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Economic Load Dispatch using Moth Flame Optimization (MFO)

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ABSTRACT

This paper shows how economic load dispatch can be executed by the application of Moth flame optimization (MFO). A number of generators in a generating plant produce the required energy for the system load. It is not economical to distribute this load equally among the generators. Economic load dispatch tends to distribute the load among the generating units in such a way that minimum cost of generation is achieved while maintaining reliability of supply. In this paper, MFO was used to determine the optimal power output of each generator within the plant, which resulted in the minimum cost of fuel required to generate the needed power. This paper investigates a power plant consisting of six generating units. It shows how a load of 1800 MW was distributed among the generators in order to achieve minimum cost, possible, of generation. Moth flame optimization was applied as the search algorithm to locate the optimal power outputs of the generating units and their respective costs of generation, as well as the minimum generation cost of the entire plant. The optimal powers generated by the six generating units were 245.3896 MW, 276.3117 MW, 407.2338 MW, 276.3117 MW, 375.1506 MW, and 219.6026 MW. These power outputs were deemed optimal because they satisfy the optimization constraints and achieve a minimum generation cost of $24,121.

1. INTRODUCTION

A power system consists of many generating stations, transmission and distribution facilities. Sufficient electrical energy must be produced at suitable locations, transmitted to various load centers, and then distributed to the various consumers, while maintaining quality and reliability at an economic price. To operate an electric power system economically and make electrical energy cost-effective to the consumer is the goal of every power system. Economic operation of a power system demands that the contribution of electric power from each generator within a plant must be such that the cost of electrical energy produced is a minimum. Thus, the basic economic load dispatch problem is to reduce as much as possible the cost of generation of a given amount of power. To achieve this, the load demand on the system should not be shared by the power generating units equally. Economic load dispatch (ELD) is the achievement of optimum operation of a power system at the lowest cost possible. It determines the optimal output of a number of electricity generators, to meet the system load, at the minimum cost, subject to transmission and operational constraints (Kuma *et al.*, 2015).

Power supply must always meet the load demand, while satisfying all system constraints. Hence the size of electrical power systems are rapidly increasing in order to meet the total loads demand. The objective of ELD is to optimally distribute the system load among the committed generating units so that minimum cost is achieved. Of course, all unit and system equality and inequality constraints must be satisfied. Load demand, transmission power losses and generation cost coefficients are the parameters usually taken into consideration when ELD problem is discussed (Bakare *et al.*, 2005; Sahu and Swarnkar, 2014; Bhushan and Gawande, 2015). System load varies daily. Therefore, some generators should start up and some shut down in a certain order chosen by the power system operator to sustain optimization. This is known as unit commitment, and it is part of the ELD strategy to minimize operational cost, and transition cost (start-up/shut down cost), (Rahul and Sharma, 2006). The variable operating costs of a unit within a plant are expressed in terms of the power output of the generating unit. Fuel cost is the principal factor in ELD, and it encompasses all other costs. It is expressed in dollars per megawatt hour ($/MWh) (Grainger and Stevenson, 1994). In this paper, the most economic distribution of the power output of a plant between the generating units within the plant is determined by applying the Moth Flame Optimization. Such distribution results in the minimum cost possible for maintaining the load demand. The paper shows how the output of each of the generators within the plant is scheduled to obtain optimum cost of power supplied to the load. Many advanced approaches have been developed towards solving the economic load dispatch problem. Among them are quadratic programming (QP), interior point method (IP), linear programming (LP), lambda iteration (LI), genetic algorithm GA), Bat algorithm (BA), Moth flame optimization (MFO).

Moth flame optimization (MFO) is a bio-inspired, intelligent optimization method based on the flying property of moths towards a flame of light. In this algorithm, the moth is taken as the best solution while the position of the moth with reference to flame is taken as the solution at a given time. The MFO is very effective in searching the search or solution space as compared to other algorithms, due to the mechanism of a moth being subjected to the corresponding solution or flame. The mechanism of the MFO avoids local stagnation or premature convergence, yet speedy convergence is obtainable (Mirjalili, 2015). The MFO has been employed in this paper to optimally distribute a load of 1800 MW among six generators in order reduce generation cost to the minimum value possible. It is a robust and effective algorithm capable of locating the optimum power output and the respective cost of generation of each generator, as well as the minimum operating cost of the whole plant. Any of the optimization algorithms mentioned above can be used to generate solutions, search and locate the optimal solution. The use of the MFO to do this is the focus of this paper.

2. METHODOLOGY

2.1. Distribution of Load between Units within a Plant

The fuel cost and generated power are related by a cost function, and can be a quadratic function or a quadratic function with ripples (Vijay, 2014). Thus, the fuel cost (f_i) of the i^{th} generating unit is given in terms of the power output of the unit as follows (Grainger and Stevenson, 1994):

$$f_i = \frac{a_i}{2} P_{gi}^2 + b_i P_{gi} + c_i \tag{1}$$

P_{gi} is the power output of unit i in MW and a_i, b_i and c_i are constants.

The incremental fuel cost of the unit is given as:

$$\lambda_i = \frac{df_i}{dP_{gi}} = a_i P_{gi} + b_i \quad (2)$$

The approximate incremental fuel cost at any particular output is the additional cost in dollars per hour to increase the output by 1 MW, and in order to achieve economic load dispatch, all the units within a plant must operate at the same incremental fuel cost (Grainger and Stevenson, 1994). Thus, for a plant having two units operating under ELD:

$$\lambda = \frac{df_1}{dP_{g1}} = a_1 P_{g1} + b_1$$
$$\lambda = \frac{df_2}{dP_{g2}} = a_2 P_{g2} + b_2 \quad (3)$$

Where $\lambda =$ incremental fuel cost of plant

From Equation (3):

$$P_{g1} = \frac{\lambda - b_1}{a_1} \quad (4)$$

$$P_{g2} = \frac{\lambda - b_2}{a_2} \quad (5)$$

It can be shown from the foregoing that:

$$\lambda = a_T P_{gT} + b_T \quad (6)$$

Where:

$$a_T = \left(\sum_{i=1}^{2} \frac{1}{a_i} \right)^{-1} \quad (7)$$

$$b_T = a_T \left(\sum_{i=1}^{2} \frac{b_i}{a_i} \right) \quad (8)$$

$$P_{gT} = P_{g1} + P_{g2} \quad (9)$$

2.2. The ELD Objection Function

For a system consisting of n generating units, the total power generated is:

$$P_{gT} = \sum_{i=1}^{n} P_{gi} \quad (10)$$

The total cost of fuel for the entire plant is the sum of the fuel costs of individual generators. Thus, the cost function is given by Equation (11) while the ELD objective function is given by Equation (12) (Hosseinnezhad and Babaei, 2013; Revathy, 2014):

$$f = \sum_{i=1}^{n} f_i = \sum_{i=1}^{n} \frac{a_i}{2} P_{gi}^2 + b_i P_{gi} + c_i \tag{11}$$

Minimize:

$$f = \sum_{i=1}^{n} \frac{a_i}{2} P_{gi}^2 + b_i P_{gi} + c_i \tag{12}$$

Optimization is the optimal distribution of the total load demand (P_D) among the various generating units in order to minimize the cost of production, while satisfying some constraints. Thus, the following constraints need to be satisfied:

Equality constraint: the sum of power generated must always be equal to the total power demand on the system.

$$P_D = P_{gT} = \sum_{i=1}^{n} P_{gi} \tag{13}$$

$$\sum_{i=1}^{n} P_{gi} - P_D = 0 \tag{14}$$

Equations (13) and (14) are called power-balance equations, neglecting losses.

Inequality constraint: this is the output power constraint, which is due to physical and operational limitations of the units and components. It is given as:

$$P_{gi\,(\min)} \le P_{gi} \le P_{gi\,(\max)} \tag{15}$$

Equation (15) requires that each generating unit must operate within some limits: between minimum generation value ($P_{gi(min)}$) and the generator rating ($P_{gi(max)}$). For illustration, consider the fuel cost functions in \$/h of six units in a plant as:

$$\begin{aligned}
\text{f}_1 &= 0.002035P_{g1}^2 + 8.4321P_{g1} + 85.6348 \\
\text{f}_2 &= 0.003866P_{g2}^2 + 6.4103P_{g2} + 303.7780 \\
\text{f}_3 &= 0.002182P_{g3}^2 + 7.4289P_{g3} + 847.1484 \\
\text{f}_4 &= 0.001345P_{g4}^2 + 8.3015P_{g4} + 274.2241 \\
\text{f}_5 &= 0.002182P_{g5}^2 + 7.4289P_{g5} + 847.1484 \\
\text{f}_6 &= 0.005963P_{g6}^2 + 6.9156P_{g6} + 202.0258
\end{aligned} \tag{16}$$

$150 \le P_{gi} \le 546$, and the load is $1380 \le P_D \le 2380$

Then their incremental fuel costs, λ become:

$$\begin{aligned} \lambda_1 &= 0.00407 P_{g1} + 8.4321 \\ \lambda_2 &= 0.007732 P_{g2} + 6.4103 \\ \lambda_3 &= 0.004364 P_{g3} + 7.4289 \\ \lambda_4 &= 0.00269 P_{g4} + 8.3015 \\ \lambda_5 &= 0.004364 P_{g5} + 7.4289 \\ \lambda_6 &= 0.011926 P_{g6} + 6.9156 \end{aligned} \tag{17}$$

2.3. Moth Flame Optimization Algorithm

The moth flame optimization algorithm was applied to achieve the objective of ELD, which is to obtain minimum production cost possible, while maintaining the system load, and system constraints. This sophisticated algorithm was proposed in 2015 (Mohamad et *al*., 2018). It is a population-based algorithm. It is reported that the moth flame optimization is the best algorithm for searching the search space as compared to other algorithms. This is because the mechanism of each individual moth is subjected to the corresponding solution (flame) (Buch *et al*., 2017). This mechanism avoids the local stagnation or premature convergence of MFO algorithm. The MFO coding for ELD is as follows (Mirjalili, 2015):

Step 1: Definition of load demand, maximum and minimum power limits of generators.
Step 2: The economic load dispatch objective function is defined, as well as the equality constraints using power balance violation.
Step 3: The moth's position is mapped to the generator's power.
Step 4: With respect to the number of generating units in a system, the dimension of moth position is specified.
Step 5: Positions of moths are initialized in accordance with the maximum and minimum limits of generators.
Step 6: Set iteration to 1.
Step 7: Equation (18) is used to update flame number

$$Flame(number) = round\left(N - l\,x\frac{N-l}{T}\right) \tag{18}$$

Where l = current number of iterations, N = maximum number of flames and T = maximum number of iterations. In this work, $N = 40$, $T = 100$

Step 8: With reference to generator power limits, moths which are outside the search space are brought back.

Step 9: Sort moth's fitness and position while iteration count is one. Based on the fitness sorted, select the best moth and assign it to the flame (F_j)

Step 10: With iteration count greater than 1, moth's fitness and position are sorted, based on the previous iteration and current iteration. Select the best moth's fitness and position based on the fitness sorted and assign it to the flame (F_j).

Step 11: Equation (19) is used to compute "a"

$$a = (-1 + current\ \ iteration)\,x\left(\frac{-1}{Maximum\ \ iteration}\right) \tag{19}$$

Step 12: Equation (20) is used to compute "t"

$$t = (a-1)\,x\ \ rand + 1 \tag{20}$$

t is a random number in [-1, 1]

Step 13: Equation (21) is used to calculate the distance of moth according to the corresponding flame.

$$D_i = \left| F_j - M_i \right| \tag{21}$$

Where F_j is a position of the j^{th} flame and M_i is a position of the i^{th} moth

Step 14: Update moth's position using Equation (22)

$$Moth\_Position = D_i \, e^{bt} \cos(2\pi t) + F_j \tag{22}$$

Where b is a constant of defining the shape of a logarithmic spiral

Step 15: Increase the iteration.

Step 16: Step 7-14 are repeated until the maximum number of iteration is reached.

Step 17: Display the best flame fitness which gives the value of the objective function. This is the total cost of generation/fuel cost. The corresponding moth position is displayed too. This gives the amount of power generated in each unit.

The flow chart of moth flame optimization algorithm is given in Figure 1.

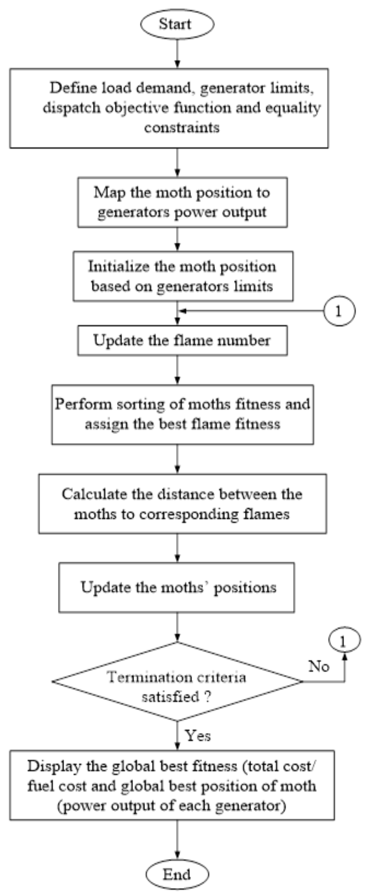

Figure 1: Moth flame optimization algorithm flow chart

Table 1 shows moth flame optimization implementation in economic load dispatch. Table 1 shows the correspondence between the syntax for MFO algorithm and that of conventional ELD solution. The information in the table was used for the MFO coding.

Table 1: Moth flame optimization implementation in economic load dispatch

Moth flame optimization	Economic dispatch
Decision variable (dimension)	Number of generating units in a system
Moths' position	Power dispatched
Fitness	Cost of generation
Lower and upper boundaries	Generator limits

3. RESULTS AND DISCUSSION

Equation (17) is plotted as shown in Figure 2. This is the incremental fuel cost versus the power outputs of the generators and the plant. The vertical dashed line denotes the load demand of 1800MW. The horizontal dashed line denotes the incremental fuel cost of the plant. It can be noted from Figure 2 that this line corresponds to incremental fuel cost of 8.4355 \$/MWh on the vertical axis. It has been stated earlier that, in order to achieve economic load dispatch, all the units within a plant must operate at the same incremental fuel cost. So to achieve economic load dispatch, all the 6 units within the plant must operate at the incremental fuel cost of 8.4355 \$/MWh. Figure 3 is the plot of output of each generating unit versus the total plant output (Equation 9) for economic operation of the plant. The dotted vertical line corresponds to 1800MW. The contribution of each generating unit to the total plant output can easily be deduced from Figure 3. Figure 3 is used to determine the power contributed by each generating unit to a given load demand or total plant output.

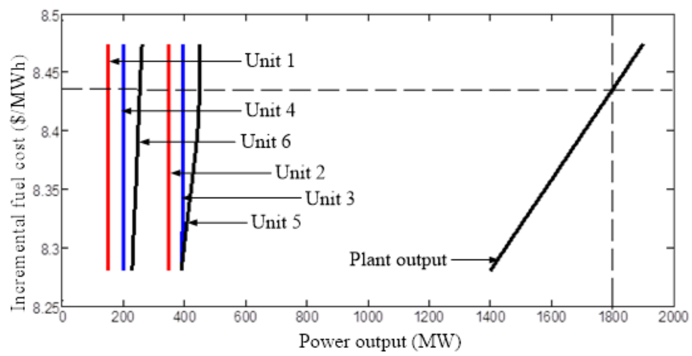

Figure 2: Incremental fuel cost versus the power outputs of the generators and the plant

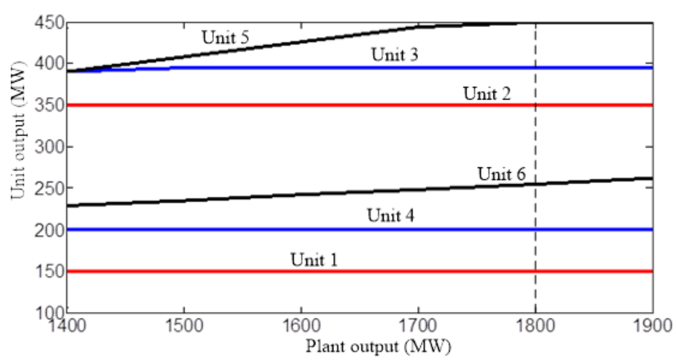

Figure 3: Output of each generating unit versus the total plant output

The cost functions of six units system for this study are given in Table 2. The information in Table 2 is not a result. It is data used to execute the MFO algorithm. It is similar to Equation (16).

Table 2: Fuel cost coefficients and generator limits of six units test system

Unit	a_i (\$/MW^{2}h)	b_i (\$/MW-h)	c_i (\$/h)	P_{max} (MW)	P_{min} (MW)
1	0.002035	8.4321	85.6348	400	150
2	0.003866	6.4103	303.7780	400	200
3	0.002182	7.4289	847.1484	500	350
4	0.001345	8.3015	274.2241	400	200
5	0.002182	7.4289	847.1484	546	270
6	0.005963	6.9156	202.0258	300	170

Load demand, P_D=1800 MW

According to the maximum number of flames given in this work (40), the optimization algorithm generated 40 sets of power outputs. Each set has six outputs in accordance with the number of generators. For want of space, only 7 of the 40 sets of power outputs are displayed here (Table 3 to Table 9). Table 3 contains the least amount of total power output (1378.3772MW) that can be generated and Table 9 contains the maximum power (2363.6951MW) that can be generated. The output power of each generating unit is shown in each of the tables. Among the 40 sets of solution Table 6 only satisfies the requirements of optimization and power balance. That is, in Table 6 the power balance equation (Equation (13)) has been satisfied. These 40 solutions are contained in the search space or solution space, and it is the function of the optimization algorithm to search the space and locate the optimal solution, which is Table 6.

Table 3: Results of optimization by MFO

Generating unit	Power generated (MW)
1	157.9582
2	206.3666
3	354.7749
4	206.3666
5	278.7726
6	174.1383
Total	1378.3772

Table 4: Results of optimization by MFO

Generating unit	Power generated (MW)
1	219.6246
2	255.6996
3	391.7747
4	255.6996
5	346.7491
6	206.2048
Total	1675.7521

Table 5: Results of optimization by MFO

Generating unit	Power generated (MW)
1	229.2749
2	263.4199
3	397.5649
4	263.4199
5	357.3869
6	211.2229
Total	1722.2894

Table 6: Results of optimization by MFO

Generating unit	Power generated (MW)
1	245.3896
2	276.3117
3	407.2338
4	276.3117
5	375.1506
6	219.6026
Total	1800

Table 7: Results of optimization by MFO

Generating unit	Power generated (MW)
1	248.0568
2	278.4454
3	408.8341
4	278.4454
5	378.0907
6	220.9895
Total	1812.8719

Table 8: Results of optimization by MFO

Generating unit	Power generated (MW)
1	255.4403
2	284.3523
3	413.2642
4	284.3523
5	386.2298
6	224.8290
Total	1848.4689

Table 9: Results of optimization by MFO

Generating unit	Power generated (MW)
1	362.2823
2	369.8259
3	477.3694
4	369.8259
5	504.0048
6	280.3868
Total	2363.6951

Having located the optimum power outputs of the generators as shown in Table 6, the algorithm computes iteratively the cost of generation (fuel cost) of these optimum power outputs of the generating units, as well as the cost (24,120.9 USD) of generation of total generated power (1800MW). These results are displayed in Table 10. About 30 iterations were performed before convergence was reached, obtaining the optimum values of cost shown in Table 10. One hundred iterations were executed. Figure 4 is the plot of iteration numbers versus cost of generation. It is the convergence curve of the ELD, obtained with the MFO algorithm. The horizontal part of the curve in Figure 4 corresponds to 24,121 USD. It shows that after many iterative computations the cost of generation converges to an optimum value of $24,121.

Table 10: Results of optimization by MFO

Generating unit	Power generated (MW)	Generation cost or fuel cost ($/hr.)
1	245.3896	2769.3
2	276.3117	3612.2
3	407.2338	6201.1
4	276.3117	3612.2
5	375.1506	4879.8
6	219.6026	3046.3
Total	1800	24,120.9

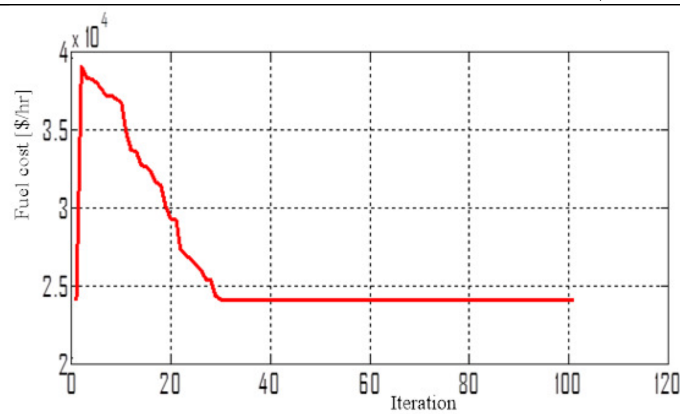

Figure: 4 Convergence curve of ELD at load demand of 1800 MW

4. CONCLUSION

The results show that the result of the fuel cost objective function optimization is $24,121, i.e., the minimum generation cost possible is $24,121. In this paper, economic load dispatch has been executed using the moth flame optimization algorithm. The MFO algorithm is an easy and efficient method of finding the optimum power outputs of the generators, the cost of running each generator, and the minimum cost of total generation. The results of the optimization process were tabulated, and plotted as well, for easy observation. The minimum cost possible of generating 1800 MW was found to be $24,121.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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