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# Solution of Unit Commitment Problem Using Monarch Butterfly Algorithm

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**Abstract**

In this paper, monarch butterfly algorithm (MBA) is used to solve the short-term unit commitment problem (UCP) and the enhanced lambda iteration (ELI) method is used to solve the economic dispatch (ED) sub-problem. Based on MBA, the migration and butterfly adjusting operators have been utilized in the operation of MBA and thus, enhanced the quality of the solution. Performance of MBA is tested on 2 test systems comprising of 4-unit and 10-unit over the scheduling time horizon of 8 hours and 24 hours respectively. Results demonstrate that the proposed method is superior to the other reported methods in the literature.

**Keywords:** economic dispatch; monarch butterfly algorithm; unit commitment

## Introduction

Unit Commitment Problem (UCP) is one of the most important optimization task which has to be performed by power engineers in a daily operation planning of power systems so that obtained generation schedule results in a great savings of dollars for power generation companies especially in a deregulated environment where each GENCO runs its own generator in order to obtain more profit. Since the load demand varies throughout the day and reaches to a different peak values from one day to another and thus, the total power generation can't be kept constant [1]. The main objective of conventional UCP is to minimize the total generation cost (operating fuel cost, start-up and shutdown costs) over the scheduling time horizon of 24-h or 168-h with 1-h time interval subject to the number of system (or coupling) and unit (or local) constraints.

Many optimization techniques have been proposed in the past to solve the UCP and mainly classified into three groups. These groups are classical (or mathematical) techniques, stochastic (or heuristic) techniques and hybrid techniques. The mostly used mathematical techniques are priority list (PL) method [2], dynamic programming (DP) [3], branch-and-bound (BB) method [4], mixed-integer linear programming (MILP) [5] and lagrangian relaxation (LR) method [6]. Out of which, PL method is fast but produces sub-optimal solution. DP faces dimensionality problem as the problem size increases. MILP requires large memory and suffers from great computation delay for large scale UCP. LR suffers from numerical convergence and solution quality problems. Although the solution produced by mathematical techniques is accurate and optimal, but requires large computation time even for medium sized UCP. The stochastic techniques are highly heuristic in nature and mainly classified as simulated annealing (SA) [7], evolutionary programming (EP) [8], genetic algorithm

(GA) [10], particle swarm optimization (PSO) [11], differential evolution (DE) [12], bacterial foraging algorithm (BFA) [13], imperialistic competition algorithm (ICA) [14], harmony search algorithm (HSA) [15] and artificial bee colony algorithm (ABC) [16]. Since these techniques are parameter sensitive and thus, require proper tuning in order to obtain the near global optimal solution in least execution time. Improper tuning of these parameters results in premature or slow convergence which may lead the solution to local optimum. Some hybrids of the methods have been also proposed in the past which utilizes the feature of one method to overcome the drawback of another method. The mainly consist hybrid methods are GA and LR [17], GA and tabu search (TS) [18], artificial neural network (ANN) and DP [19]. The hybridization reduces the search space for large scale UCP and thereby, reduces the execution time.

The MBA is a population based search algorithm based on the behavior of North American monarch butterfly [9]. MBA has been successfully applied to many non-linear large scale engineering optimization problems. In this work, monarch butterfly algorithm (MBA) is used to decide the ON/OFF status of the thermal units in each hour of the scheduling time horizon and the power generation values of the committed units are determined by solving the economic dispatch sub-problem using enhanced lambda iteration (ELI) method adopted from [20]. Moreover, the performance of MBA for UCP has been enhanced by constraints repairing and unit decommitment strategies.

The rest of the work is organized as follows: Section II presents the unit commitment (UC) problem formulation, Section III presents the mapping of MBA for UCP, Section IV provides the simulation results and their discussions and finally Section V concludes the paper.

**Problem Formulation**

**Objective Function**

The main objective of UCP is to determine the optimum ON/OFF schedule so as to minimize the total generation cost ($TC$) over the scheduling time horizon of 24-h with 1-h time interval by satisfying various system and unit constraints. Mathematically the problem to be minimized [2] is

$$TC = \sum_{t=1}^{T}\sum_{i=1}^{N}[F_i(P_i^t) + SU_{i,t}(1-U_i^{t-1})]\times U_i^t \quad (1)$$

where

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

$$SU_{i,t} = \begin{Bmatrix} HS_i,\ if\ \ T_{i,down} \le T_{i,off}^t \le T_{i,down} + T_{i,cold} \\ CS_i,\ if\ \ T_{i,off}^t > T_{i,down} + T_{i,cold} \end{Bmatrix} \quad (3)$$

where $F_i(P_i^t)$ is the quadratic fuel cost function representing production cost of $i^{th}$ unit at hour t in S/h, $a_i$, $b_i$ and $c_i$ are the fuel cost coefficients of $i^{th}$ unit, $P_i^t$ is the real power generation of $i^{th}$ unit at hour t in MW, $SU_{i,t}$ is the start-up cost of $i^{th}$ unit at hour t in S/h, $HS_i$ and $CS_i$ are the hot and cold start-up costs of $i^{th}$ unit in \$/h respectively, $U_i^t$ is the ON/OFF status of $i^{th}$ unit at hour t ($1 \rightarrow on$, $0 \rightarrow off$), $N$ is the number of thermal units, $T$ is the number of scheduling time intervals in hours, $T_{i,down}$ is the minimum-down time of $i^{th}$ unit in hours, $T_{i,off}^t$ is the continuously-off time of $i^{th}$ unit till time t in hours, $T_{i,cold}$ is the cold start-up time of $i^{th}$ unit in hours.

**Constraints**

The various system and unit constraints imposed on the system are:

*Power balance constraint:* The generated power must be equal to the load demand as follows

$$\sum_{i=1}^{N} P_i^t U_i^t - P_D^t = 0 \qquad (4)$$

where $P_D^t$ is the load demand at hour t in MW.

*Spinning reserve constraint:* System spinning reserve is expressed as excess power generation as follows

$$\sum_{i=1}^{N} P_i^{\max} U_i^t \geq P_D^t + R^t \qquad (5)$$

where $P_i^{\max}$ is the maximum power generation capacity of $i^{th}$ unit in MW, $R^t$ is the system spinning reserve at hour t in MW.

*Generation limit constraint:* Each committed unit must be within its specified generation limits as follows

$$P_i^{\min} U_i^t \leq P_i^t \leq P_i^{\max} U_i^t \qquad (6)$$

where $P_i^{\min}$ is the minimum power generation capacity of $i^{th}$ unit in MW

*Minimum up and down time constraint:* A unit must be on/off for a minimum number of hours before committing and decommitting as follows

$$U_i^t = \begin{cases} 0 \rightarrow 1, \; if \;\; T_{i,off}^{t-1} \geq T_{i,down} \\ 1 \rightarrow 0, \; if \;\; T_{i,on}^{t-1} \geq T_{i,up} \\ 0 \; or \; 1, \; otherwise \end{cases} \qquad (7)$$

where $T_{i,up}$ is the minimum-up time of $i^{th}$ unit in hours, $T_{i,on}^{t-1}$ is the continuously ON time of $i^{th}$ unit till hour (t-1) in hours.

**Monarch Butterfly Algorithm (MBA) For Unit Commitment Problem (UCP)**

In this section, the implementation of MBA for UCP has been presented. The control parameters involved in MBA are population size, butterfly adjusting rate, max walk step, migration period, migration ratio and the maximum generations required for obtaining the optimal solution for UCP.

**Representation of Chromosomes for UCP**

In UCP, the decision variables are binary strings which show the ON/OFF status of the thermal units over the complete scheduling time horizon. If *N* is the total number of thermal units and *T* is the complete scheduling time intervals, then a chromosome in a population consist of $N \times T$ binary bits. Each bit in a chromosome represents a gene having 1 or 0 binary values. A chromosome in a population itself represents an individual solution for UCP.

**Population Initialization**

For the complete $N_P$ chromosomes, each chromosome $X_j$ is randomly initialized as follows

$$X_j = [x_j^1 \; x_j^2 \ldots x_j^d \ldots x_j^n] \; ; \; j \in \{1, 2, \ldots, N_P\} \; ; d \in \{1, 2, \ldots, n\} \qquad (8)$$

where *j* represents the chromosome in a population, *d* represents the dimension of a chromosome, *n* represents the total number of binary variables equals to $N \times T$ binary bits and $N_P$ is the population size (number of chromosomes). The position of $x_j^d$ is generated using a uniformly distributed random number, which generates either 0 or 1 and they are equally likely.

**Fitness Function Evaluation**

After generating the initial population, the economic dispatch (ED) has to be performed only on feasible chromosomes so as to economically dispatch the load demand in each hour of the scheduling time horizon. The enhanced lambda iteration (ELI) algorithm is used to solve the ED sub-problem and then the production cost can be calculated using (2). The fitness of each chromosome is the total generation cost (*TC*) which can be calculated using (1). The chromosome having least *TC* has the highest fitness value.

**Generate trial solutions**

After random initializing the monarch butterflies positions in a search space using Eq. (8), each butterfly update its current position $X_j$ using butterfly migration and adjusting operators. By idealizing the migration behavior of the monarch butterfly individuals, MBA method can be formed. According to Monarch Butterfly Algorithm (MBA), firstly, all the parameters are initialized followed by the generation of initial population and evaluation of the same by means of its fitness function. Subsequently, the positions of all monarch butterflies are updated step by step until certain conditions are satisfied. It should be mentioned that, in order to make the population fixed and reduce fitness evaluations, the number of monarch butterflies, generated by migration operator and butterfly adjusting operator, are NP1 and NP2, respectively. The procedural steps of MBA for solving UCP are described as follows:

**Step 1: Initialization.** Set the generation counter $t = 1$; initialize the population *X* of *NP* monarch butterfly individuals randomly; set the maximum generation $g_{max}$, monarch butterfly number $NP_1$ in Land 1 and monarch butterfly number $NP_2$ in Land 2, max step $S_{max}$, butterfly adjusting rate BAR, migration period *peri*, and the migration ratio *p*.

**Step 2: Fitness evaluation.** Evaluate each monarch butterfly according to its position.

**Step 3:** While the best solution is not found or $t < g_{max}$ do

Sort all the monarch butterfly individuals according to their fitness.

Divide monarch butterfly individuals into two subpopulations (Land 1 and Land 2);

for $i = 1$ to $NP_1$ (for all monarch butterflies in Subpopulation 1) do

Generate new Subpopulation 1 according to Algorithm 1 [9].

end for i

for j = 1 to NP2 (for all monarch butterflies in Subpopulation 2) do

Generate new Subpopulation 2 according to Algorithm 2 [9].

end for *j*

Combine the two newly-generated subpopulations into one whole population;

Evaluate the population according to the newly updated positions;

$t = t + 1$.

**Step 4:** end while

**Step 5:** Output the best solution

**Repairing Infeasible Solutions**

When the solution is randomly initialized and whenever the modification in the solution is made throughout the search process, the infeasible solutions have to be repaired in order to improve the solution quality at faster rate. The constraints in (5) and (7) have been repaired based on the strategies adopted from [11].

**Simulation Results**

To demonstrate the feasibility and effectiveness of the proposed MBA method for UCP, MBA method is applied to two test systems comprising of 4-unit and 10-units over the scheduling time intervals of 8-hour and 24-hour respectively. The spinning reserve is considered as 10% of the total load demand in each hour of the scheduling time horizon and thus, reduced the probability of load interruptions [7]. The simulation is performed on Intel core2duo, 2.20 GHz processor PC and written in MATLAB 7.9.

**Test System 1**

This test system comprises of 4 thermal units over the scheduling time horizon of 8 hours with 1-h time interval. The cost characteristics and load demand are adopted from [1] and mentioned in Tables I and II respectively. For this system, the population size was kept 10 and the maximum generation count was kept 100. The range of $S_{\max}$ is [0, 1]. The higher value of $S_{\max}$ at the beginning of the process is used to emphasize the exploration capability of the search process that decreases gradually with the lapse of cycles to reach $S_{\min}$ to exploit the search space and thereby, balance the exploration and exploitation process of the search. In order to maintain the diversity in the solution search space, the optimal settings of butterfly adjusting rate (BAR) and migration ratio (*p*) are essential. Whenever slow or premature convergence is observed, the values of BAR and *p* are increased or decreased respectively. The optimal value of migration period (*peri*) is set as 1.2 for both the systems.

The best UC schedule along with the dispatch values, production cost ( $P_{cost}$ ), start-up cost ( $SU$ ) and total generation cost (*TC*) are listed in Table III. From Table III, it can be deduced that the obtained UC schedule has satisfied all the problem constraints and thus, produces the quality solution. Also, the total online capacity of generators in each hour of the scheduling time horizon is more than the load plus spinning reserve requirements. The same problem was also solved with GA and compared with MBA and the results are presented in Table IV which also presents the comparison of obtained results with that of LR. Since, it is a small system comprising of 4 thermal units, best cost was also achieved by GA but the difference is found in terms of CPU time.

Table 1 : Unit Characteristics for 4-Unit System [1]

| | **Unit 1** | **Unit 2** | **Unit 3** | **Unit 4** |
|---|---|---|---|---|
| $P_i^{\max}$ (MW) | 80 | 250 | 300 | 60 |
| $P_i^{\min}$ (MW) | 25 | 60 | 75 | 20 |
| $a_i$ ($/h) | 213.00 | 585.62 | 684.74 | 252.00 |
| $b_i$ ($/MWh) | 20.875 | 17.998 | 17.458 | 23.800 |
| $c_i$ ($/MW$^2$h) | 0.00396 | 0.00261 | 0.00289 | 0.0051 |
| $INS_i$ (h) | -5 | 8 | 8 | -6 |

| | Unit 1 | Unit 2 | Unit 3 | Unit 4 |
|---|---|---|---|---|
| $T_{i,up}$ (h) | 4 | 5 | 5 | 1 |
| $T_{i,down}$ (h) | 2 | 3 | 4 | 1 |
| $HS_i$ ($) | 150 | 170 | 500 | 0 |
| $CS_i$ ($) | 350 | 400 | 1100 | 0.02 |
| $T_{i,cold}$ (h) | 4 | 5 | 5 | 0 |

Table 2 : Load Pattern For 4-Unit System [1]

| **Hour (h)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|---|---|
| **Load (MW)** | 450 | 530 | 600 | 540 | 400 | 280 | 290 | 500 |

Table 3 : Optimal Generation Schedule For 4-Unit System

| ***T*** | **Dispatch Values (MW)** | | | | $P_{cost}$ **($)** | ***SU*** **($)** | ***TC*** **($)** |
|---|---|---|---|---|---|---|---|
| | **U1** | **U2** | **U3** | **U4** | | | |
| 1 | 25 | 174.23 | 250.77 | 0 | 9782.53 | 150 | 9932.53 |
| 2 | 25 | 216.27 | 288.73 | 0 | 11303.69 | 0 | 11303.69 |
| 3 | 30 | 250 | 300 | 20 | 13003.46 | 0.02 | 13003.48 |
| 4 | 25 | 221.52 | 293.48 | 0 | 11495.29 | 0 | 11495.29 |
| 5 | 0 | 161.09 | 238.91 | 0 | 8573.23 | 0 | 8573.23 |
| 6 | 0 | 98.03 | 181.97 | 0 | 6332.32 | 0 | 6332.32 |
| 7 | 0 | 103.29 | 186.71 | 0 | 6517.54 | 0 | 6517.54 |
| 8 | 0 | 213.63 | 286.37 | 0 | 10470.83 | 0 | 10470.83 |
| **Total generation cost in 8-h ($)** | | | | | **77,478.89** | **150.02** | **77,628.91** |

Table 4 : Comparison in Terms of Cost ($) and CPU Time (s)

| **Method** | **Cost ($)** | **CPU time (S)** |
|---|---|---|
| LR [6] | 76,975.33 | 2.5 |
| GA | 77,628.91 | 3.96 |
| MBA | 77,628.91 | 1.62 |

**Test System 2**

This test system comprises of 10 thermal units over the scheduling time horizon of 24 hours with 1-h time interval. The cost characteristics and load demand are adopted from [14] and presented in Tables V and VI respectively. In order to fine tune the MBA parameters, the simulation was repeated for 10 random trials. In each trial, the population size was kept 30 to show the effect of small population size and the maximum number of generations was kept 100, in order to reduce the computational efforts.

Table 5 : Unit Characteristics for 10-Unit System [14]

| | **Unit 1** | **Unit 2** | **Unit 3** | **Unit 4** | **Unit 5** |
|---|---|---|---|---|---|
| $P_i^{max}$ (MW) | 455 | 455 | 130 | 130 | 162 |
| $P_i^{min}$ (MW) | 150 | 150 | 20 | 20 | 25 |
| $a_i$ (\$/h) | 1000 | 970 | 700 | 680 | 450 |
| $b_i$ (\$/MWh) | 16.19 | 17.26 | 16.60 | 16.50 | 19.70 |
| $c_i$ (\$/MW$^2$h) | 0.00048 | 0.00031 | 0.00200 | 0.00211 | 0.00398 |
| $INS_i$ (h) | 8 | 8 | -5 | -5 | -6 |
| $T_{i,up}$ (h) | 8 | 8 | 5 | 5 | 6 |
| $T_{i,down}$ (h) | 8 | 8 | 5 | 5 | 6 |
| $HS_i$ (\$) | 4500 | 5000 | 550 | 560 | 900 |
| $CS_i$ (\$) | 9000 | 10000 | 1100 | 1120 | 1800 |
| $T_{i,cold}$ (h) | 5 | 5 | 4 | 4 | 4 |
| | **Unit 6** | **Unit 7** | **Unit 8** | **Unit 9** | **Unit 10** |
| $P_i^{max}$ (MW) | 80 | 85 | 55 | 55 | 55 |
| $P_i^{min}$ (MW) | 20 | 25 | 10 | 10 | 10 |
| $a_i$ (\$/h) | 370 | 480 | 660 | 665 | 670 |
| $b_i$ (\$/MWh) | 22.26 | 27.74 | 25.92 | 27.27 | 27.79 |
| $c_i$ (\$/MW$^2$h) | 0.00712 | 0.00079 | 0.00413 | 0.00222 | 0.00173 |
| $INS_i$ (h) | -3 | -3 | -1 | -1 | -1 |
| $T_{i,up}$ (h) | 3 | 3 | 1 | 1 | 1 |
| $T_{i,down}$ (h) | 3 | 3 | 1 | 1 | 1 |
| $HS_i$ (\$) | 170 | 260 | 30 | 30 | 30 |
| $CS_i$ (\$) | 340 | 520 | 60 | 60 | 60 |
| $T_{i,cold}$ (h) | 2 | 2 | 0 | 0 | 0 |

Table 6 :Load Pattern for 10-Unit System [14]

| **Hour (h)** | **Load (MW)** | **Hour (h)** | **Load (MW)** | **Hour (h)** | **Load (MW)** |
|---|---|---|---|---|---|
| 1 | 700 | 9 | 1300 | 17 | 1000 |
| 2 | 750 | 10 | 1400 | 18 | 1100 |
| 3 | 850 | 11 | 1450 | 19 | 1200 |
| 4 | 950 | 12 | 1500 | 20 | 1400 |
| 5 | 1000 | 13 | 1400 | 21 | 1300 |
| 6 | 1100 | 14 | 1300 | 22 | 1100 |

| Hour (h) | Load (MW) | Hour (h) | Load (MW) | Hour (h) | Load (MW) |
|---|---|---|---|---|---|
| 7 | 1150 | 15 | 1200 | 23 | 900 |
| 8 | 1200 | 16 | 1050 | 24 | 800 |

The range of $S_{max}$ is kept as [0, 1]. The higher value of $S_{max}$ at the beginning of the process is used to emphasize the exploration capability of the search process that decreases gradually with the lapse of cycles to reach $S_{min}$ to exploit the search space and thereby, balance the exploration and exploitation process. The value of BAR and $p$ are kept as 0.42. Whenever slow or premature convergence is observed, the values of BAR and $p$ are increased or decreased respectively.

Table 7 :Optimal Generation Schedule for 10-Unit System

| ***T*** | **Generating Unit** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| 1 | 455 | 245 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 455 | 295 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 455 | 370 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 0 |
| 4 | 455 | 455 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 |
| 5 | 455 | 390 | 0 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 6 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 7 | 455 | 410 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 8 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 |
| 9 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 |
| 10 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 |
| 11 | 455 | 455 | 130 | 130 | 162 | 73 | 25 | 10 | 10 | 0 |
| 12 | 455 | 455 | 130 | 130 | 162 | 80 | 25 | 43 | 10 | 10 |
| 13 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 |
| 14 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 |
| 15 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 |
| 16 | 455 | 310 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 17 | 455 | 260 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 18 | 455 | 360 | 130 | 130 | 25 | 0 | 0 | 0 | 0 | 0 |
| 19 | 455 | 455 | 130 | 130 | 30 | 0 | 0 | 0 | 0 | 0 |
| 20 | 455 | 455 | 130 | 130 | 162 | 33 | 25 | 10 | 0 | 0 |
| 21 | 455 | 455 | 130 | 130 | 85 | 20 | 25 | 0 | 0 | 0 |
| 22 | 455 | 455 | 0 | 0 | 145 | 20 | 25 | 0 | 0 | 0 |
| 23 | 455 | 425 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| 24 | 455 | 345 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 8: Best Cost Solution for 10-Unit System

| ***T*** | $P_{cost}$ **(\$/h)** | ***SU* (\$/h)** | ***TC* (\$/h)** | ***T*** | $P_{cost}$ **(\$/h)** | ***SU* (\$/h)** | ***TC* (\$/h)** |
|---|---|---|---|---|---|---|---|
| 1 | 13683 | 0 | 13683 | 13 | 30058 | 0 | 30058 |
| 2 | 14555 | 0 | 14555 | 14 | 27251 | 0 | 27251 |
| 3 | 16809 | 900 | 17709 | 15 | 24150 | 0 | 24150 |
| 4 | 18598 | 0 | 18598 | 16 | 21514 | 0 | 21514 |
| 5 | 20020 | 560 | 20580 | 17 | 20642 | 0 | 20642 |
| 6 | 22387 | 1100 | 23487 | 18 | 22387 | 0 | 22387 |
| 7 | 23262 | 0 | 23262 | 19 | 24150 | 0 | 24150 |
| 8 | 24150 | 0 | 24150 | 20 | 30058 | 490 | 30548 |
| 9 | 27251 | 860 | 28111 | 21 | 27251 | 0 | 27251 |
| 10 | 30058 | 60 | 30118 | 22 | 22736 | 0 | 22736 |
| 11 | 31916 | 60 | 31976 | 23 | 17645 | 0 | 17645 |
| 12 | 33890 | 60 | 33950 | 24 | 15427 | 0 | 15427 |
| **Total generation cost in 24-h (\$)** | | | | | **559,848** | **4090** | **563,938** |

[a] All decimals are rounded off to the nearest integers.

The simulation was again repeated 20 times on the best found parameters mentioned above. The best generation schedule obtained in a set of 20 independent runs is presented in Table VII whereas Table VIII shows the cost solution comprising of production cost ($P_{cost}$), start-up cost ($SU$) and total generation cost ($TC$) obtained on the best generation schedule mentioned in Table VII. From Table VII, it can be inferred that the obtained UC schedule has satisfied all the problem constraints imposed on the system and thus, produces the quality solution. Fig. 1 shows the convergence graph for GA and MBA for solving UCP and it is revealed that the quality of the solution has been enhanced by using MBA. Fig. 2 shows the curves for total online capacity of units, load and spinning reserves and it is inferred that the sufficient amount of generation is available in each hour which can satisfy the load plus reserve requirements.

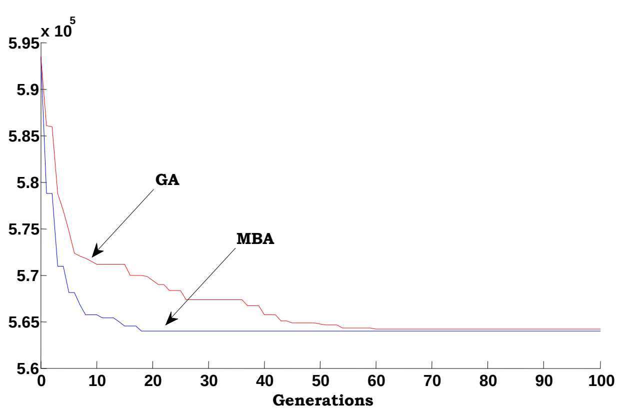


Fig. 1. Convergence characteristics of MBA and GA for 10-unit system.

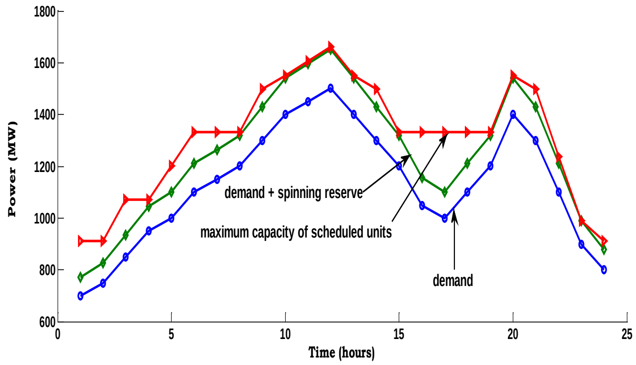


Fig. 2. Online capacity, load and spinning reserve curves for 10-unit system.

Table IX shows the comparison of MBA solution with the other classical and stochastic methods reported in the literature like enhanced priority list (EPL), lagrangian relaxation (LR), simulated annealing (SA), evolutionary programming (EP), improved binary particle swarm optimization (IBPSO), differential evolution (DE), bacterial foraging algorithm (BFA), imperialistic competition algorithm (ICA), harmony search algorithm (HSA), binary/real artificial bee colony algorithm (BRABC), hybrid of LR and GA (LRGA). From Table IX, it is revealed that MBA produces quality solution in terms of total generation cost compared to most of the methods. Although the BRABC method produces approximately the same best cost solution, but computationally slow compared to the proposed MBA method. Moreover, the CPU time taken by EPL and SA are less than that of MBA, but produce sub-optimal cost solutions compared to the proposed MBA method.

Table 9 : Performance Comparison of Proposed MBA with the Other Methods for 10-Unit System

| **Method** | **Best Cost ($)** | **Mean Cost ($)** | **Worst Cost ($)** | **Time (s)** |
|---|---|---|---|---|
| EPL [2] | 563,977 | - | - | 0.72 |
| LR [6] | 565,673.13 | - | - | 6.9 |
| SA [7] | 565,828 | 565,988 | 566,260 | 3.35 |
| EP [8] | 564,551 | 565,352 | 566,231 | 100 |
| IBPSO [11] | 563,977 | 564,155 | 565,312 | 27 |
| DE [12] | 563,938 | - | - | 27.4 |
| BFA [13] | 564,842 | - | - | 110 |
| ICA [14] | 563,938 | 564,408 | - | 48 |
| HSA [15] | 565,827 | - | - | 79 |
| BRABC [16] | 563,937.72 | 564,040 | 565,640 | 40.75 |
| LRGA [17] | 564,800 | - | - | 518 |
| GA | 564,217.08 | 564,377.21 | 564,878.96 | 31.11 |
| **MBA** | **563,937.17** | **563,979.12** | **564,036.22** | **3.78** |

**Conclusions**

In this paper, monarch butterfly algorithm (MBA) is successfully implemented to solve the unit commitment problem (UCP) for 4-unit and 10-unit test systems over the scheduling time horizon of 8 hours and 24 hours respectively and enhanced lambda iteration (ELI) method is used to solve the economic dispatch (ED) sub-problem. The problem specific operators used in MBA have reduced the chance of search to get trapped at local optimum solution during the iterative process. Moreover, the constraint repairing strategies keep the search space feasible and thus, accelerate the convergence process. The obtained results demonstrate the robustness of the proposed MBA method for UCP.

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