A Modified Artificial Bee Colony Algorithm Application for Economic Environmental Dispatch

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Abstract. In conventional fossil-fuel power systems, the economic environmental dispatch (EED) problem is a major problem that optimally determines the output power of generating units in a way that cost of total production and emission level be minimized simultaneously, and at the same time all the constraints of units and system are satisfied properly. To solve EED problem which is a non-convex optimization problem, a modified artificial bee colony (MABC) algorithm is proposed in this paper. This algorithm by implementing weighted sum method is applied on two test systems, and eventually, obtained results are compared with other reported results. Comparison of results confirms superiority and efficiency of proposed method clearly.

1. Introduction

Traditionally, the main goal of power system operators was only determining of optimal output power of generating units with minimum fuel cost for system and environmental pollution was not considered as an important problem. But in recent years, regulations of governments due to increasing concerns on environmental issues have led to taking this issue into consideration seriously. Therefore, power utilities must plan to reduce emissions of generating units because of mentioned regulations [1]. So, minimizing of fuel cost and emission level of generating units simultaneously is the aim of power system operators nowadays.

In recent years, numerous intelligent optimization methods have been used to solve EED problem, some of which are: the genetic algorithm (GA) [2-6], the evolutionary programming (EP) [7-9], the particle swarm optimization (PSO) [10-11], the interactive honey bee mating optimization (IHBMO) algorithm [12], the artificial bee colony algorithm [14, 16], the multi-objective differential evolution (MODE) [2, 16], the harmony search algorithm [17], the gravitational search algorithm [18], the ant colony optimization [19], the flower pollination algorithm [20] and several hybrid and combined methods.

The ABC algorithm is a relatively new intelligent swarm-based optimization technique which is introduced by Karaboga in 2005 [21]. The ABC algorithm has been widely utilized to handle with various optimization problems due to its advantages including simple concept, easy-to-use, flexibility and powerful exploration capability. Nevertheless, some disadvantages such as poor exploitation capability and low convergence rate can cause major difficulties in more complex problems [22].

In this paper, a modified artificial bee colony algorithm has been used for solution of EED problem. The main advantages and superiority of proposed method are listed below:
1) The original ABC algorithm has some weaknesses such as inappropriate exploitation ability and convergence rate besides its powerful features. To overcome this weakness and improvement of algorithm performance, three modifications have been exerted in EED problem and the ABC algorithm procedure. The purpose of these modifications is to improve the exploitation capability of algorithm and to enhance its convergence rate by preventing impracticable solutions generation.

2) In comparison with other reported methods, better results are obtained. The superiority of obtained results in terms of minimizing emission and generating cost and computation time, is demonstrated clearly in following sections of paper.

3) The promising performance of proposed method in handling with complex non-convex optimization problems indicates that this method can be considered as an appropriate and powerful technique to solve complicated problems.

To solve EED problem that is a multi-objective problem, the weighted sum technique is employed in solution method of this paper. The weighted sum is a well-known technique for solving of multi-objective problems which converts several objectives to a single objective with specific weights [23]. Eventually, the proposed modified ABC algorithm by employment of weighted sum technique is tested on two different systems and then compared with results of other reported methods in order to assess its efficiency.

The arrangement of this paper is done as follows. Section 2 explains the formulation details of economic environmental dispatch (EED) problem. Section 3 describes the problem solution. Section 4 provides obtained results and comparison with results of other reported methods. Finally, Section 5 concludes the paper.

2. Formulation of the EED Problem

To solve EED problem which is a constrained multi-objective optimization problem, the optimum output power of generating units should be determined in a way that cost and emission level are minimized simultaneously while satisfying all constraints of system and units. Above-mentioned objectives and constraints are explained as follows:

2.1 Fuel cost

By considering valve-point loading effect [6], total fuel cost of generating units is expressed as (1):

\[
F = \sum_{i=1}^{N_G} [a_i + b_i P_i + c_i P_i^2 + d_i \sin(e_i (P_i^{\text{min}} - P_i))] \tag{1}
\]

where \(a_i, b_i, c_i, d_i\) and \(e_i\) are cost coefficients of \(i\)th generating unit; \(N_G\) is total number of the system generating units; \(P_i^{\text{min}}\) and \(P_i\) are lower limit of output power and actual output power of \(i\)th unit, respectively.

2.2 Emission

Due to using fossil fuel to generate electric power, some pollutants such as NO\(_x\) and SO\(_x\) are released into the air. Emission function of these pollutants can be expressed separately [25], but in this paper, emission function is a quadratic and exponential function which includes both mentioned pollutants [26]. Therefore, the emission function is expressed as follows:

\[
E = \sum_{i=1}^{N_G} [\alpha_i + \beta_i P_i + \gamma_i P_i^2 + \eta_i \exp(\delta_i P_i)] \tag{2}
\]

where \(\alpha_i, \beta_i, \gamma_i, \eta_i\) and \(\delta_i\) are emission coefficients of \(i\)th generating unit.

2.3 Constraints

\textit{Power balance:} The constraint of power balance is given as (3)

\[
\sum_{i=1}^{N_G} P_i = P_D + P_{\text{LOSS}} \tag{3}
\]
where \( P_D \) and \( P_{\text{LOSS}} \) are the demand of system and power loss of transmission lines, respectively. 
\( P_{\text{LOSS}} \) is typically expressed by using B-coefficient method [27]. Therefore, the system power loss equation is given as below:

\[
P_{\text{LOSS}} = \sum_{i=1}^{N_G} \sum_{k=1}^{N_{ik}} P_i B_{ik} P_k + \sum_{i=1}^{N_{ik}} P_i B_{i0} + B_{00} \quad \quad (4)
\]

**Generation limits:** The output power of each generating unit should be within its lower and upper boundaries. These limits are represented by (5)

\[
P_i^{\text{min}} < P_i < P_i^{\text{max}} \quad (i = 1, \ldots, N_G) \quad \quad (5)
\]

where \( P_i^{\text{min}} \) and \( P_i^{\text{max}} \) are lower and upper boundaries of power generation for \( i \)th unit.

### 3. Problem Solution

#### 3.1 Artificial Bee Colony

The artificial bee colony (ABC) algorithm is an intelligent optimization method introduced by Karaboga in 2005 [21]. The ABC algorithm animated the sagacious behavior of honeybees for food attainment.

The colony of artificial bees consists of three types of bees, which are called as employed, onlookers, and scout bees. The employed bees compose one-half of the colony, and the onlooker bees compose second half of it. For every food source, only one employed bee is allocated.

At first, ABC algorithm produces an initial random population of \( P \) solutions with \( D \) elements, where \( P \) and \( D \) are the numbers of population members and the number of problem parameters, respectively. In the ABC algorithm, each food source position represents a feasible solution, and its nectar quality shows the quality of the related solution. The initial population is generated as below:

\[
x^j_i = x^j_{\text{min}} + \text{rand} (0,1)(x^j_{\text{max}} - x^j_{\text{min}}) \quad i = 1, 2, \ldots, P \quad \quad (6)
\]

where \( j=1,2,\ldots,D \) and \( x^j_{\text{min}} \) and \( x^j_{\text{max}} \) indicate minimum and maximum limits of the parameter \( j \), respectively. Furthermore, \( x^j_i \) represents a food source position.

Assessment of solutions is executed subsequently, and then it is applied to repetitive cycles of the algorithm. In each cycle, the employed bees produce a new position (solution) which is called neighboring food source and then assesses the quality of content (fitness value) of the new position (new solution). The mentioned neighboring food source \( (v) \) is generated as follows:

\[
v_{ij} = x_{ij} + \phi_{ij} (x_{ij} - x_{ij}) \quad i = 1, 2, \ldots, P \quad \quad (7)
\]

where \( j \) is a random integer number in the range of \([1, D]\), \( k \) is a random integer number in the range of \([1, P]\) which should not be the same as \( i \) and \( \phi_{ij} \) is a random number in the range of \([-1,1]\). The employed bee compares the new and old solution and memorizes the solution with higher quality. When all of the employed bees complete their process, they share the obtained information related to the food sources with the onlooker bees which are waiting in the dancing area of the hive by waggle dancing. After that, the onlooker bee starts to evaluate the information of all employed bees and subsequently selects a food source according to the probability of each source. For defining mentioned probabilities, the fitness value of each solution should be computed. Fitness value of solution \( i \) is calculated as follows:

\[
\text{Fitness}_i = \begin{cases} 
1 & f_i \geq 0 \\
1 + \text{abs}(f_i) & f_i < 0 
\end{cases} \quad \quad (8)
\]

where \( \text{Fitness}_i \) and \( f_i \) are the fitness value and the cost value of a solution \( i \), respectively.

For calculating the being chosen probability for each food source, equation \((9) \) is employed:

\[
P_i = \frac{\text{Fitness}_i}{\sum_{i=1}^{SN} \text{Fitness}_i} \quad \quad (9)
\]
A food source (solution) with better content clearly will absorb more onlooker bees in comparison with poor one. According to aforementioned probabilities, onlooker bees choose their food sources and then similar to the employed bees, the operations of producing a neighbor food source position, assessment, comparison and choosing the better one are executed.

During the ABC algorithm procedure, every solution has a chance of a predetermined number of cycles to be improved (which is known as a limit parameter). When no improvement occurs, the allocated employed bee leaves that food source and after that changes to a scout bee and begins its search process for a new food source. The mentioned procedure is repeated for a certain number of cycles which is called by maximum cycle number (MCN).

3.2 Modifications of problem and ABC algorithm

3.2.1 Specifying slack generating unit and its generation

To satisfy of power balance constraint perennially, one generating unit is determined as a slack unit [28]. In this case, generation of slack unit is specified by total generation of residual \( N_G - 1 \) units as follows:

\[
P_s = P_D + P_L - \sum_{i=1}^{N_G} P_i
\]

where \( s \) is the chosen unit as slack one.

Therefore, the system power loss equation should be rewritten as (11):

\[
P_L = B_s P_s^2 + (2 \sum_{i=1}^{N_G} B_i P_i + B_{0s}) P_s + \sum_{i=1}^{N_G} \sum_{j=1}^{N_G} B_{ij} P_i P_j + \sum_{i=1}^{N_G} B_{0i} P_i + B_{0s}
\]

Combining (10) and (11) results in:

\[
B_s P_s^2 + (2 \sum_{i=1}^{N_G} B_i P_i + B_{0s} - 1) P_s + (P_D + \sum_{i=1}^{N_G-1} \sum_{j=1}^{N_G} P_i B_{ij} P_j + \sum_{i=1}^{N_G-1} B_{0i} P_i - \sum_{i=1}^{N_G-1} P_i + B_{0s}) = 0
\]

By solving (12) generation of the slack unit will be determined.

3.2.2 Enhancement of ABC algorithm exploitation ability

To improve the ABC algorithm weakness in exploitation, two changes are implemented in the process of ABC algorithm:

1) In the process of producing new food source, onlooker bees can be propelled towards better positions. For this purpose, influenced by PSO [29], a global best solution which is achieved from prior cycles of the algorithm, can be employed. So the generation of new food source (solution) by onlooker bees is carried out as below:

\[
v_{ij} = x_{ij} + \phi_{ij} (x_{ij} - x_{gij}) + \beta (G_{best} - x_{gij})
\]

where \( G_{best} \) is the best solution of the algorithm in previous cycles and \( \beta \) is a random number in \([-1,1]\).

Scout bees have the analogous procedure. After quitting of a food source by its employed bee, the new scout bee produces new food source (new solution) by taking the global best solution into consideration as follows:

\[
x'_{gij} = rand (x_{gij}^{min}, x_{gij}^{max}),
\]

\[
x_{gij}^{new} = x'_{gij} + \alpha (G_{best} - x'_{gij})
\]

where \( \alpha \) is an arbitrary number in the range of \([-1,1]\).

2) Range damping of \( \phi \) is an effective technique for improvement of poor exploitation capability of ABC algorithm. By range damping of \( \phi \) in each cycle, the opportunity of solutions to improve will be enhanced and each solution can be exploited adequately to reach better solutions.
3.3 The Weighted Sum Method

The weighted sum is a common method for solving multi-objective problems that convert some objectives to a single objective with specific weights. The importance of each objective and priority of decision-makers are two basic factors for determining the value of mentioned weights. These values commonly should be chosen in a way that summation of weights is equivalent to one [30]. Therefore, the multi-objective EED problem by using the weighted sum method is formulated as below:

\[
\begin{align*}
\text{minimize} & \quad w_1 \times F(P_i) + w_2 \times \alpha \times E(P_i) \\
\text{subject to} & \quad w_1 + w_2 = 1
\end{align*}
\]

Where \(w_1\) and \(w_2\) are relevant weights of objectives. \(\alpha\) is an important factor which solves the probable range difference of objective functions. In this paper, the \(\alpha\) factor is calculated by following procedure [31]:

1- Computing the ratio between the maximum fuel cost of each generating unit and its maximum emission:

\[
\alpha_i = \frac{F(P_{i,\text{max}})}{E(P_{i,\text{max}})}
\]

2- Sort \(\alpha_i\) in ascending order. Start to sum of \(P_{i,\text{max}}\) from the unit with lowest \(P_{\text{max}}\) till reaching power demand \(P_0\).

3- The \(\alpha_i\) of last generating unit in stage 2 is selected as \(\alpha\) factor for the optimization problem.

By implementing the above-mentioned process, for example, the obtained \(\alpha\) factor for system 1 is equal to 62.03564.

4. Results

To demonstrate superior performance and efficiency of proposed method, three different systems are studied. The results of studies have been obtained by using MATLAB software on a PC of Pentium-IV, 3.0 GHz and 4 GB RAM. The obtained results have been compared with some reported methods in [2] which are MODE, PDE, NSGA-II and SPEA 2 algorithms.

System 1: This system has 6 generating units with given specifications in Table 1. The system demand is 1200 MW [2]. The loss coefficients of system are given as follows:

\[
B = 10^{-6} \times \begin{bmatrix}
140 & 17 & 15 & 19 & 26 & 22 \\
17 & 60 & 13 & 16 & 15 & 20 \\
15 & 13 & 65 & 17 & 24 & 19 \\
19 & 16 & 17 & 71 & 30 & 25 \\
26 & 15 & 24 & 30 & 69 & 32 \\
22 & 20 & 19 & 25 & 32 & 85
\end{bmatrix}
\]

| Unit | \(P_{\text{min}}\) (MW) | \(P_{\text{max}}\) (MW) | \(a\) (\$/h) | \(b\) (\$/MW\(h\)) | \(c\) (\$/MW\(2\)h) | \(\alpha\) (l/b/h) | \(\beta\) (l/b/MWh) | \(\gamma\) (l/b/(MW\(2\)h)) |
|------|----------------|----------------|-------------|----------------|----------------|----------------|----------------|----------------|
| 1    | 10             | 125            | 756.7988    | 38.5390       | 0.15247        | 13.8593        | 0.32767        | 0.00419        |
| 2    | 10             | 150            | 451.3251    | 46.1591       | 0.10587        | 13.8593        | 0.32767        | 0.00419        |
| 3    | 35             | 210            | 1243.5311   | 38.3055       | 0.03546        | 40.2669        | -0.54551       | 0.00683        |
For execution of proposed algorithm, its main parameters should be determined. Colony size, limit value and maximum cycle number (MCN) for this system are 20, 30 and 200, respectively.

Besides the aforementioned algorithms, the obtained results of multi-objective MABC algorithm are listed in Table 2.

The best result of proposed method is obtained when  \( w_1 = 0.7768 \) and  \( w_2 = 0.2232 \). From Table 2, it is clear that the MABC has the minimum fuel cost (64842 $) in comparison with others. This method also is the best one in terms of execution time with 2.32 seconds. Although the minimum level of emission is not related to MABC, this algorithm shows the better overall performance compared to its competitors.

| Table 2. Obtained results of system 1 |
|-------------------------------------|
| **MABC** | **MODE [2]** | **PDE [2]** | **NSGA-II [2]** | **SPEA 2 [2]** |
| P₁ (MW)  | 105.9614     | 108.6284    | 107.3965        | 113.1259       | 104.1573      |
| P₂ (MW)  | 119.4011     | 115.9456    | 122.1418        | 116.4488       | 122.9807      |
| P₃ (MW)  | 206.6863     | 206.7969    | 206.7536        | 217.4191       | 214.9553      |
| P₄ (MW)  | 206.1632     | 210.0000    | 203.7047        | 207.9492       | 203.1387      |
| P₅ (MW)  | 308.0475     | 301.8884    | 308.1045        | 304.6641       | 316.0302      |
| Cost ($) | 64842        | 64843       | 64920           | 64962          | 64884         |
| Emission (lb) | 1285.2 | 1286       | 1281           | 1281          | 1285         |
| CPU time (s) | 2.32 | 3.09      | 3.52           | 5.42          | 7.05         |

System 2: This system has 10 generating units with given specifications in Table 3. The system demand is 2000 MW [2]. The loss coefficients of system are given as follows:

\[
B = 10^{-6} \times \begin{bmatrix}
49 & 14 & 15 & 15 & 16 & 17 & 17 & 18 & 19 & 20 \\
14 & 45 & 16 & 16 & 17 & 15 & 15 & 16 & 18 & 18 \\
15 & 16 & 39 & 10 & 12 & 12 & 14 & 14 & 16 & 16 \\
15 & 16 & 10 & 40 & 14 & 10 & 11 & 12 & 14 & 15 \\
16 & 17 & 12 & 14 & 35 & 11 & 13 & 13 & 15 & 16 \\
17 & 15 & 12 & 10 & 11 & 36 & 12 & 12 & 14 & 15 \\
17 & 15 & 14 & 11 & 13 & 12 & 38 & 16 & 16 & 18 \\
18 & 16 & 14 & 12 & 13 & 12 & 16 & 40 & 15 & 16 \\
19 & 18 & 16 & 14 & 15 & 14 & 16 & 15 & 42 & 19 \\
20 & 18 & 16 & 15 & 16 & 18 & 16 & 19 & 44 & 44 \\
\end{bmatrix}
\] 

(18)
The main parameters of proposed algorithm which are colony size, limit value and maximum cycle number (MCN) for this system have been determined as 20, 30 and 300, respectively.

Table 4 lists obtained result of MABC algorithm besides results of its competitors.

Table 3. Specifications of system 2

| Unit | \( P_{\text{min}} \) (MW) | \( P_{\text{max}} \) (MW) | \( a \) ($/h) | \( b \) ($/MW) | \( c \) ($/h) | \( d \) ($/h) | \( e \) ($/h) | \( \alpha \) (lb/h) | \( \beta \) (lb/(h*MW)) | \( \gamma \) (lb/(h*MW)) | \( \eta \) (lb/h) | \( \delta \) (h/MW) |
|------|-----------------|-----------------|-------|-------|-------|-------|-------|--------|--------|--------|--------|-------|
| 1    | 10              | 55              | 1000.403 | 40.5407 | 0.12951 | 33    | 0.0174 | 360.0012 | -3.9864 | 0.04702 | 0.25475 | 0.01234 |
| 2    | 20              | 80              | 950.606 | 39.5804 | 0.10908 | 25    | 0.0178 | 350.0056 | -3.9524 | 0.04652 | 0.25475 | 0.01234 |
| 3    | 47              | 120             | 900.705 | 36.5104 | 0.12511 | 32    | 0.0162 | 330.0056 | -3.9023 | 0.04652 | 0.25163 | 0.01215 |
| 4    | 20              | 130             | 800.705 | 39.5104 | 0.12111 | 30    | 0.0168 | 330.0056 | -3.9023 | 0.04652 | 0.25163 | 0.01215 |
| 5    | 50              | 160             | 756.799 | 38.5390 | 0.15247 | 30    | 0.0148 | 13.8593  | -3.9864 | 0.04702 | 0.25475 | 0.01234 |
| 6    | 70              | 240             | 451.325 | 46.1592 | 0.01087 | 20    | 0.0163 | 13.8593  | -3.9524 | 0.04652 | 0.25475 | 0.01200 |
| 7    | 60              | 300             | 1243.531| 38.3055 | 0.03546 | 20    | 0.0152 | 40.2669  | -0.5455 | 0.00680 | 0.24990 | 0.01203 |
| 8    | 70              | 340             | 1049.998| 40.3965 | 0.02803 | 30    | 0.0128 | 40.2669  | -0.5455 | 0.00680 | 0.24990 | 0.01203 |
| 9    | 135             | 470             | 1658.569| 36.3278 | 0.02111 | 60    | 0.0136 | 42.8955  | -0.5112 | 0.00460 | 0.25470 | 0.01234 |
| 10   | 150             | 470             | 1356.659| 38.2704 | 0.01799 | 40    | 0.0141 | 42.8955  | -0.5112 | 0.00460 | 0.25470 | 0.01234 |

Table 4. Obtained results of system 2

|       | MABC  | BSA [32] | MODE [2] | PDE [2] | NSGA-II [2] | SPEA-2 [2] |
|-------|-------|----------|----------|---------|-------------|------------|
| \( P_1 \) (MW) | 54.8825 | 55       | 54.9487  | 54.9853  | 51.9515     | 52.9761    |
| \( P_2 \) (MW) | 83.9065 | 86.5308  | 79.4294  | 83.9842  | 73.6879     | 78.1128    |
| \( P_3 \) (MW) | 82.5526 | 86.9844  | 80.6875  | 86.5942  | 91.3554     | 83.6088    |
| \( P_4 \) (MW) | 137.3777| 129.1542 | 136.8551 | 144.4386 | 134.0522    | 137.2432   |
| \( P_5 \) (MW) | 168.3053| 146.9258 | 172.6393 | 165.7756 | 174.9504    | 172.9188   |
| \( P_6 \) (MW) | 300      | 300      | 283.8233 | 283.2122 | 289.435     | 287.2023   |
| \( P_7 \) (MW) | 308.6352| 323.9002 | 316.3407 | 312.7709 | 314.0556    | 326.4023   |
| \( P_8 \) (MW) | 429.1395| 435.9938 | 448.5923 | 440.1135 | 455.6978    | 448.8814   |
| \( P_{10} \) (MW)| 439.6692| 440.0149 | 436.4287 | 432.6783 | 431.8054    | 423.9025   |
| Cost ($)       | 113450  | 112807.37| 113480  | 113510  | 113540      | 113520     |
| Emission (lb)  | 4188.0926| 4188.0926| 4124.9  | 4111.4  | 4130.2      | 4109.1     |
| CPU time (s)   | 3.19    | N/A      | 3.82    | 4.23    | 6.02        | 7.53       |

The best result of proposed method is obtained when \( w_1 = 0.8465 \) and \( w_2 = 0.1535 \). From Table 4, it can be observed that the MABC algorithm has minimum fuel cost (113450 $) and minimum competition time (3.19 seconds) in comparison with mentioned methods. The minimum emission amount is obtained by SPEA-2 method but this result cannot be an appropriate solution because of its higher generation cost. Overall, it can be seen that the proposed method has the better performance compared to its competitors.
5. Conclusion
This paper has applied multi-objective MABC algorithm to solve the environmental economic dispatch (EED) problem. The weighted sum technique has been used to handle with this multi-objective optimization problem.

The presented algorithm has been tested on two systems with different specifications for assessment of its efficiency and subsequently, its results have been compared with other reported methods. Obtained results clearly show that proposed method has competitive and suitable performance. The shorter computation time and the better solutions confirm this matter that the multi-objective MABC algorithm has a great capability for solving more complex optimization problems.

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