International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 5 (2018) pp. 3083-3092

Combined Economic Emission Dispatch for Microgrid Considering Solar and Wind Power Cost Functions Using Harmony Search Algorithm

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Abstract

The Energy Management System (EMS) in microgrids includes the problem of economic dispatch (ED) and environmental economic dispatch which called combined economic emission dispatch (CEED). In this paper, the harmony search (HS) algorithm is employed to solve the environmental economic dispatch problem for the microgrid considering the cost functions of wind power, solar power and battery sources. The test system used in this paper consists of three thermal generators, wind power source, solar power source and battery as energy storage device. To show the effectiveness of the employed method, three different scenarios are used. Also, the results are compared with those obtained by other recently published methods.

Keywords: Environmental economic dispatch; harmony search; solar cost function; wind cost function

INTRODUCTION

The microgrid (MG) can be defined as a low-voltage distribution system which contained micro powers, electrical loads and control units, etc. The micro powers typically consist of distributed generators such as PV modules, wind power sources and energy storage devices. With the growth of distribution technologies, the MG offers an effective way for the inclusive use of renewable energy sources [1-2]. Inclusion the renewable energy sources with the power system leads to some problems due to their intermittence nature.

The MG has two modes of operation. The first one is the islanded mode while the second one is the grid connected mode. Under normal situations, the MG is connected into the main grid, which supplies power to all loads with the micro powers. In the event of emergency, the MG continue to deliver power to the local (critical) loads using the micro powers only [3]. The sources of micro powers in MG differs from the source power in conventional sources in power grid. Therefore, the economic dispatch strategy can be obtained via reasonable scheduling [4].

Economic dispatch (ED) aims to reduce the total operating costs as much as possible with satisfying all equality and inequality constraints by reasonable outputs of the sources of micro powers [5]. In literature, there are various optimization techniques used to solve the ED problem in the MG. The authors in [6] discussed the minimization of fuel cost in a MG which has a diversity of power sources. Also, the improved particle swarm optimization algorithm is proposed in [1] to solve the ED problem of the MG. In addition, reduced gradient algorithm method is employed in [7] to solve the problem of ED with energy storage for the grid connected MG. Moreover, the harmony search algorithm is presented in [2] to solve the dynamic ED problem for MG.

However, minimizing the total operating cost is one of very important goal of any utility operator, minimizing the total emission level is also very important to the utility operator. To achieve both goals, the combined economic emission dispatch (CEED) is used. The CEED problem can be solves as a multi-objective optimization problem or converting it into a single objective function using a price penalty factor. To solve the CEED problem for a system consisting of renewable sources with conventional sources, the gradient method is used in [8]. In addition, the interior search method and ant colony algorithm are presented in [9] and [10] to solve the CEED problem of microgrids, respectively.

Recently, the powerful algorithm called harmony search (HS) algorithm which inspired by music improvisation process is proposed in [11]. The HS algorithm is a robust, highly efficient algorithm. Also, it has an ability to find the global optimal solution. The HS algorithm or its hybridization with other metaheuristic algorithm are employed to solve different optimization problem with success [12,13].

In this paper, to solve the CEED problem for the MG considering the cost functions of wind, solar and battery sources, HS algorithm is employed. The employed algorithm is tested using microgrid model for different scenarios and compared with reduced gradient algorithm that employ the same data.

The rest of this paper is organized as follow: Section **Error! Reference source not found.**, the problem formulation is explained. In Section 0, the HS algorithm is reviewed. Experiments results and discussion about them is introduced in section **Error! Reference source not found.**. Finally, the paper is concluded in section 0.

FORMULATION OF CEED FOR MICROGRID

Objective function

The CEED problem for MG can be formulated as a single optimization problem as follows:

$$\min(C) = \sum_{i=1}^{N} F_i(P_i) + \nabla \sum_{i=1}^{N} E_i(P_i) + \sum_{w=1}^{N_w} C_w(P_w) + \sum_{s=1}^{N_s} C_s(P_s) + \sum_{e=1}^{N_e} C_e(P_e) \quad (1)$$

where C is the total operating cost to be minimized, $F_i(P_i)$ is the fuel cost of generator i, $E_i(P_i)$ is the emission of generator i, P_i is the output power of generator i, N is the number of generators, ∇ is the price penality factor, $C_w(P_w)$ is the cost finction of wind power, P_w is the wind power, $C_s(P_s)$ is the cost finction of solar power, P_s is the solar power, N_w is the number of wind power sources, N_s is the number of solar power sources, $C_e(P_e)$ is the cost function of energy storage, P_e is the power of energy storage device and N_e is the number of energy storage devices.

The total fuel cost of all conventional generators (F_t) can be defined as follows [14]:

$$F_t = \sum_{i=1}^{N} a_i + b_i P_i + c_i P_i^2 \quad (2)$$

where a_i, b_i and c_i are the cost coefficients for the generator i.

The total emission of all conventional generators (E_t) can be defined as follows [14]:

$$E_t = \sum_{i=1}^{N} x_i + y_i P_i + z_i P_i^2 \quad (3)$$

where x_i, y_i and z_i are the emission coefficients for the generator i. The price penalty factor is the ratio between the fuel cost and the emission of corresponding generating unit. In this paper the max-max price penalty factor is employed as follows [15]:

$$\nabla = \frac{F_t(P_i^{max})}{E_t(P_i^{max})} \quad (4)$$

where P_i^{max} is the maximum output power of generator i.

The cost functions of wind (C_w), solar (C_s) and energy storage (C_e) can be obtained based on the following equation [7,16]:

$$C_{rs} = a l^p P_{rs} + G^E P_{rs} \quad (5)$$

$$a = \frac{r}{[1-(1+r)^{-N}]} \quad (6)$$

where P_{rs} is the renewable energy source generation, a is the annuitization coefficient, r is the interest rate (0.09), N is the investment lifetime (20 years), l^p is the investment cost per unit installed power and G^E is the operation and maintenance cost. In this paper, l^p and G^E are taken as 1400 \$/kW and 1.6 cents/kW, respectively for wind power sources. They are taken as 5000 \$/kW and 1.6 cents/kW, respectively for solar power sources. While they are takes as 1000 \$/kW and 1.6 cents/kW, respectively for energy storage devices.

Constraints

Grid connected mode of microgrid

In this work, the loads are considered as critical and non-critical loads. The critical load is always supplied with power in islanded and grid connected modes of operation of the microgrid. Whereas, the non-critical loads is supplied only in the grid connected mode [7].

In this mode, the microgrid is connected to the main grid via the point of common coupling where the non-critical load is supplied. The power supplied from the main grid is limited to the value of the non-critical load to reduce the total power export from the main grid.

System power balance

$$\sum_{i=1}^{N} P_i + P_w + P_s + P_e = P_D \quad (7)$$

where P_D is the total load demand.

Generation limits

$$P_i^{min} \le P_i \le P_i^{max} \quad (8)$$

$$P_w^{min} \le P_w \le P_w^{max} \quad (9)$$

$$P_s^{min} \le P_s \le P_s^{max} \quad (10)$$

$$P_e^{min} \le P_e \le P_e^{max} \quad (11)$$

where P^{max} and P^{min} are maximum and minimum output power of each source, respectively.

Energy Storage

In this work, a Lithium-Ion battery of 500kW power rating is considered as energy storage device. Also, the rates of charging and discharging are taken as C/2 and C/3. The battery charges for every 2 hours and discharges for every 3 hours [17]. During charging mode, the battery acts as a load. A minimum State of Charge (SOC) of 10% and a maximum state of charge of 90% is always maintained as a constraint for a battery.

HARMONY SEARCH (HS) ALGORITHM

The HS algorithm consists from five steps. In the first step, the parameters of the algorithm are randomly generated. These parameters are harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR) and bandwidth (BW). The second step is initializing the harmony memory (HM). In the third step, a new harmony is improvised from HM. Then the new harmony is evaluated and HM is updated in the fourth step. In the fifth step, the stooping criterion is checked [12]. These steps can be summarized as follows:

Initialize the problem and algorithm parameters

$$Minimizing\ g(x) \quad (12)$$

$$x_i^{min} \le x_i \le x_i^{max} \qquad i = 1,2,\dots,D \tag{13}$$

where x_i^{min} and x_i^{max} are the minimum and maximum vales for the variables of the problem, respectively and D is the dimension of the problem. In addition, the HS algorithm's parameters are initialized in this step [18].

Formation of harmony memory

The decision variables of the optimization problem are generated randomly within their minimum and maximum values and then they are sorted according to their fitness values in the matrix form. The number of rows is equal to the harmony memory size while the number of column equal to number of decision variables as follows [2]:

$$M = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_D^1 \\ x_1^2 & x_1^2 & \dots & x_D^2 \\ \dots. & \dots & \dots & \dots. \\ x_1^{MHS} & x_1^{HMS} & \dots & x_D^{HMS} \end{bmatrix} \tag{14}$$

Improvise a new harmony

Based on the HM initialized in previous step, a new harmony solution, can be created based on the three rules: memory consideration, pitch adjustment or random generation. This means that the HS algorithm chooses whether to pick an already existing solution from the matrix oh HM or to randomly create a new solution. First, the HMCR parameter is employed to select a new value as follows [2,11]:

$$x_i' = \begin{cases} x_i' \in \{x_i^1, \dots, x_i^{HMS}\} & with\ respect\ to\ HMCR \\ x_i' \in X_i & with\ respect\ to\ (1 - HMCR) \end{cases} \tag{15}$$

Then, each value selected from HM matrix is tested to determine whether it must be pitch adjusted based on the PAR parameter as follows [2, 11]:

$$Pitch\ adjusting\ rule\ for\ x_i' = \begin{cases} Yes & with\ respect\ to\ PAR \\ No & with\ respect\ to\ (1 - PAR) \end{cases} \tag{16}$$

If the decision of pitch adjustment rule is yes for any x_i', the pitch-adjusted value will be:

$$x_i' = x_i' + r \times BW \tag{17}$$

where *BW* is the bandwidth parameter and *r* is a random uniformly distributed number (r ϵ [-1; 1]).

Update the HM

If the fitness value of the new solution vector is better than the worst solution in the stored HM, the new solution is inserted into HM matrix instead of the worst one. Then, the matrix of HM is sorted according to the fitness values [2].

Check the stopping criterion

Checking the stopping criterion. If the stopping criterion is satisfied, stop the computation. Otherwise, steps 3.3 and 3.4 are repeated.

Figure 1 shows the pseudo-code of the HS algorithm.

SIMULATION RESULTS

The microgrid system employed in this paper have three conventional generators, one wind unit, one solar unit and one battery as an energy storage device. Table 1 shows the data of the three conventional generators [19].

Table 1: Data of the three conventional generators.

	Generator 1	Generator 2	Generator 3
a ($/h)	15.30	14.88	9
b ($/MWh)	0.21	0.3	0.306
c ($/MW2h)	0.00024	0.000435	0.000315
x (kg/h)	60	45	30
y (kg/MWh)	-1.355	-0.6	-0.555
z (kg/MW2h)	0.0105	0.008	0.012

```
Harmony search algorithm
1- Initialize the data of optimization problem.
2- Set the algorithm parameters (HMS, HMCR, PAR, BW and max_it).
3- Generate the harmony vectors randomly.
4- Sort the harmony vectors according to their fitness (objective function) values.
5- k = 1
6- while k <= max_it
     for i = 1 to D do
        if rand ≤ HMCR then
           x'i = xi,r where r ϵ (1,2,….,HMS)
           if rand ≤ PAR then
              if rand( ) ≤ 0.5 then
                 x'i = x'i + rand × BW            (pitch adjustment)
              else
                 x'i = x'i − rand × BW            (pitch adjustment)
              end if
           end if
        else
           x'i = xi,min + rand × (xi,max − xi,min)   (random consideration)
        end if
     end for
7- if f(x') < f(x^worst) then
8- Include x' to HM and exclude x^worst from HM.
9- end if
10- Checking the stopping criterion, k = k+1, end while.
```

Figure 1: Pseudo code of the HS algorithm

Table 2 shows the constraints of different energy sources used in this paper [19]

Table 2: Constraints of Energy Sources.

Generator 1: $0 \le P_1 \le 1.5$ MW	Generator 2: $0 \le P_2 \le 1$ MW	Generator 3: $0 \le P_3 \le 1$ MW
Wind energy: $0 \le P_w \le 500$ kW	Solar energy: $0 \le P_s \le 500$ kW	Battery: $100 \le P_2 \le 400$ kW

Tables 3 and 4 show a daily load profile employed in this paper for both critical and non-critical loads, respectively [2, 19]. The power supplied to the non-critical load is from the main grid. The generation cost of the power from the main grid is 7 cents/kW [2,19].

Table 3: Critical Load Profile over 24 Hour.

Time (hr)	1	2	3	4	5	6	7	8
Load (MW)	2.1	2.1	2.2	2.25	2.3	2.35	2.35	2.4
Time (hr)	9	10	11	12	13	14	15	16
Load (MW)	2.4	2.45	2.5	2.5	2.5	2.4	2.4	2.3
Time (hr)	17	18	19	20	21	22	23	24
Load (MW)	2.3	2.25	2.2	2.15	2.14	2.1	2.1	2

Table 4: Non-critical Load Profile over 24 Hour

Time (hr)	1	2	3	4	5	6	7	8
Load (kW)	400	410	415	420	422	425	430	435
Time (hr)	9	10	11	12	13	14	15	16
Load (kW)	440	445	450	460	470	480	490	500
Time (hr)	17	18	19	20	21	22	23	24
Load (kW)	500	490	480	470	460	450	440	430

Regarding the renewable sources, a location in the east coast of USA is considered in this paper. Figures 2 and 3 show the one-day values of both solar power and wind power at this location [2,19]. Figure 4 shows the profile of the battery which used in this paper as energy storage device [19].

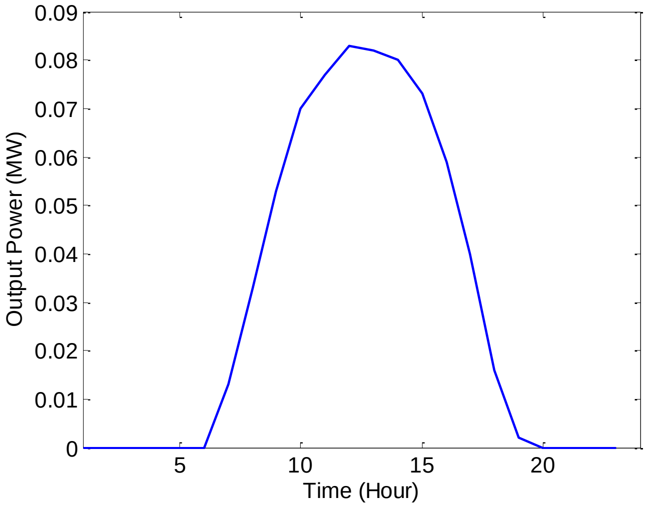

Figure 2: Solar power generation.

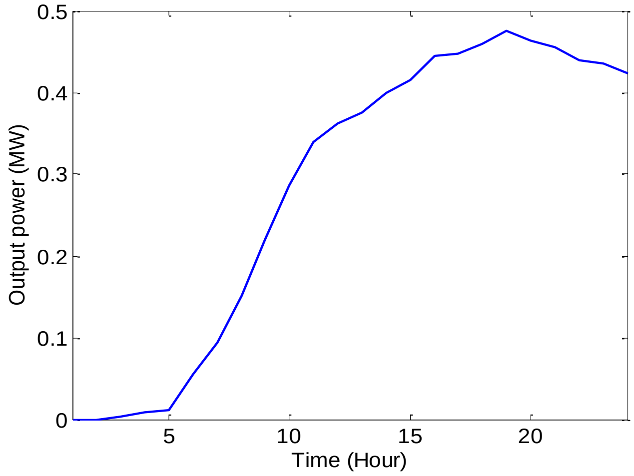

Figure 3: Wind power generation.

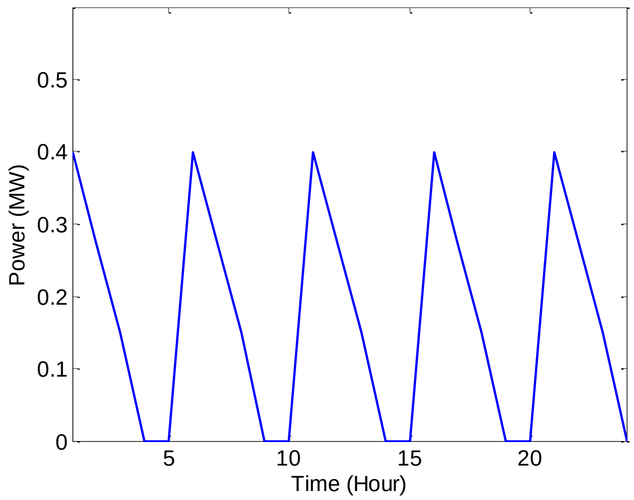

Figure 4: Battery profile.

To implement the HS algorithm, there are several parameters should be determined. In this paper, the values of the HS algorithm parameters were selected using empirical tests by running the HS algorithm several times with different combinations of these parameters. To evaluate the employed algorithm in solving the optimization problem of CEED for microgrid three scenarios are carried out:

- All sources included without emission for grid connected mode.
- All sources included with emission for grid connected mode.
- All sources excluding the solar with emission for grid connected mode

Scenario 1: All sources included without emission for grid connected mode.

In this scenario, the HS algorithm is employed to solve the ED problem (without emission) of the grid connected microgrid considering the cost functions of wind, solar and battery. To evaluate the effectiveness of the HS algorithm, its results are compared with the results of reduced gradient algorithm (RGA). The results of RGA are extracted from [2, 19]. For the fair comparison, the battery storage device is considered in this scenario, while the emission is neglected. Table 5 shows the results of this scenario using the HS algorithm, while table 6 shows the comparison between HS algorithm and RGA using the total cost. These results are depicted in Figure 5.

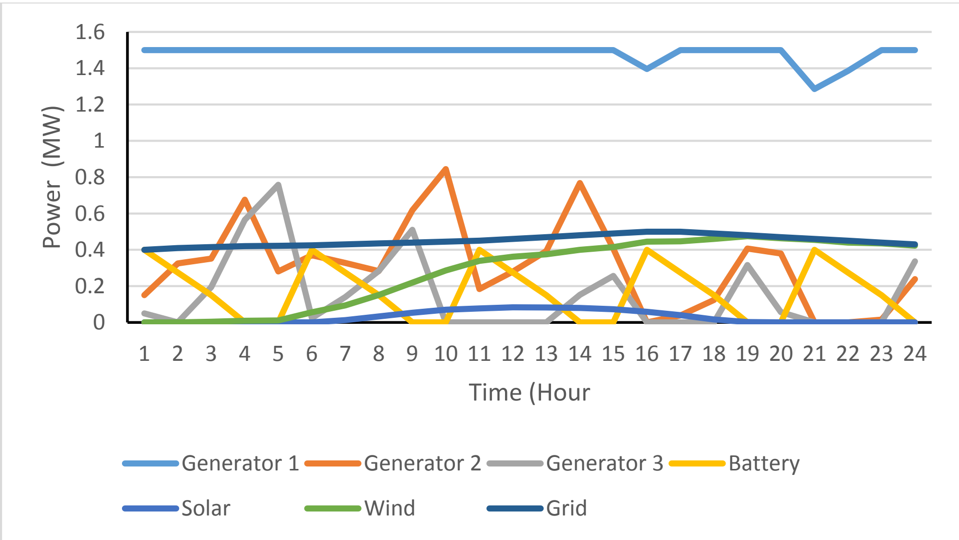

Figure 5: Power generated from all sources (scenario 1)

Table 5: The results of HS algorithm when all sources included without emission (scenario 1)

Time Hour	Gener.1 (MW)	Gener. 2 (MW)	Gener. 3 (MW)	Battery (MW)	Solar (MW)	Wind (M)W	Grid (MW)	Cost ($/h)
1	1.5	0.150214	0.049786	0.4	0	0	0.4	87.18
2	1.5	0.325	0	0.275	0	0	0.41	72.35
3	1.5	0.351147	0.194853	0.15	0	0.004	0.415	58.15
4	1.5	0.676075	0.564925	0	0	0.009	0.42	41.27
5	1.5	0.281017	0.757983	0	0	0.011	0.422	41.52
6	1.5	0.370176	0.023824	0.4	0	0.056	0.425	95.79
7	1.5	0.327967	0.140033	0.275	0.013	0.094	0.43	93.82
8	1.5	0.282886	0.283114	0.15	0.033	0.151	0.435	98.58
9	1.5	0.61761	0.51039	0	0.053	0.219	0.44	102.17
10	1.5	0.844	0	0	0.07	0.286	0.445	121.58
11	1.5	0.184	0	0.4	0.077	0.339	0.45	180.89
12	1.5	0.28	0	0.275	0.083	0.362	0.46	172.82
13	1.5	0.393	0	0.15	0.082	0.375	0.47	159.42
14	1.5	0.767968	0.152032	0	0.08	0.4	0.48	144.45
15	1.5	0.406011	0.255989	0	0.073	0.415	0.49	142.85

16	1.396	0	0	0.4	0.059	0.445	0.5	187.18
17	1.5	0.038	0	0.275	0.04	0.447	0.5	162.29
18	1.5	0.124	0	0.15	0.016	0.46	0.49	136.34
19	1.5	0.406568	0.316432	0	0.002	0.475	0.48	112.19
20	1.5	0.379846	0.057154	0	0	0.463	0.47	110.32
21	1.285	0	0	0.4	0	0.455	0.46	156.52
22	1.385	0	0	0.275	0	0.44	0.45	139.38
23	1.5	0.015	0	0.15	0	0.435	0.44	123.77
24	1.5	0.238348	0.336652	0	0	0.423	0.43	104.26
Total cost								2846.2368

These results show that the HS algorithm gives better results (Total costs) than the RGA method. The difference is not big, this is due to the small load used. Also, we can notice that the generator 1 is alwayes operate with maximum output because generator 1 has the smallest fuel cost among the three generatos. This will lead to reduce the total cost of the system. The results show the effectivness of the HS algorithm in solving the ED problem for microgrid model.

1.1. Scenario 2: All sources included with emission for grid connected mode.

In this scenario, the HS algorithm is employed to solve the CEED problem of the grid connected microgrid considering the cost functions of wind, solar and battery. The battery profile of scenario 1 is also considered in this scenario [2,19]. Table 7 shows the results of this scenario using the HS algorithm. These results are depicted in Figure 6. From these results, we can notice that the total costs are higher than the costs of scenario 1 as expected. This is due to adding the costs of the emission.

1.2. Scenario 3: All sources excluding the solar with emission for grid connected mode.

The solar is very expensive when compared to wind energy. Therefore, in this scenario, the HS algorithm is employed to solve the CEED problem of the grid connected microgrid considering the cost functions of wind and battery without considering solar power. The battery profile of scenario 1 is also considered in this scenario [2,19]. Table 8 shows the results of this scenario using the HS algorithm. These results are depicted in Figure 7. From these results, we can notice that the total costs are higher than the costs of scenario 1 as expected. This is due to adding the costs of the emission. Also, the costs of these case are less than the costs of scenario 2 because the solar power source is not considered.

Figure 8 shows the comparison between the three scenarios regarding to the costs. The total cost of scenario 1 is 2846.2368 $ which is less than the other two scenario due to neglecting the emission. While the total cost of scenario 3 is 3401.1966 $ which is less than the total cost of scenario 2 which is equal to 3768.4945 $ due to neglecting the solar source.

Table 6: Comparison between HS algorithm and RGA when all sources included without emission

Time Hour	RGA [2, 19]	HS
	Total Cost ($/h)	Total Cost ($/h)
1	87.26	87.18
2	72.41	72.35
3	58.21	58.15
4	41.30	41.27
5	41.56	41.52
6	95.85	95.79
7	93.88	93.82
8	98.63	98.58
9	102.21	102.17
10	121.63	121.58
11	180.96	180.89
12	172.89	172.82
13	159.48	159.42
14	144.50	144.45
15	142.91	142.85
16	187.25	187.18
17	162.36	162.29
18	136.42	136.34
19	112.29	112.19
20	110.38	110.32
21	156.59	156.52
22	139.45	139.38
23	123.85	123.77
24	104.31	104.26

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 5 (2018) pp. 3083-3092
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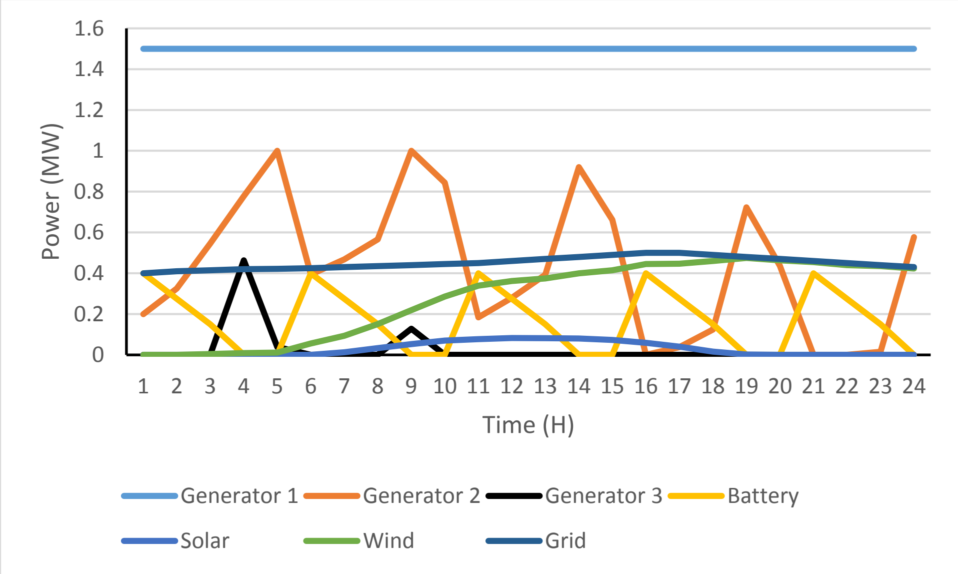

Figure 6: Power generated from all sources (scenario 2)

Table 7: The results of HS algorithm when all sources included with emission (scenario 2)

Time Hour	Gener.1 (MW)	Gener. 2 (MW)	Gener. 3 (MW)	Battery (MW)	Solar (MW)	Wind (M)W	Grid (MW)	Cost ($/h)
1	1.5	0.2	0	0.4	0	0	0.4	125.56
2	1.5	0.325	0	0.275	0	0	0.41	110.71
3	1.5	0.546	0	0.15	0	0.004	0.415	97.00
4	1.5	0.777893	0.463108	0	0	0.009	0.42	83.02
5	1.5	1	0.039	0	0	0.011	0.422	82.18
6	1.5	0.394	0	0.4	0	0.056	0.425	135.21
7	1.5	0.468	0	0.275	0.013	0.094	0.43	132.95
8	1.5	0.566	0	0.15	0.033	0.151	0.435	137.54
9	1.5	1	0.128	0	0.053	0.219	0.44	143.31
10	1.5	0.844	0	0	0.07	0.286	0.445	161.20
11	1.5	0.184	0	0.4	0.077	0.339	0.45	219.18
12	1.5	0.28	0	0.275	0.083	0.362	0.46	210.94
13	1.5	0.393	0	0.15	0.082	0.375	0.47	197.45
14	1.5	0.92	0	0	0.08	0.4	0.48	184.48
15	1.5	0.662	0	0	0.073	0.415	0.49	181.49
16	1.5	0	0	0.4	0.059	0.445	0.5	223.93
17	1.5	0.038	0	0.275	0.04	0.447	0.5	199.10
18	1.5	0.124	0	0.15	0.016	0.46	0.49	172.93
19	1.5	0.723	0	0	0.002	0.475	0.48	152.30
20	1.5	0.437	0	0	0	0.463	0.47	147.76
21	1.5	0	0	0.4	0	0.455	0.46	192.68
22	1.5	0	0	0.275	0	0.44	0.45	175.38
23	1.5	0.015	0	0.15	0	0.435	0.44	159.77
24	1.5	0.577	0	0	0	0.423	0.43	142.44
Total cost								3768.4945

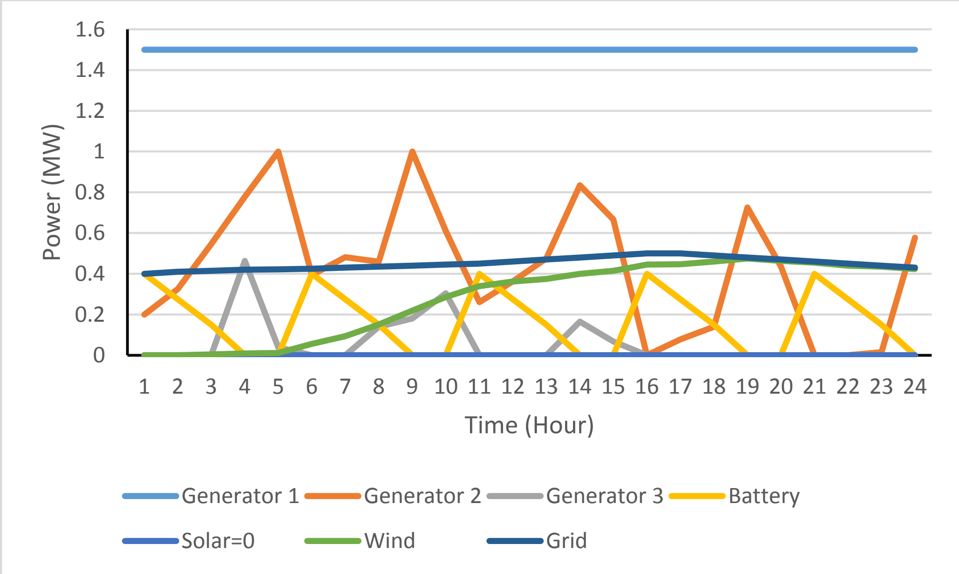

Figure 7: Power generated from all sources (scenario 3)

Table 8: The results of HS algorithm when all sources without solar with emission (scenario 3)

Time Hour	Gener.1 (MW)	Gener. 2 (MW)	Gener. 3 (MW)	Battery (MW)	Solar (MW)	Wind (M)W	Grid (MW)	Cost ($/h)
1	1.5	0.2	0	0.4	0	0	0.4	125.56
2	1.5	0.325	0	0.275	0	0	0.41	110.71
3	1.5	0.546	0	0.15	0	0.004	0.415	97.00
4	1.5	0.777893	0.463108	0	0	0.009	0.42	83.02
5	1.5	1	0.039	0	0	0.011	0.422	82.18
6	1.5	0.394	0	0.4	0	0.056	0.425	135.21
7	1.5	0.481	0	0.275	0	0.094	0.43	125.94
8	1.5	0.45937	0.139631	0.15	0	0.151	0.435	119.74
9	1.5	1	0.181	0	0	0.219	0.44	114.72
10	1.5	0.610114	0.303887	0	0	0.286	0.445	123.45
11	1.5	0.261	0	0.4	0	0.339	0.45	177.65
12	1.5	0.363	0	0.275	0	0.362	0.46	166.17
13	1.5	0.475	0	0.15	0	0.375	0.47	153.22
14	1.5	0.834746	0.165255	0	0	0.4	0.48	141.33
15	1.5	0.666887	0.068113	0	0	0.415	0.49	142.12
16	1.5	0	0	0.4	0	0.445	0.5	192.10
17	1.5	0.078	0	0.275	0	0.447	0.5	177.53
18	1.5	0.14	0	0.15	0	0.46	0.49	164.30
19	1.5	0.725	0	0	0	0.475	0.48	151.22
20	1.5	0.437	0	0	0	0.463	0.47	147.76
21	1.5	0	0	0.4	0	0.455	0.46	192.68
22	1.5	0	0	0.275	0	0.44	0.45	175.38
23	1.5	0.015	0	0.15	0	0.435	0.44	159.77
24	1.5	0.577	0	0	0	0.423	0.43	142.44
Total cost								3401.1966

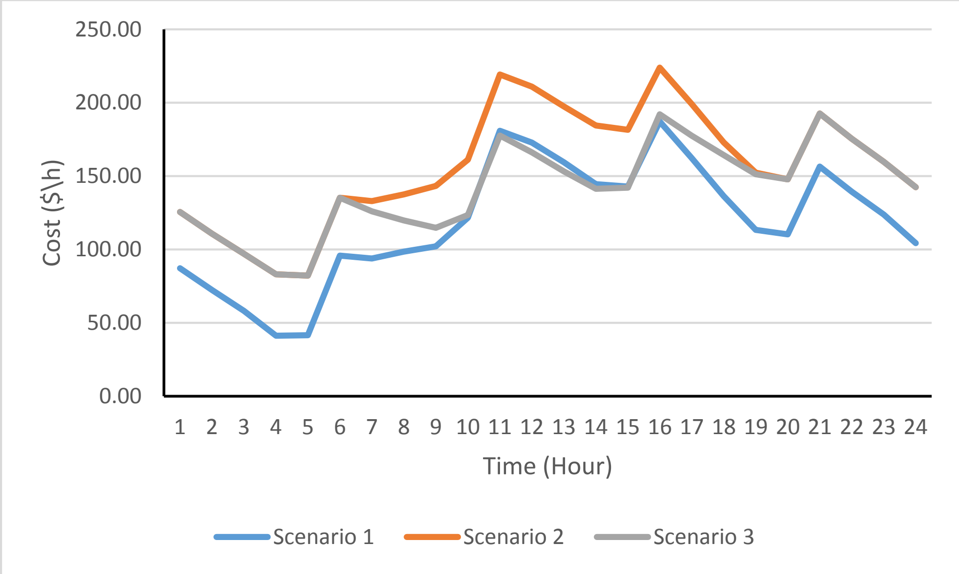

Figure 8: Cost Curve in the three scenarios for 24 Hours of a day

CONCLUSION

In this paper, HS algorithm is employed to solve the combined economic emission dispatch (CEED) problem for the grid connected microgrid considering the cost function of wind, solar and battery. The CEED problem is solve by converting the multi-objective optimization function into a single optimization function using the price penalty function. A microgrid consists of three conventional generators, wind source, solar source and battery as energy storage device is employed in this paper to test the effectiveness of the HS algorithm. Three different scenarios are employed n this paper. The results show that the HS algorithm gives better performance than the RGA method. In addition, the total cost is high when all sources are included, and emission is considered. The cost of solar power is higher than the wind power, so by neglecting the solar source the total cost is reduced.

ACKNOWLEDGMENT

The authors gratefully acknowledge the Tail University for its support to carry out this work. It funded this project with a fund number 1-438-5483.

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