119.9471	79.0164	54.6309
6	1628	225.4215	222.5711	213.6715	228.2530	242.6621	159.9878	129.8467	120.0000	79.8508	55.0000
7	1702	227.0550	229.5311	270.5051	241.2863	242.7695	160.0000	129.9926	120.0000	79.8466	54.9499
8	1776	238.4353	285.7945	271.9418	251.8366	242.7378	159.9548	129.9989	119.9550	79.9813	54.8954
9	1924	310.6733	268.2763	328.1483	300.0000	243.0000	160.0000	130.0000	119.7051	80.0000	55.0000
10	2022	333.2844	348.2763	332.1050	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
11	2106	370.0101	395.8515	340.0000	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
12	2150	379.8183	434.6320	339.9988	300.0000	243.0000	159.9996	129.9898	120.0000	80.0000	54.9974
13	2072	346.7647	381.6563	339.9993	300.0000	242.9996	160.0000	130.0000	119.9996	80.0000	55.0000
14	1924	301.5018	309.3229	297.5694	299.1253	242.7888	159.9693	130.0000	119.8599	79.9724	55.0000
15	1776	226.5174	281.1815	280.4419	259.4422	242.9823	159.9822	130.0000	119.9019	79.8971	54.9842
16	1554	166.2949	220.8815	207.6120	241.2538	242.7329	159.8839	129.7025	119.9068	55.0000	54.9975
17	1480	165.7953	218.9567	186.1916	191.2538	238.5098	160.0000	129.6792	120.0000	54.7836	55.0000
18	1628	221.3204	185.1205	266.1916	241.2538	243.0000	160.0000	130.0000	120.0000	55.0000	55.0000
19	1776	230.2074	265.1205	285.6013	291.2538	243.0000	160.0000	130.0000	120.0000	55.0000	55.0000
20	1972	302.8445	330.4365	325.7604	300.0000	243.0000	160.0000	130.0000	120.0000	80.0000	55.0000
21	1924	300.4512	308.9562	298.1015	300.0000	243.0000	159.9233	129.9537	119.8344	79.8688	55.0000
22	1628	220.5563	228.9562	218.2020	250.1006	222.0327	158.8343	129.3097	119.5980	80.0000	49.6611
23	1332	165.6431	149.4620	148.3914	200.1006	172.0327	157.8073	129.4965	114.9818	80.0000	46.1548
24	1184	165.0766	135.0000	88.5262	149.3317	170.0795	127.0480	122.3975	119.7664	78.6989	53.6795
Total cost ($)						2523862.9					
Total emission (ton)						300963.6					
Total losses (MW)						1301.03					

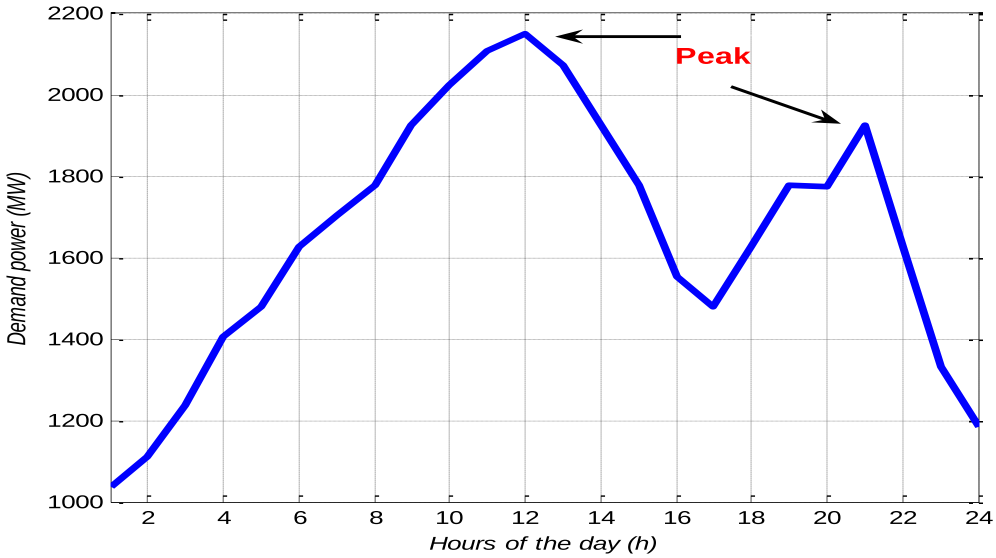

Figure 5. Hourly demand.

Figure 5 represents the daily power demand curve of the proposed case study and demonstrates that the 17th hour is the valley and the 12th and 20th hours are the peak hours in this test system.

Table 4. Comparison with other meta-heuristic techniques (for the ten-unit system).

	Minimum total cost ($/h)		**Minimum total emission (ton/h)**	
Method	Without POZs	With POZs	Without POZs	With POZs
GCABC	2474472.8	2484750.6	293416.3	293651.3
IBFA	2481733.3	NA	295833.0	NA
NSGAII	2.5168x106	NA	3.1740x105	NA

7. CONCLUSION

DEED is a tricky optimization problem in electrical power system. The quality of its optimal solution is influenced by the operating constraints, such as valve-point loading effects, prohibited operating zones and ramp rate limits (RRLs). Within this context, this study presented a new artificial bee colony (ABC)-based technique for solving the DEED problem. All above constraints were considered. Moreover, power balance constraint was considered. Unlike previous works, the RRLs have been embedded in the solution procedure during transition from one day to the next. The proposed optimization technique incorporates Cauchy operator and the grenade explosion method in the classical ABC approach to avoid the random search in the different ABC phases. To provide adequate compromise solution for the decision makers, an approach based on extended entropy-weighted reference was proposed. The validation of the proposed optimization algorithm was verified on ten-unit system test with POZs. Comparison results with more than ten metaheuristic techniques used recently in the literature show that the used approach gives the best optimum solutions.

Due to the aforementioned reasons, some countries of the world are directed towards the use of renewable energy sources (RESs). In such future work, the proposed optimization technique will be used to solve the stochastic DEED problem integrated RESs.

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