Optimal Economic and Emission Dispatch of Photovoltaic Integrated Power System Using Firefly Algorithm

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Abstract: The main purpose of Economic Load Dispatch (ELD) is to determine the optimal output of generating units to meet the power demand at lowest possible cost and subjected to the operational constraints. Various ELD optimization methods have been developed in order to deal with the challenges of continuous and sustainable power at optimal cost. The deficiency of fossil fuel reserve and rapid increase of fuel prices to generate electricity have encouraged the use of Renewable Energy (RE). Furthermore, the concerns over environmental pollution also become a factor to incorporate the RE and fossil fuel in generating electricity. This paper proposes the Firefly Algorithm (FA) to solve Economic and Emission Load Dispatch (EELD) problems by considering the photovoltaic integration power systems. The FA algorithm is used to determine the optimal cost and emission level of power generation. The test case considered in this paper is Static Combined Economic and Emission Dispatch (SCEED) that been simulated for each hour. The test system with 6 units of thermal generator and 13 units of PV generator are used to optimize SCEED problem by using FA. The Weight Sum Method (WSM) approach is used to determine the best compromise solution among the cost and emission. It found that FA can provide the fast convergence in finding the global minima value. It can be concluded that FA can solve the problem of economic and emission dispatch accurately.

Keywords: Combined economic emission dispatch, economic dispatch, firefly algorithm, renewable energy

1. Introduction

To generate electricity, electrical power generation system largely depends on fossil fuel that powered by thermal plant [1]. During the period of 1990 to 2016, more than 90% of electricity generated for peninsular Malaysia was attained from fossil fuel. In 2016, 52% of the electrical energy generation is provided by coal while gas contribute 44% [2]. The availability of fossil fuels such as oil, coal and natural gas is decreasing, and power demand is increasing day by day. In addition, the cost of the fossil fuel is being increase which is creating a bigger problem [3]. Hence, the deficiency of fossil fuel reserve and rapid increase of fuel prices has encouraged the use of Renewable Energy (RE). According to the expert, the fossil fuel reserves are limited and may be run out within 2050 [4].

Furthermore, concerns over environmental pollution also become a factor incorporate the RE and fossil fuel in generating electricity. Malaysia has targeted to reduce the carbon emission intensity by 40% by the year 2020 and 45% by the year 2030 [2] [5]. Environmental concerns have placed investment in low-carbon power generation technologies as one of the priorities of the energy agendas of many countries around the world [6]. The problem of pollutant gas emission that cause environment pollution also motivate a researcher to work on minimizing the use of fossil fuel in thermal plant during the process of electricity generation [1].

Hence, RE become a new alternative in generating electricity. There are many alternative ways to generate electricity such as hydropower, bio energy, solar energy, wind energy and tidal energy. However, fossil fuel stills remain as a main source to generate electricity [1]. In Turkey, renewable energy generation has contributed 6% to the total generation in 2015. They expecting the proportion of renewable energy generation been grown at least 30% in the total amount of energy generation in 2023 [6]. Malaysia is well endowed with abundant non-renewable and renewable sources of energy, especially biomass and solar [7]. Our Country has set an ambitious target for 20% of country's electricity be generated from renewable sources by 2030 [8].

In order to determining the optimum economic and emission dispatch, many optimization methods have been used. There are two categories of optimization methods which are classical method and meta-heuristic optimization method [9]. Some researchers have combined two or more algorithms to achieve superior performance compare to the stand alone methods in order to solve CEED problems [1]. Optimization techniques have been employed to solve the generation scheduling problem [10]. The classic method such as lambda iteration [11], gradient method, integer programming, quadratic programming, and linear programming [12]. Modern heuristic optimization methods are proposed by researcher based on artificial intelligence concepts such as Evolutionary Programming (EP), Genetic Algorithm (GA), Hopfield Neural Network, Particle Swarm Optimization (PSO) [13], Ant Colony Algorithm (ACO), Ant-Lion Algorithm (ALO), Krill Herd Algorithm (KHA), and Firefly Algorithm (FA) [14].

Economic Load Dispatch (ELD) problem relates to the optimum generation power system to minimize fuel cost while to satisfy the load demand and operational constraint [15]. ELD with both cost and emission minimization becomes a multi objective optimization problem and is named as Combined Economic and Emission Dispatch (CEED) [16]. In solving CEED problem, Fuzzy Based Mechanism and Weighted Sum Method (WSM) used to find the best compromise solution. The test cases that has been considered is Static Combined Economic and Emission Dispatch (SCEED). SCEED is performed for full solar radiation level as well as for reduced radiation level and it was been simulated by single hour [16].

Firefly Algorithm is widely used by previous researcher for solving economic and emission load dispatch considering thermal generators. However, less researcher solved the CEED problem with both thermal and photovoltaic generators. Firefly Algorithm (FA) has been developed by Xin She Yang in 2008 that based on the movement of flashing behavior of firefly as an idea [17]. All fireflies are unisex and they will move towards more attractive and brighter ones without considering their gender [18]. The advantages of firefly algorithm is flexibilities and using simple concept where it depend on communication of the swarming particles [19].

This paper proposes a FA technique to minimize both cost and emission of power generating considering on photovoltaic system. Optimization of economic dispatch problem considering emission as constrained with photovoltaic generating units using FA is carried out. The test system consists of 6 thermal generating units and 13 PV generating units are tested using FA in MATLAB 2019 software to obtain the optimal solution.

2. Problem Formulation

The objective function of this paper is to optimize an economic and emission load dispatch for thermal and photovoltaic generating units. The power demand and others constraint need to be considered. The objective function corresponding to the fuel cost production can be represent as follow:

i. Economic Load Dispatch
ii. Emission Load Dispatch
iii. Static Combined Economic and Emission Dispatch (SCEED)

2.1 Economic Load Dispatch

The aims of solving ELD problem is to minimize total operation cost and satisfied the power demand and other constraints. The fuel cost can be mathematically expressed as [20]:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \quad (1)$$

The objective function of ELD problem is to minimize the total generation cost as follows [20]:

$$Min\ F_i(P_i) = \sum_{i=1}^{n} (a_i {P_i}^2 + b_i P_i + C_i) \quad (2)$$

where,
$F_i(P_i)$: Generation cost for generator
$a_i\ b_i\ c_i$: Cost function coefficient for i^{th} generating unit
P_i : Real power output of generator *i*
n : Number of thermal generators

i. *Solar generated by each unit PV generation:*

PPV is a power generated by solar photovoltaic (PV) according to parameters that can be calculated as follow [16]:

$$PPV = P_{rated}\{1 + (T_{ref} - T_{cell}) \times \alpha\} \times \frac{S_i}{1000} \quad (3)$$

where,
P_{rated} : Rated power
T_{ref} : Reference temperature
T_{cell} : Cell temperature
α : Temperature coefficient
S_i : Incident solar radiation

The temperature reference (T_{Ref}) and temperature coefficient (α) for minimum power performance, MPP is 25C° and -0.37% respectively [21].

ii. Solar cost equation:

To optimize the cost, not all the solar (PV) generation will be operated at certain time. The PV generating units with high efficiency are used to operate and can be calculated as [16]:

$$Solar\ Cost = \sum_{j=1}^{m} (PU\ cost_j \times PPV_j \times Us_j) \quad (4)$$

where,

$PUcost_j$: Per unit of j^{th} solar plant

PPV : Power available from j^{th} solar plant

Us_j : Status of j^{th} solar plant eithere1 (ON) eore0 (OFF)

m : Number of solar panels

Therefore, the minimization of Total cost of power generation by thermal and PV power plant (F_T) are as follow [16]:

$$Min\ F_T = \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i) + \sum_{j=1}^{m} (PUcost_j \times PPV_j \times Us_j) \quad (5)$$

2.2 Emission Load Dispatch

The aim of emission load dispatch is to minimize the total pollution gas from combustion of thermal power generation. The objective function of emission dispatch can be defining as [16]:

$$Min\ E_i(P_i) = \sum_{i=1}^{n} (d_i P_i^2 + e_i P_i + \gamma_i) \quad (6)$$

where,

$E_i(P_i)$: Emission generated by thermal generator

P_i : Power generated by thermal

$d_i\ e_i\ \gamma_i$: Emission coefficient of i^{th} generating unit

2.3 Static Combined Economic and Emission Dispatch (SCEED)

The Static CEED problem has been investigate using FA and Weight Sum Method (WSM) to solve the problem of Economic emission dispatch. The weighting factors of WSM used are from 0 to 1 with the increment steps of 0.1. total power generated by thermal and solar state also recorded for every set of iteration from w=0 until w=1. When solar state displayed 1 means the solar systems unit is ON and supplying power. If solar state displayed 0 means the solar system is OFF and did not supply power.

Combined economic and emission dispatch becomes an important role in determining the reduction of total emission produce by thermal generation units and cost for the electricity generation by thermal and solar PV panel. By using Weighted Sum Method (WSM), the best method can be found with the best resolution for the objective conflict that be expressed by Min Y in equation (7). The penalty factor, h is formed from the ratio of maximum cost and maximum emission level of corresponding generator [22].

$$Min\ Y = w[\ \sum_{i=1}^{n} (a_i P_i^2 + b_i P_i + c_i)) + \sum_{j=1}^{m} \left(PUcost_j \times PPV_j \times Us_j\right) + (1-w) h_i \sum_{i-1}^{n} (E_i\ P_i)] \quad (7)$$

where,

$Min\ F_T$: Total cost power generation

$E_i(P_i)$: Emission generated by thermal

w : Weighting factor

h_i : Penalty factor

2.4 Fuzzy Based Mechanism

In finding the most precise value from the set of obtains solutions, Fuzzy Based Mechanism used. The membership (μ) us used as a decision maker that satisfying the objective function. The membership function of the objective function represented as follow [23]:

$$\mu_i(P_{gi}) = \frac{f_i^{max} - f_i(P_{gi})}{f_i^{max} - f_i^{min}} \quad (8)$$

where,

f_i^{max} : Maximum value of the objective function.

f_i^{min} : Minimum value of the objective function.

$f_i(P_{gi})$: i^{th} objective function of the set solution.

The best compromised solution for SCEED problem is the maximum value of Fuzzy Decision Making (FDM). FDM are formed from equation represented in equation (3.9). *M* represents the total number of the set solution. FDM is equal to sum of two membership function divided with the total summations both membership functions and can be expressed as [23].

$$FDM^k = \frac{\left[\sum_{i-1}^{2} FDM_i^k(P_{gi})\right]}{\left[\sum_{j-1}^{M}\sum_{i-1}^{2} FDM_i^j\right]} \quad (9)$$

2.5 Problem Constraint

There are two constraint that will be considered and need to be satisfied in this system which are equality and inequality constraint. The equality constraint is formulated as equation below [22]:

i. Equality constraint:

In economic dispatch, equality constraint is the total power generated by thermal and PV panel is equal to power demand. This relation can be expressed as

$$\sum P_i + \sum PPV - P_D = 0 \quad (10)$$

where,

P_i : Power generated for i^{th} thermal generator.

P_D : Total power demand.

ii. Inequality constraint:

Generating units capacity limits is the inequality constraint based on minimum and maximum power generation. The real power output of each generating unit must vary between lower and upper limits as given:

$$P_{imin} \le P_i \le P_{imax} \quad (11)$$

where,

P_{imin} : Minimum power limits

P_{imax} : Maximum power limits

Equations (12) show the power generated by photovoltaic system must be less than or equal to power demand required for the photovoltaic that must not be exceed than 30% of power demand [24]. This regulation is to balance the total power generation between thermal and PV generation to cover the power demand as a power balance constraint. Besides, to minimize the difference between the total solar power in order to achieve the maximum benefit of solar availability and can be written as

$$\sum_{j=1} PPV \times Us_j \le 0.3 \times P_D \;\; With \;\; \forall\, Us_j \in \{0, 1\} \quad (12)$$

3. Proposed Firefly Algorithm for Solving Economic Emission Dispatch

Xin She Yang has developed natured inspired algorithm called Firefly Algorithm that inspired from the flashing behavior of the fireflies [17]. Firefly produce flashlight where the main purpose of that acts to attract others firefly towards it. This algorithm is formulated by assuming three idealized rules [25].

i. All fireflies are unisex and they move towards the more attractive and brighter one without considering their sex.
ii. The level off attraction of firefly is proportional to brightness which reduces with the increase in the distance

between two fireflies since air absorbs the light.

iii. The brightness or light intensity is determined by the value of the objective function of a given problem and it is proportional to the light intensity for maximization problem.

Attractiveness of firefly algorithm that attract all fireflies to move toward brighter fireflies that mathematically express as [26]:

$$(\beta_r) = \beta_0 e^{-\gamma^m}, with\ m \geq 1 \tag{13}$$

where,

β_0 : The attractiveness of r when equal to zero.

r : Distance between any two fireflies.

Movement of firefly algorithm from one point to another point toward the light is defined as follows [26]:

$$x_i^{t+1} = x_i^t + \beta_r\left(x_j^t - x_i^t\right) + \alpha_t \varepsilon_i^t \tag{14}$$

where,

x_i : The position of each fireflies.

β_r : The attractiveness of the i^{th} firefly receives from the j^{th} fireflies.

α_t : Randomization parameter.

ε_i^t : Vector of the random number drawn from Gaussian distribution on the iteration.

Figure 1 shows the flowchart for Firefly Algorithm. In solving Economic emission dispatch problem on thermal and photovoltaic, objective function is defines using equation (2), (6), and (7). The random initial possible solution with respect to the constraint are generated in (10), (11), and (12). Then, evaluate the new solution of FA with respect to the objective function which are to minimize cost, minimize emission and minimize the combined economic and emission. The new solution is ranked, and the best solution is stored. The FA is used to gain the optimal result by the movement using equations (13) and (14) where the less bright firefly moves toward brighter one and brightest firefly will move randomly. This happen according to the firefly algorithm rules.

In solving SCEED problem, the pareto set solution is constructed by using WSM to obtain the best compromise solution. Equations (7), (8) and (9) are used to get the compromise solution respect to the maximum iteration. This study is focused on Static Combined Economic Emission Dispatch (SCEED) which are the evaluation on new solution of FA is repeated until it reached the maximum number of iterations and the best optimize solution is stored.

4. Results and Discussion

In this section, the proposed FA algorithm is implemented in the following test system for solving EELD and SCEED problem.

4.1 Test System

The considered test system consists of 6 unit's thermal and 13 units PV power generation as illustrated in Figure 2. The thermal and PV generation units are used to generate electricity according to the load demand. The system operational constraint needs to be considered to generate power as in equation (10).

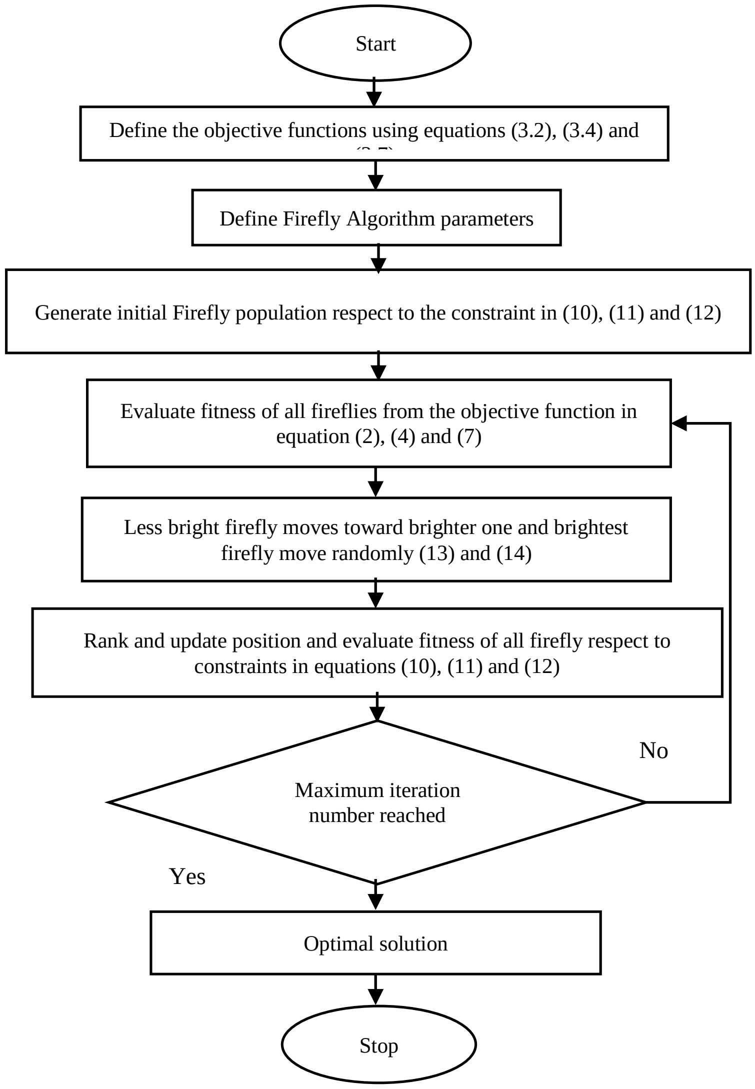

Fig. 1 - Flowchart of Firefly Algorithm

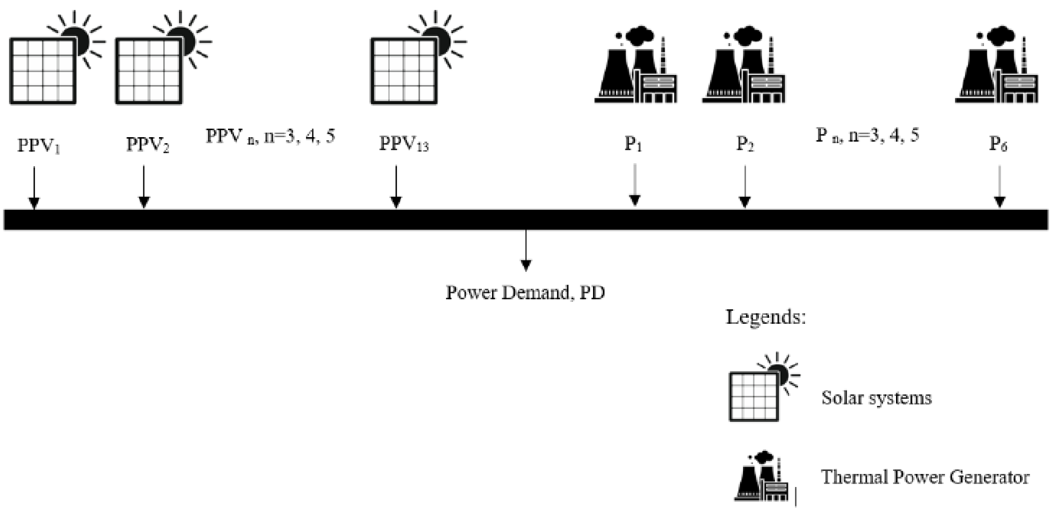

Fig. 2 - Illustration of the test system

The cost and emission coefficients for thermal generating units is taken from [27]. Table 1 shows the information of solar radiation, power demand and temperature for 24 hours. The type of solar panel used is Q.PEAK DUO-G5 315-330 solar module from Q CELLS that engineered in Germany [21]. The cost of each solar power generation is presented in Table 2 [27].

Table 1 - Power demand, solar radiation and temperature [27]

Hours	Power demand (MW)	Global solar radiation (W/m2)	Temperature (Cº)
1	965	0	30
2	1142	0	29
3	1177	0	28
4	1198	0	28
5	1153	5.4	28
6	1136	101	-
7	1138	253.7	29
8	1060	541.2	31
9	1155	530.4	33
10	1244	793.9	34
11	1088	1078	35
12	1240	1125.6	36
13	1135	1013.5	37
14	1318	848.2	37
15	1074	726.7	37
16	1190	654	38
17	1276	392.9	38
18	1154	215.1	37
19	1333	38.5	35
20	1322	0	34
21	1269	0	34
22	1139	0	33
23	1202	0	32
24	1291	0	-

(-: temperature not provided in reference)

Table 2 - Solar PV power rate [27]

Hours	Power demand (MW)	Global solar radiation (W/m2)	Temperature (Cº)
PV1	20	0.22	PV1
PV2	25	0.23	PV2
PV3	25	0.23	PV3
PV4	30	0.24	PV4
PV5	30	0.24	PV5
PV6	35	0.25	PV6
PV7	35	0.26	PV7
PV8	40	0.27	PV8
PV9	40	0.27	PV9
PV10	40	0.275	PV10
PV11	40	0.28	PV11
PV12	40	0.28	PV12
PV13	40	0.28	PV13

4.2 Cost Minimization

The main purpose of this study is to minimize the cost of power generation and determine the corresponding emission. It found that only few photovoltaic units have been used to generate electricity because the price of PV generation is higher than thermal generation. In minimizing cost, the solar state show that the solar panel used is less because of price of solar PV is expensive. However, the solar PV price does not give big impact on total cost because thermal generators are more used to generate power and cause the emission amount increase.

Figure 3 shows the hourly cost and corresponding emission obtained by FA for cost minimization. The total cost and corresponding total emission for 24 hours 1722707.577 ($/h) and 31275.565 (kg/h) respectively.

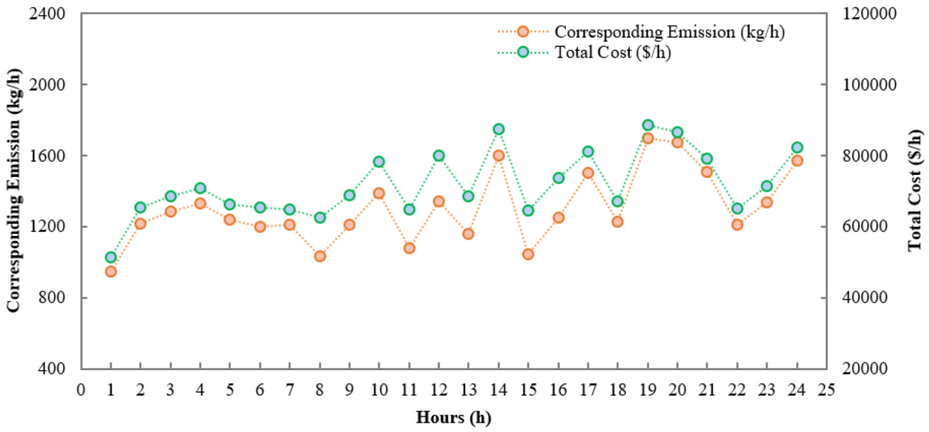

Fig. 3 - Hourly cost and corresponding emission for cost minimization using FA

4.3 Emission Minimization

The objective of this study is to minimize the total emission and determine the corresponding total cost of power generation. The solar state shows that most of photovoltaic units have been used to generate electricity.

Figure 4 shows the result of hourly emission minimization for 24 hours. The total emission minimizes and corresponding are 24128.104 (kg/h) and 2325713.049 ($/h) respectively. From the graph shows that the emission emitted is inversely proportional to the total cost. When the emission is high, the cost will be lower and vice versa. The total cost become high because of the PV plant are used to meet the power demand with minimal emission. Where, the cost of photovoltaic is quite high compare to thermal.

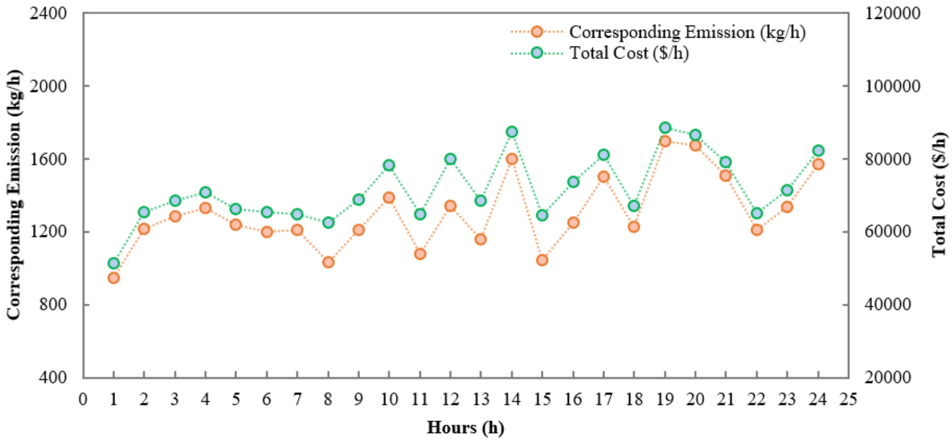

Fig. 4 - Hourly cost and corresponding emission for cost minimization using FA

4.3.1 Convergence characteristics

The convergence behavior of cost and emission for selected hours are shown in Figure 5. It found that both objective functions started to converge on the best optimal value before 50th iterations

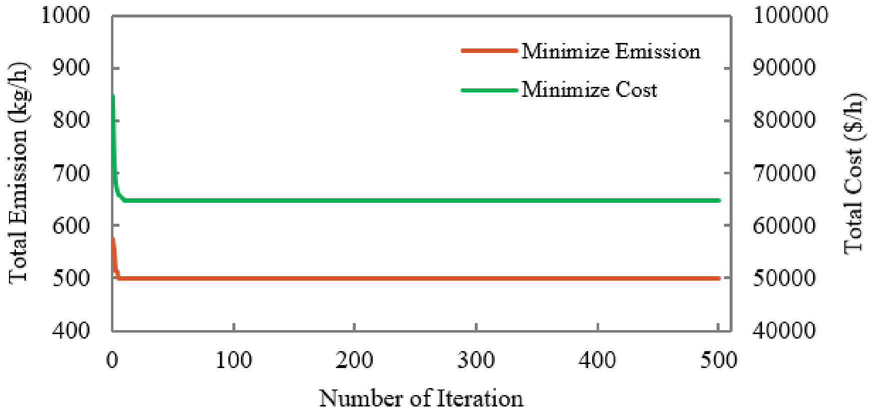

Fig. 5 - Convergence characteristic of FA for cost and emission minimization (hour 11)

4.3.1 Robustness of FA for Cost and Emission Minimization

The FA algorithm has been run for 30 times to analyze the consistency characteristic to generate the optimal cost and emission individually. The robustness describes the capability of proposed FA to obtain the consistent result after 30 trials. Figure 6 present the robustness for selected hour 11.

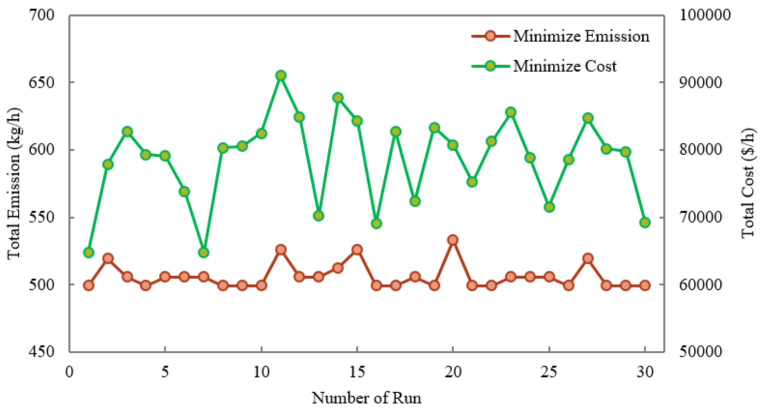

Fig. 6 - Robustness of FA for cost and emission minimization (hour 11)

4.4 Minimize both economic and emission (SCEED)

The purpose of this study is to minimize total cost and emission of the considered test system by using FA. The SCEED has been investigate using FA and Weight Sum Method (WSM).

4.4.1 Pareto front of FA using WSM

Figure 7 shows the pareto front produced by FA when the weighting factor (w) is set to 0 until 1 with steps of 0.1 for hour 12.00.

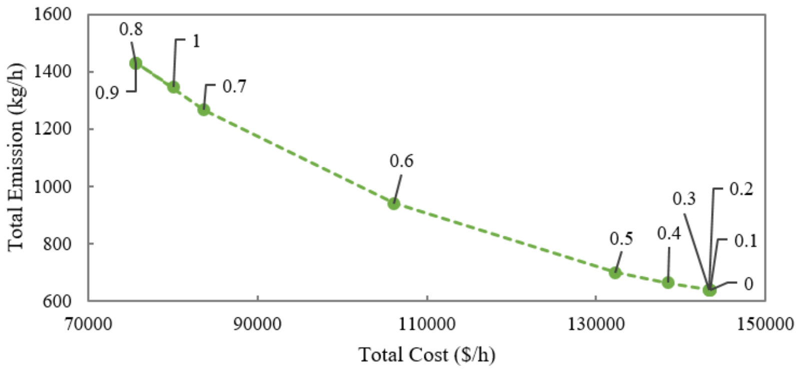

Fig. 7 - Pareto Front obtained with WSM for hours 12.00

It found that the best solution chosen is at *w*=0.6 based on Fuzzy Decision Making in equations (8) and (9).

4.4.2 SCEED for 24 hours (1 day)

Static combined economic emission dispatch (SCEED) is an optimization of both cost and emission. The optimization simulation has been run by single hours. The pareto set solution is determined by the best solution of optimization for every hour. Solar panel PV did not generate any power at hours 1.00 to 4.00 and hours 20.00 to 24.00 due to solar radiation absence. A combination of PV and thermal in generating power is at hours 5.00 to 19.00.

Figure 8 shows the best cost and emission of SCEED best compromise solution that using Pareto set solution, Weight Sum Method and Fuzzy Based Mechanism (3.7), (3.8) and (3.9).

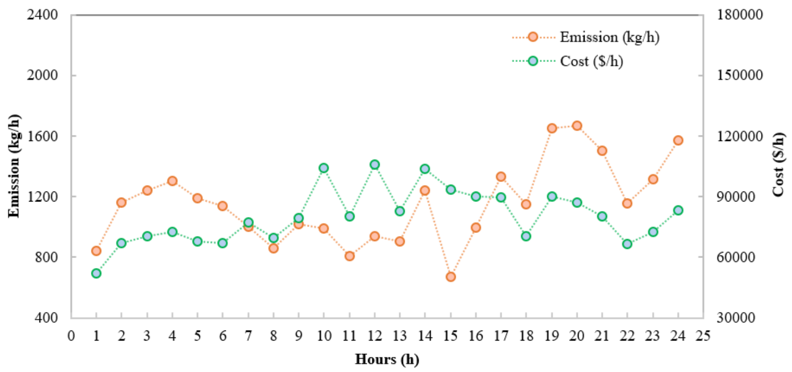

Fig. 8 - SCEED best solution

Tables 3 to 4 present the results of SCEED for hour 11.00 and 14.00 that power generate by solar system (PV) and thermal. The increase or decrease of solar share are based on the availability of solar radiation and temperature. The appropriate solar unit that ON (1) and OFF (0) influence the increase and decrease of solar share. All the thermal generation units P_1-P_6 are satisfied all the considered limits and constraints.

Table 3 - Result of SCEED at hour 11.00 (P_D 1088 MW)

Features	P1	155.180
Thermal Generation	P2	162.470
	P3	188.562
	P4	150.000
	P5	200.000
	P6	120.000
	PV_1, PV_2, … PV_{13}	1111000000000
Solar Generation	**Solar Share**	111.789
	Fuel Cost	54582.000
Cost	**Solar Cost**	25823.000
	Total Cost ($/h)	80405.364

Emission	**Emission (kg/h)**	808.670

Table 4 - Result of SCEED at hour 14.00 (P_D 1318 MW)

Features	**P1**	228.660
Thermal Generation	**P2**	200.000
	P3	273.180
	P4	150.000
	P5	200.000
	P6	120.000
Solar Generation	**PV1, PV2, … PV13**	1111110000000
	Solar Share (MW)	146.1667
Cost	**Fuel Cost**	69400.000
	Solar Cost	34593.000
	Total Cost ($/h)	103992.640
Emission	**Emission (kg/h)**	1240.900

The solar share is influencing the value of cost by turning ON and OFF the appropriate solar units. As the solar share is increased, the thermal share gets reduced for given power demand. Thus, the solar cost will increase as the solar share is increases while the thermal fuel cost and emission will get reduced. The solar share gives a greater influence on total cost compared to the thermal.

4.4.3 Convergence characteristic

The convergence characteristic in Figure 9 shows that the FA reach the optimal value before the iteration reach at 50th for every four hours. It shows that FA is effective in determining the optimal value.

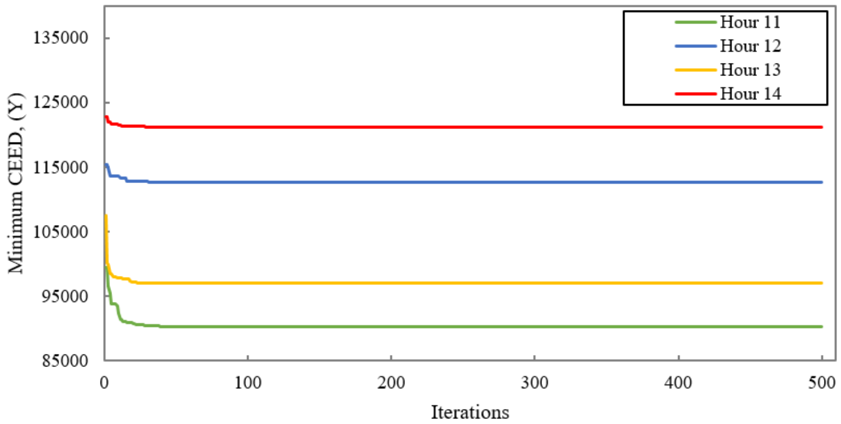

Fig. 9 - Convergence characteristic for four hours of SCEED minimization

4.5 Comparison of Best Compromise Solution

Comparison of total cost and total emission for minimize cost, minimize emission and minimize SCEED are tabulated in Table 5.

Table 5 - Total cost and total emission

Features	**Total Cost ($/h)**	**Total Emission (kg/h)**
Minimize Cost	1722707.577	31275.565
Minimize SCEED	1925391.125	27659.384
Minimize Emission	2325713.049	24128.104

Figure 10 present the optimal total cost and total emission for minimization of cost and emission individually and minimize both cost and emission.

It can be seen in minimization of cost, the total cost was the lowest but the total emission emitted was high because used more thermal at point (31275.565 kg/h, 1722707.577 $/h). In minimizing cost, the solar photovoltaic generation is optimized and thermal power generation is been fully utilized to generate electricity. The total cost is successfully optimized but the big amount of emission emitted lead to high total emission.

For emission minimization, it can be seen the total emission became lowest value and total cost at the highest value at point (24128.104 kg/h, 2325713.049 $/h). In minimizing of emission, the thermal power generation is optimized and photovoltaic been fully utilized to generate electricity. The total emission successfully optimized but the high photovoltaic prices lead to high total cost.

The combined economic and emission shows the balance between total cost and total emission at (27659.384 kg/h, 1925391.125 $/h). From the graph, the SCEED has got the best solution that satisfied economic and emission.

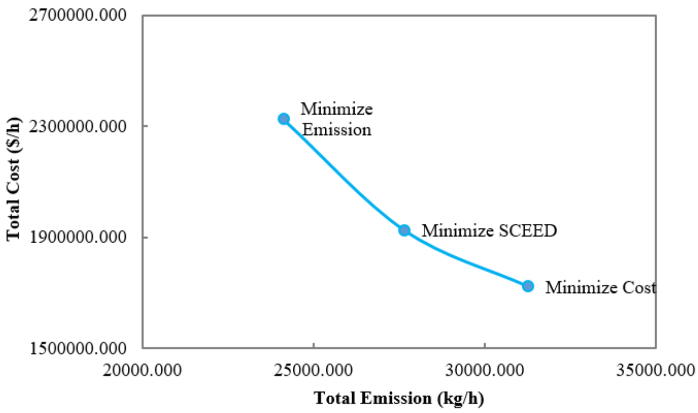

Fig. 10 - Total cost versus total emission

5. Conclusion

This paper presents the application of FA for solving the optimal economic and emission load dispatch in power generation system. This formulates the EELD problem for minimizing cost and emission of thermal and solar PV generating units. From the MATLAB simulation, it found that the total cost that obtained for minimizing cost is 1722707.577 ($/h) with corresponding emission of 31275.565 (kg/h). For minimizing emission, total cost obtained was 2325713.049 ($/h) and produced emission amount 24128.104 (kg/h). In finding the best solution of Static Combined Economic Emission Dispatch (SCEED), the Weight Sum Method (WSM) and Fuzzy Based Mechanism has been implemented. The combined economic and emission shows the balance between total cost and total emission are 27659.384 kg/h, 1925391.125 $/h respectively. From the comparison, the SCEED has obtained the best solution in optimizing the economic and emission. The effectiveness of FA in solving the optimal problem on cost and emission are investigated revealed based of the fast convergence behaviour and robustness. Thun, FA has high potential to best used for solving other type of optimization problems.

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