Optimal Power Flow With Four Conflicting Objective Functions Using Multiobjective Ant Lion Algorithm: A Case Study of the Algerian Electrical Network

O. Herbadji*, L. Slimani* and T. Bouktir*(C.A.)

Abstract: In this study, a multiobjective optimization is applied to Optimal Power Flow Problem (OPF). To effectively achieve this goal, a Multiobjective Ant Lion algorithm (MOALO) is proposed to find the Pareto optimal front for the multiobjective OPF. The aim of this work is to reach good solutions of Active and Reactive OPF problem by optimizing 4-conflicting objective functions simultaneously. Here are generation cost, environmental pollution emission, active power losses, and voltage deviation. The performance of the proposed MOALO algorithm has been tested on various electrical power systems with different sizes such as IEEE 30-bus, IEEE 57-bus, IEEE 118-bus, IEEE 300-bus systems and on practical Algerian DZ114-bus system. The results of the tests proved the versatility of the algorithm when applied to large systems. The effectiveness of the proposed method has been confirmed by comparing the results obtained with those obtained by other algorithms given in the literature for the same test systems.

Keywords: Optimal Power Flow, Multiobjective Ant Lion Algorithm, Algerian Electrical Network, Generation Cost, Environmental Pollution Emission, Active Power Losses, Voltage Deviation.

1 Introduction

Optimal Power Flow (OPF) is one of the tasks in power system planning that helps the operators to run the system optimally under specific constraints. It has been extensively investigated since the pioneering work of Carpentier [1] in 1962. OPF can be applied periodically to minimize the total thermal unit fuel cost, emission of particulate and gaseous pollutants, real power loss, and to enhance voltage stability and to improve voltage profile as well. These can be achieved while satisfying certain constraints imposed by the network.

The OPF problem has been developed through the years from a single-objective optimization problem into a multiobjective optimization problem. Several methods have been developed to solve multiobjective optimization problems. For example, the method of the penalty function [2] and the weighted sum method [3] have been used to solve various multiobjective optimization problems. However, these methods have shortcomings and face difficulties. For example the penalty function method, choosing the appropriate penalty factors is a difficult task and it is too sensitive to the associated penalty parameters [4]. The weighted sum approach combines all the objectives with one goal using weighting factors. This formulation may lose the importance of the objective function and there is no a rational basis for determines the weighting factors of the non-commensurable objectives [5]. In order to overcome the drawbacks of these optimization methods, a wide variety of global optimization techniques have been developed to solve OPF in such complex power systems. These techniques are based on heuristic and stochastic aspects such as; Genetic algorithm (GA) [6-8], Particle Swarm Optimization (PSO) [9], Differential evolution (DE) [10], Artificial bee colony (ABC) [11], Biogeography based optimization method (BBO) [12, 13], Gravitational search algorithm (GSA)...
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[14]. Black hole algorithm (BH) [15], Cuckoo Optimization Algorithm (COA) [14], Grey Wolf Optimization (GWO), Ant Lion Optimization (ALO), Crow Search Algorithm (CSA), Dragonfly Algorithm (DA) [16].

Because of the nature of multi-objective problems, relational arithmetic operators cannot perform the comparison between different solutions. The concepts of Pareto optimal dominance allow us to compare multi-solutions in a multi-objective search space. There is no best solution, but a preferable solution. This means that several solutions are calculated, with different trade-offs between conflicting objectives and the engineer will select among them the most preferable for the problem at hand [17].

The OPF is an example of multi-objective optimization problems involving two, three objectives and in practically; the OPF can have more than three objectives [18-21].

In [18], authors proposed the use of multi-objective modified imperialist competitive algorithm (MOMICA) for the OPF problem which is applied to IEEE 30-bus and 57-bus test systems in order to solve four conflicting functions, generation cost, environmental pollution, voltage magnitude deviations and power losses.

In [19], Artificial bee colony algorithm with dynamic population (ABCDP) is proposed to solve multi-optimal power flow problems in power systems that consider the fuel cost, power losses, and emission impacts as objective functions.

Authors in [20] proposed two novel Jaya-based algorithms for solving different MOOPF problems; the modified Jaya algorithm (MJaya) and quasi-oppositional modified Jaya algorithm (QOMJaya). In this study the objectives functions were the fuel cost and the gas emission.

In [21], we proposed the use of multiobjective Dragonfly algorithm to solve single-objective, discrete, and multiobjective problems. The objectives were to reduce the total generation fuel cost, environmental pollution caused by fossil-based thermal generating units, active power losses and the voltage deviation.

In this paper a multiobjective optimization of optimal power flow (MOOPF) is carried out by using one of the latest meta-heuristic optimization techniques; the multiobjective ant lion algorithm (MOALO) using elitist non-dominating solution. MOALO technique is a new bio-inspired algorithm developed by Seyedali Mirjalili in 2016 [22], inspired from the behavior of ant lion to hunt a prey in nature.

The developed MOALO-based algorithm is applied and tested on the IEEE 30-bus, IEEE 57-bus, IEEE 118-bus systems and the Algerian electrical network DZ 114-bus for six cases of MOOPF problems. Fuel cost, total gas emission, total active losses and voltage deviation were considered to be the objective functions to be optimized. The Obtained results are compared with those of algorithms given in the literature for the same test systems to prove the effectiveness and the superiority of the proposed algorithm [21-23].

The remainder of this paper is organized as follows; in Section 2, the MOOPF problem is mathematically formulated. Then, the details of the proposed method are discussed. Next, we apply the proposed MOALO approach to solve the multiobjective OPF problem. Simulation results are presented and discussed in Section 5. Finally, Section 6 concludes the paper.

2 Problem Formulation

The task of multiobjective optimization is to find solutions to problems with several objective functions to optimize [25]. Multiobjective problem can be formulated as follows:

Minimize \( F(\vec{x}) = \{f_1(\vec{x}), f_2(\vec{x}), f_3(\vec{x}), \ldots\} \)

Subject to:

\( g_i(\vec{x}) \geq 0, \quad i = 1,2,3,\ldots,m \) \hspace{2cm} (2)

\( h_i(\vec{x}) = 0, \quad i = 1,2,3,\ldots,p \) \hspace{2cm} (3)

\( L_i \leq x_i \leq U_i, \quad i = 1,2,3,\ldots,n \) \hspace{2cm} (4)

where \( f_1(\vec{x}), f_2(\vec{x}), f_3(\vec{x}), \ldots \) are the objective functions, \( \vec{x} \) is the vector of control variables, \( g_i \) and \( h_i \) are the \( i \)-th inequality and equality constraints respectively, \( n \) is the number of variables, \( \text{no}_j \) is the number of objective functions, \( m \) and \( p \) are the numbers of equality and inequality constraints respectively and \( L_i, U_i \) are the limits of \( i \)-th variable.

The MOOPF is formulated as to minimize simultaneously different objective functions namely: the total fuel cost, the total emission, the active power losses and the voltage deviation.

2.1 Total Fuel Cost Function

The total fuel cost of production \( F_1 \) of the real power of the interconnected generators is given by the quadratic function [26, 27].

\[ F_i(\vec{x}) = \sum_{i=1}^{ng} (A_i + B_i P_{gi} + C_i P_{gi}^{2}) \] \hspace{2cm} (5)

where \( A_i, B_i \) and \( C_i \) are the fuel cost coefficients of the generating unit \( i \), \( P_{gi} \) is the generated active power at bus \( i \) and \( ng \) is number of generators including the slack bus.

2.2 Total Emission Function

The objective function \( F_2 \) for emission minimization can be expressed as a combination of quadratic and exponential functions of the generated active power [28]:

\[ F_2(\vec{x}) = \sum_{i=1}^{ng} h_1(\vec{x}) \]

where \( h_1(\vec{x}) \) is the emission function of the generated active power at bus \( i \).
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\[ F_2(x) = \sum_{i=1}^{n} \left( a_i + b_i P_{gi} + c_i P_{gi}^2 + d_i \exp\left( e_i P_{gi} \right) \right) \]  

where \( a_i, b_i, c_i, d_i \) and \( e_i \) are the total emission coefficients.

2.3 Function of Active Power Losses

The minimization of real power losses in the transmission network is one of the important objectives of the OPF problem. The function of active power transmission losses \( (F_3) \) is given by

\[ F_3(x) = P_{\text{loss}} = \sum_{i=1}^{n} \left( G_K \left( V_i^2 + V_j^2 - 2V_i V_j \cos \delta_j \right) \right) \]

where \( n \) is the branch number on the network, \( K \) is a branch with conductance \( G \) connecting the \( i \)-th bus to the \( j \)-th bus.

2.4 Voltage Magnitude Deviation Function

The objective is to minimize the voltage magnitude deviation at the load buses given by

\[ F_4(x) = \Delta V = \sum_{i=1}^{N_{\text{bus}}} |V_M(i) - 1| \]

where \( V_M \) is the voltage in each bus of the network.

2.5 Minimization of the Voltage Stability Index (VSI)

The voltage stability index (VSI) is one of the different indices for voltage stability and voltage collapse prediction. The voltage stability index can be defined as:

\[ F_5(x) = F_{\text{VSI}}(x) = \min (\text{VSI}) = \text{Min} \left( \max (L_j) \right) \]

with

\[ L_j = \frac{V_j}{\left( 1 - \sum_{i=1}^{N_{\text{bus}}} \left( -V_i Y_{11} V_j + V_i Y_{12} \right) \right)} \times \left( \frac{V_j}{V_j} \right) \cdot \left( \theta_j + (\delta_i - \delta_j) \right) \]

\[ j = 1, 2, \ldots, N_{\text{bus}} \]

where \( Y_1 \) and \( Y_2 \) are the sub-matrices of the \( Y_{\text{bus}} \) and the operating range of \( L \) was set between \([0-1]\).

2.6 Equality and Inequality Constraints

The multiobjective OPF constraints can be split into two parts: equality and inequality constraints. Equality constraints are the active and reactive power balance equations (Eq. (11)).

\[ P_{ei} - P_{di} = V_j \sum_{j=1}^{N_{\text{bus}}} \left( g_{ij} \cos \delta_j + z_{ij} \sin \delta_j \right) \]

The inequality constraints are presented as follows:

- Generators limits:
  \[ P_{g_i}^{\min} \leq P_{ei} \leq P_{g_i}^{\max} \]

- Tap transformer limits:
  \[ T_i^{\min} \leq T_i \leq T_i^{\max} \]

- Voltage magnitude for load buses limits:
  \[ V_i^{\min} \leq V_i \leq V_i^{\max} \]

- Power flow of transmission lines limits:
  \[ S_i^{\min} \leq S_i \leq S_i^{\max} \]

3 Multiobjective Antlion Optimizer (MOALO)

Antlion Optimizer (ALO) is a new nature-inspired algorithm proposed by Seyedali Mirjalili in 2016 [22] for solving constrained engineering optimization problems. ALO algorithm mimics the hunting mechanism of antlions in nature and the interaction of their favorite prey-ants- with them. The general steps of ALO which, describe the interaction between antlions and ants in the trap are as follows: Random walk of ants, building traps, entrapment of ants in traps, catching preys and rebuilding the traps and elitism.

Fig. 1(a) represent one of the cone-shaped pits building by the antlions. In Fig. 1(b) the predator (antlion) hide in the bottom of the pit and waiting his prey (ant) to catch it. After catching the prey, the antlion...
rebuilding the traps for the next hunt. The main inspiration of ALO method is that the predators tend to dig a big trap when they are hungry.

The original random walk used in the ALO algorithm to simulate the random walk of ants is expressed as follows:

\[
X(t) = \left[ 0, \text{cumsum} \left( 2r(t_{i}) - 1 \right), \right. \\
\text{cumsum} \left( 2r(t_{j}) - 1 \right), \ldots, \\
\left. \text{cumsum} \left( 2r(t_{n}) - 1 \right) \right]
\]  

where, \text{cumsum} determines the cumulative sum, \(n\) shows the maximum number of iteration, \(t\) presents the step of random walk (iterations), and \(r(t)\) is a stochastic function given as:

\[
r(t) = \begin{cases} 
1 & \text{if } \text{rand} > 0.5 \\
0 & \text{if } \text{rand} \leq 0.5 
\end{cases}
\]  

where \(\text{rand}\) is a random number generated in the interval [0, 1].

To keep the random walk in the limits of the search space and prevent the ants from overshooting, the random walk is designated using the following expression:

\[
X'_{i} = \frac{(X'_{j} - a_{i})(d'_{j} - c_{i})}{(b_{i} - a_{i})} + c_{i}
\]  

where \(d'_{j}\) and \(c_{i}\) indicate the maximum and minimum of \(i\)-th variable at \(t\)-th iteration respectively, \(a_{i}\) and \(b_{i}\) are the minimum and maximum of random walks corresponding to the \(i\)-th variable, respectively.

The model of the trapping mechanism of antlion around the selected antlion by the roulette wheel and the elite. The elitism mechanism is explained by this equation:

\[
\text{Ant}^{'}_{i} = \frac{R'_{i} + R'_{E}}{2}
\]  

where, \(R'_{i}\) is the random walks selected by the roulette wheel at \(t\)-th iteration around the elite, and \(R'_{E}\) is the random walk at \(t\)-th iteration around the elite.

- Pareto Optimal Solution

The paroptimal approach includes a group of dominated answers that make compromise between objective functions. The Pareto-optimal solutions are illustrated as a diagram named “Pareto diagram”. In the multiobjective optimization problem, any solution \(X_{1}\) is dominated and none dominant the other solution \(X_{2}\). Generally, \(X_{1}\) is assumed to dominate \(X_{2}\) only if two conditions are satisfied [29]:

\[
\forall i \in \{1, 2, \ldots, n\} : F_{i}(X_{1}) \leq F_{i}(X_{2}) \quad \exists j \in \{1, 2, \ldots, n\} : F_{j}(X_{1}) < F_{j}(X_{2})
\]  

- Best Compromise Solution (BCS)

In the MOALO approach, the non-dominated solutions are saved in a repository in all iterations. These solutions are stored by the decision maker function (power system operator). To select the best solution from the Pareto optimal solution, we apply the roulette wheel method at each iteration to obtain a membership function. The membership function \(\mu^{*}_{i}\) of
the \( i \)-th objective function \( F_i \) is defined as [29]:

\[
\mu^k_i = \begin{cases} 
1 & F_i \leq F_i^{\text{min}} \\
\frac{F_i^{\text{max}} - F_i}{F_i^{\text{max}} - F_i^{\text{min}}} & F_i^{\text{min}} \leq F_i \leq F_i^{\text{max}} \\
0 & F_i \geq F_i^{\text{max}}
\end{cases} 
\] (26)

where, \( F_i^{\text{min}} \) and \( F_i^{\text{max}} \) represent the minimum and the maximum value of the \( i \)-th objective function \( F_i \).

When Eq. (26) is a maximum, the best non-dominated solution is defined as follows:

\[
\mu^k = \frac{\sum_{i=1}^{N_{\text{pop}}} \mu^k_i}{\sum_{i=1}^{M} \sum_{j=1}^{N_{\text{pop}}} \mu^k_j} 
\] (27)

where, \( M \) presents the number of the non-dominant solution.

- MOALO utilizes an archive to store and retrieve the best approximations of the non-dominated Pareto optimal set during optimization. Then, the solutions are chosen from this archive by the mechanism of the roulette wheel based on the coverage of solutions as ant lions to lead ants towards promising regions of multiobjective search spaces.

The details of the MOALO method are represented in Fig. 2 as a follows:

4 MOALO for Multiobjective Optimal Power Flow (MOOPF)

The computational procedure for solving the MOOPF problems using MOALO method is described in the following steps:

- **Step 1:** Initialize the parameters of system, and specify the boundaries of all variables.
- **Step 2:** Generate the initial population \( \text{Pop} \) based on the upper and lower limits of the control variables Eq. (25).

The vector of control variable can be generated using active and reactive powers, bus voltage magnitudes, and transformers tap values, etc.

```
While the end condition is not met
    For every ant
        Select a random antlion from the archive
        Select the elite using roulette wheel from the archive
        Update \( c^t \) and \( d^t \) using Eqs. (21) and (22)
        Create a random walk and normalize it using Eqs. (16) and (18)
        Update the position of the ant using Eq. (23)
    End for
    Calculate the objective values for all ants
    Update the archive
End while
Return archive
```

Fig. 2 Pseudo code of MOALO approach.

\[
\text{Pop} = \begin{bmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,n} \\ u_{2,1} & u_{2,2} & \cdots & u_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n,1} & u_{n,2} & \cdots & u_{n,n} \end{bmatrix} 
\] (28)

The variable \( u_{i,j} \) of the population can be described as follows:

\[
u_{i,j} = u_{j,\text{min}} + \text{rand} \left( N_p, D \right) \left( u_{j,\text{max}} - u_{j,\text{min}} \right) 
\] (29)

where, \( N_p \) is the number of search agents, \( D \) is the dimension of the vector variable and \( u_{j,\text{max}} \) and \( u_{j,\text{min}} \) are the upper and lower limits of the \( j \)-th variable, respectively.

**Step 3:** Run the Newton Raphson load flow program to calculate the objective functions and evaluate the particles in the population.

**Step 4:** Apply Pareto optimal method and store the non-dominated solution.

**Step 5:** use the roulette wheel to choose a random solution from the archive and the elite, next, update parameters \( c^t \) and \( d^t \) by using Eqs. (21) and (22). After, create and normalize a random walk using Eqs. (12) and (18). Next, update the position of ant by Eq. (23).

**Step 6:** Calculate the objective values of each ant and update the archive.

**Step 7:** Determine the non-dominated solutions using the Pareto method.

**Step 8:** If the current iteration number reaches the maximum iteration number stop and go to step 5.

**Step 9:** Find the best compromise solution from the Pareto optimal solutions.

5 Case Studies

To verify the effectiveness of the proposed algorithm, different scales of power system cases have been considered: IEEE 30-bus, IEEE 57-bus, the IEEE 118-bus system and the Algerian transmission network DZ 114-bus (Fig. 3).

In these studies, six cases are discussed to demonstrate the usefulness of the proposed approach:

- **Case 1:** Fuel cost
  Minimize \( F(x) = \{ F_1(x) \} \) (30)

- **Case 2:** Fuel cost + Emission
  Minimize \( F(x) = \{ F_1(x), F_2(x) \} \) (31)

- **Case 3:** Fuel cost + Real power losses
  Minimize \( F(x) = \{ F_1(x), F_3(x) \} \) (32)

- **Case 4:** Fuel cost + Voltage magnitude deviation
  Minimize \( F(x) = \{ F_1(x), F_4(x) \} \) (33)
• Case 5: Fuel cost + Emission + Power losses
\[
\text{Minimize } F(x) = \{F_1(x), F_2(x), F_3(x)\} \quad (34)
\]
• Case 6: Fuel cost + Emission + Power losses + Voltage magnitude deviation
\[
\text{Minimize } F(x) = \{F_1(x), F_2(x), F_3(x), F_4(x)\} \quad (35)
\]

The MOALO parameters utilized in this study is represented in Table 1.

### 5.1 IEEE 30-Bus Test System

The IEEE 30-bus test system [31, 32], comprises 6 generators installed at buses n°: 1, 2, 5, 8, 11, and 13, forty one transmission lines including 4 transformers between buses (6-9), (6-10), (4-12), (28-27) and 9 compensators at the loads buses n° 10, 12, 15, 17, 20, 21, 23, 24, and 29 [33]. The total load active power of this system is 2.834 pu at 100 MVA base.

The vector of control variables of IEEE 30-bus test system includes the generated active powers, magnitude voltages of generators, transformer tap settings and the capacitor banks.

\[
x = [P_{g1}, P_{g2}, P_{g3}, P_{g4}, P_{g5}, P_{g6}, V_{g1}, V_{g2}, V_{g3}, V_{g4}, V_{g5}, V_{g6}, T_{6-9}, T_{6-10}, T_{6-12}, T_{28-27}, Q_{c10}, Q_{c12}, Q_{c15}, Q_{c17}, Q_{c20}, Q_{c21}, Q_{c23}, Q_{c24}, Q_{c29}] \quad (36)
\]

Table 1 Control parameter settings of MOALO algorithm for test systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of search agents (NSA)</td>
<td>100</td>
</tr>
<tr>
<td>Number of iterations</td>
<td>100 / 500</td>
</tr>
<tr>
<td>Archive maximum size</td>
<td>100</td>
</tr>
<tr>
<td>Search domain (rand)</td>
<td>[0 1]</td>
</tr>
</tbody>
</table>

In this simulation, 100 test runs were carried out for solving multiobjective optimal power flow problem using the proposed algorithm. Table 2 represents the best result of the simulation obtained from the MOALO algorithm for six cases, Tables 3 and 4 present the comparison between the results obtained by MOALO-MOOPF and other multiobjective techniques for All cases.

In the case 1, the only objective function is minimization of quadratic cost function. The BCS results in this case are presented in Table 2 and the convergence curve is exposed in Fig. 4. From Table 2 and Table 3; we can observe that the best compromise solutions obtained by MOALO as ($799.1436/h) is better than those obtained by the others methods.

The results obtained from case 2 through case 6 are also presented in Table 2, and the set of dominant points of these results is illustrated in Fig 5. Table 3 presents the comparison of the proposed MOALO with other heuristic methods previously cited in the literature. It is
Table 2 Best results of multiobjective OPF problem for six cases using MOALO algorithm for IEEE 30-bus power system.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Min</th>
<th>Case 01</th>
<th>Case 02</th>
<th>Case 03</th>
<th>Case 04</th>
<th>Case 05</th>
<th>Case 06</th>
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<td>121.9200</td>
<td>126.9200</td>
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<td>129.0300</td>
<td>130.9900</td>
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<td>PG2</td>
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<td>56.1451</td>
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<td>2.5251</td>
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<td>3.2858</td>
<td>2.9628</td>
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</table>

- 799.1436 831.6764 826.4556 803.0611 828.3344 826.2676 -
- 0.3679 0.2576 0.2642 0.3718 0.2668 0.2730 -
- 8.6400 5.639 5.7727 11.2870 6.0932 7.2073 -
- 2.1930 1.2870 1.2560 0.0900 1.4080 0.7160 -

Table 3 Comparison of the BCS for cases 1 of IEEE 30-bus power system.

<table>
<thead>
<tr>
<th>Fuel Cost [$/h]</th>
<th>Optimization Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>799.1436</td>
<td>Multiobjective Ant Lion Optimizer (MOALO)</td>
</tr>
<tr>
<td>799.1821</td>
<td>League Championship Algorithm (LCA) [34]</td>
</tr>
<tr>
<td>799.1974</td>
<td>Differential Evolution (DE) [35]</td>
</tr>
<tr>
<td>799.2776</td>
<td>Interior search algorithm (ISA) [36]</td>
</tr>
<tr>
<td>799.2891</td>
<td>Simulated Annealing (SA) [37]</td>
</tr>
<tr>
<td>799.9217</td>
<td>Electromagnetism-Like Mechanism (EM) [38]</td>
</tr>
<tr>
<td>800.078</td>
<td>Genetic Evolving Ant Direction HDE (EADHDE) [34]</td>
</tr>
<tr>
<td>800.1579</td>
<td>Evolving Ant Direction Differential Evolution (EADDE) [39]</td>
</tr>
<tr>
<td>800.2041</td>
<td>Particle Swarm Optimization (PSO) [40]</td>
</tr>
<tr>
<td>800.41</td>
<td>Fuzzy Particle Swarm Optimization (FPSO) [41]</td>
</tr>
<tr>
<td>800.72</td>
<td>Improved Genetic Algorithms (IGA) [42]</td>
</tr>
<tr>
<td>800.805</td>
<td>Particle Swarm Optimization (PSO) [43]</td>
</tr>
<tr>
<td>800.8882</td>
<td>Black Hole Optimization Algorithm (BH) [15]</td>
</tr>
</tbody>
</table>

clear that the application of MOALO method to the multiobjective optimal power flow is giving better solutions than other algorithms and the Pareto optimal solutions are diverse and good distributed over the Pareto front. For example, in case 6 MOALO provides a minimum fuel cost and minimum voltage magnitude deviation compared with four recent algorithms ($826.2676$/h and 0.0189 pu).

5.2 IEEE 57-Bus Test System

IEEE 57-bus test system constitutes of 7 generators, 80 transmission lines, 17 transformers and three capacitor banks [18]. The limits of voltage buses and transformer tap settings are between 0.9 and 1.1 pu [36].

The vector of control variables in this case also includes the generated active powers, magnitude voltages of generators, transformer tap settings and the capacitor banks’ sizes.

Results of simulation obtained from the proposed method of all cases are presented in Table 5. A comparison for case 1 and for the rest of cases is cited in Table 6 and Table 7, respectively.
Table 4 Comparison of the BCS for case 2 through 6 of IEEE 30-bus power system.

<table>
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<tbody>
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<td>-</td>
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<tr>
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<tr>
<td>BB-MPSO[9]</td>
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<td>-</td>
<td>5.7727</td>
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<tr>
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<td>-</td>
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<td>-</td>
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<td>MOABC/D[44]</td>
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<td>-</td>
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<tr>
<td>NKEA[20]</td>
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<td>-</td>
<td>5.8060</td>
<td>-</td>
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<tr>
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<td>-</td>
<td>4.5603</td>
<td>-</td>
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<tr>
<td>MODA[10]</td>
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<td>5.2090</td>
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<tbody>
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<td>0.3787</td>
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<tr>
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<td>0.0952</td>
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<td>-</td>
<td>0.1021</td>
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<td>-</td>
<td>0.0989</td>
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<tr>
<td>ISA[36]</td>
<td>807.6408</td>
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<td>-</td>
<td>0.1273</td>
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<tbody>
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<td>MOALO</td>
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<td>0.2668</td>
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<tr>
<td>MODA[10]</td>
<td>867.9070</td>
<td>0.2610</td>
<td>5.9110</td>
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<td>5.5851</td>
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</tr>
<tr>
<td>BB-MPSO[9]</td>
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<td>0.3945</td>
</tr>
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<td>NKEA[20]</td>
<td>834.6433</td>
<td>0.2491</td>
<td>5.8935</td>
<td>0.4448</td>
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</table>

Fig. 4 The convergence of MOALO algorithm for IEEE 30-bus system in case 1.

In this simulation, Table 5 shows the best values of four competing objectives optimized by the MOALO. Convergence diagram of the fuel cost (case 1) is shown in Fig. 6 and the Pareto-optimal results from case 2 to case 6 are illustrated in Fig. 7. The comparison shown in Tables 6 and 7 prove that MOALO gives better results except in the last case where the power losses and the fuel cost are lower than those obtained by NKEA method by a percentage of -1.76% and -19.85%, respectively, but the emission and the voltage deviation are better by 5.84% and 92.04%, respectively. As a conclusion, MOALO is better than KNEA.
Fig. 5 Pareto-optimal solutions obtained in cases 2 through 6 for best solution for IEEE 30-bus power system; a) Case 02– Fuel cost + Emission, b) Case 03– Fuel cost + Ploss, c) Case 04– Fuel cost + DV, d) Case 05– Fuel cost + Emission + Ploss, and e) Case 06– Fuel cost + Emission + Ploss + DV.
5.3 IEEE 118-Bus Test System

The IEEE 118-bus test system consists of 54 generators, 9 transformers, 14 capacitor banks, 186 transmission lines and 99 constant impedance loads, which consume total of 4242 MW and 1438 MVAR. The slack bus is the bus number 69 [25, 45].

For this system, the emission minimization is not a part of the optimization. Therefore, a new case study is discussed and explained by Eq. (37):

- Case 7: Fuel cost + Power losses + Voltage magnitude deviation

\[
\text{Minimize } F(x) = \{ F_1(x), F_2(x), F_3(x) \} 
\]

The control variable always contains the generated active powers \( P_g \), generated magnitude voltages \( V_g \), transformer tap settings \( T \) and the capacitor banks \( Q_c \). Best setting of control variables and BCS results of fuel cost, power losses and voltage magnitude deviation are presented in Table 8.

### Table 5 Results of MO-OPF problem for 6-cases using MOALO algorithm of 57-bus test system.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Case 01</th>
<th>Case 02</th>
<th>Case 03</th>
<th>Case 04</th>
<th>Case 05</th>
<th>Case 06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pg1</td>
<td>396.9100</td>
<td>214.3100</td>
<td>148.2700</td>
<td>156.3800</td>
<td>231.7600</td>
<td>207.7700</td>
</tr>
<tr>
<td>Pg2</td>
<td>119.5583</td>
<td>98.7031</td>
<td>68.4795</td>
<td>97.5843</td>
<td>19.0593</td>
<td>68.1618</td>
</tr>
<tr>
<td>Pg3</td>
<td>92.0553</td>
<td>98.5652</td>
<td>53.7031</td>
<td>49.4052</td>
<td>66.7253</td>
<td>80.1569</td>
</tr>
<tr>
<td>Pg4</td>
<td>43.8150</td>
<td>84.0391</td>
<td>99.7128</td>
<td>36.2118</td>
<td>92.0849</td>
<td>96.8831</td>
</tr>
<tr>
<td>Pg5</td>
<td>89.2414</td>
<td>383.0225</td>
<td>424.5749</td>
<td>479.7535</td>
<td>345.8168</td>
<td>337.1985</td>
</tr>
<tr>
<td>Pg6</td>
<td>453.6108</td>
<td>100.0000</td>
<td>99.2418</td>
<td>92.5269</td>
<td>99.7837</td>
<td>98.8692</td>
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<tr>
<td>Pg7</td>
<td>94.3669</td>
<td>292.6367</td>
<td>375.0308</td>
<td>365.9775</td>
<td>490.7688</td>
<td>377.2544</td>
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</table>

### Table 6 Comparison of the BCS obtained for the first case of 57-bus test system.

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<th>Fuel Cost [$/h]</th>
<th>Optimization Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>41623.1352</td>
<td>Multiobjective Ant Lion Optimizer (MOALO)</td>
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<tr>
<td>41676.9466</td>
<td>Interior search algorithm (ISA) [36]</td>
</tr>
<tr>
<td>41693.9589</td>
<td>Artificial bee colony (ABC) [46]</td>
</tr>
<tr>
<td>41815.5035</td>
<td>Linearly decreasing inertia weight PSO (LDI-PSO) [46]</td>
</tr>
<tr>
<td>41866.8987</td>
<td>Black Hole Optimization Algorithm (BH) [14]</td>
</tr>
<tr>
<td>52819.7052</td>
<td>Gravitational search algorithm (GSA) [26]</td>
</tr>
</tbody>
</table>

\[ \text{Minimize } F(x) = \{ F_1(x), F_2(x), F_3(x) \} \] (37)
Table 7 BCS comparisons for cases 2, 3, 4, 5, 6 of IEEE 57-bus power system.

<table>
<thead>
<tr>
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<tbody>
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<td>-</td>
<td>-</td>
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<td>BB-MPSO[9]</td>
<td>41947.3505</td>
<td>1.4957</td>
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<tr>
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<td>16.2646</td>
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</thead>
<tbody>
<tr>
<td>MOALO</td>
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<td>1.6349</td>
<td>15.0270</td>
<td>-</td>
</tr>
<tr>
<td>ISA[36]</td>
<td>43021.0000</td>
<td>1.9931</td>
<td>16.7039</td>
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<td>0.0830</td>
</tr>
<tr>
<td>NKEA[20]</td>
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<td>13.9764</td>
<td>1.042</td>
</tr>
<tr>
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<td>1.6312</td>
<td>16.7039</td>
<td>0.0040</td>
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</table>

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<td>15.0270</td>
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<tr>
<td>NKEA[20]</td>
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<td>16.7039</td>
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</table>

Fig. 6 The convergence of MOALO algorithm for IEEE 57-bus system in case 1.
Fig. 7 Pareto-optimal solutions obtained in cases 2 through 6 for best solution for IEEE 57-bus power system: a) Case 02–Fuel cost + Emission, b) Case 03–Fuel cost +Ploss, c) Case 04–Fuel cost + DV, d) Case 05–Fuel cost +Emission +Ploss, and e) Case 06–Fuel cost + Emission +Ploss +DV.

Table 8 Optimal results for Case 1, 3, 4 and 7 of IEEE 118-bus power system.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Case 01</th>
<th>Case 03</th>
<th>Case 04</th>
<th>Case 7</th>
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<td>73.4572</td>
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<td>498.6870</td>
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Fuel Cost [$/h]
143023.6169
157453.3741
148087.0000
157731.8400

Table 9 Comparison between MOALO, PSO [45] and ABC [45] for case 1 of IEEE 118-bus power system.

<table>
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<tr>
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<th></th>
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<td>157731.8400</td>
<td>148087.0000</td>
<td>143023.6170</td>
</tr>
</tbody>
</table>

Fig. 8 Simulation results of IEEE 118-bus system for a) case 1, b) case 3, c) case 4, and d) case 7 using MOALO algorithm.

Table 8 and Fig. 8 present the simulation results of IEEE 118-bus system for case 1, 3, 4 and 7. A comparison between the obtained results with those given by other heuristic techniques is shown in Table 9. From the results illustrated in Tables 8 and 9, these results prove once again that the proposed MOALO is effective to solve the MOOPF problem. For case 1 the fuel cost obtained by MOALO is better than those obtained by ABC and PSO methods ($143023.6170/h compared to $148087.0000/h and $157731.8400/h respectively).

On the other hand, the pareto-optimal solutions for all cases except for case 1 (in case 1 there is one objective function: the fuel cost) converge to the near-optimal solution with the large-scale power system.

The Best generated magnitude voltages, transformer...
tap settings $T$ and the capacitor banks obtained in the four cases are given in Figs. 9, 10 and 11. From this figures, we can see that all these results are between their minimum and maximum values.

5.4 DZ 114-Bus Power System

To demonstrate the applicability of the proposed MOALO algorithm in practical system; it has been examined and tested on the Algerian transmission network DZ 114-bus system [46]. This network is composed of 114 buses, 174 transmission lines, 15 generators, 16 transformers and 7 capacitor banks. It is worth mentioning that bus number 04 is the slack bus and the total load demand is 3727 MW. The minimum and maximum limits of the voltage generator buses and load buses in this system are 0.9 pu and 1.1 pu [30].

For Algerian transmission network, there are 53 control variables (15 generator power outputs, 15 generator voltages, 16 transformers and 7 capacitor banks), these variables are to be optimized. The optimal outputs of power generation are represented in Table 10, the total fuel cost, power losses and the voltage deviation are also represented in this table. The rest of the optimal values are shown in Figs. 12, 13 and 14.

![Fig. 9 Optimal voltage magnitude values of IEEE 118-bus system.](image1)

![Fig. 10 Optimal tap change values of IEEE 118-bus system.](image2)

![Fig. 11 Optimal capacitor bank values of IEEE 118-bus system.](image3)
### Table 10 Optimal results for the Algerian network DZ 114-bus power system.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Min</th>
<th>Case 01</th>
<th>Case 03</th>
<th>Case 04</th>
<th>Case 07</th>
<th>Max</th>
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<td>420.9800</td>
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<tr>
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<td>451.1905</td>
<td>531.4987</td>
<td>484.6373</td>
<td>485.1794</td>
<td>1350.0000</td>
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<td>176.6917</td>
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</table>

**Fig. 12** The optimal voltage magnitude values of the Algerian network.

**Fig. 13** The optimal tap change values of the Algerian network.

**Fig. 14** The optimal capacitor bank values of the Algerian network.
We can see that all security constraints are checked for optimal voltage magnitudes, tap change values and capacitor bank (Figs. 12, 13 and 14).

Fig. 15 indicates that the proposed MOALO for DZ 114-bus system was successfully implemented the goal was to find the best different Pareto optimal front.

5.5 IEEE 300-Bus Test System

Finally, we have applied the MOALO to solve multiobjective optimal reactive power dispatch (MOORPD) problem considering large -scale power system IEEE 300 bus [44]. The MOORPD is an important issue in power system planning and operation. It is a well-known complex optimization problem with nonlinear characteristic. ORPD is formulated as multiobjective optimization problem, in which focuses to not only reduce transmission power losses, but also simultaneously minimizes the voltage stability index (L-index) or voltage deviation.

The objective of the voltage stability indices is to quantify how close a particular point is to the steady state voltage stability margin. These indices can be used on-line or offline to help operators in real time operation of power system.

The IEEE 300-bus test system, comprises 69 generators, 411 transmission lines including 107 transformers between and 14 compensators at the loads buses n° 96, 99, 133, 143, 145, 152, 158,169, 210, 217, 219, 227, 268 and 283. The total load active power of this system is $(235.258 + j77.8797)$ pu at 100 MVA base.

The vector of control variables of IEEE 300-bus test system includes the magnitude voltages of generators, transformer tap settings and the capacitor banks.

Table 11 represents the best result of a part of the vector of control which represents 14 compensators obtained from the MOALO algorithm for different cases. The Pareto-optimal solutions are illustrated in Fig. 16.

Based on the simulation results of different case studies, it is observed that the results demonstrate the potential of the proposed approach and show clearly its effectiveness to solve practical OPF. All results obtained do not violate the generation capacity constraints. It is important to note that the security constraints are satisfied for voltage magnitudes and line flows. No load bus is under its lower limit of 0.90 pu.
Recently developed MOALO algorithm. The power flow optimal power flow (OPF) for small, medium and large scale electrical networks. The results obtained were compared with those obtained from two other algorithms namely MOMICA and MODA. The outcomes of the comparison confirm the effectiveness and the superiority of the proposed MOALO method in solving the optimal power flow (OPF) for small, medium and large scale electrical networks. Furthermore, MOALO has the ability more than the other algorithms (MOMICA, MODA) in solving the problems with more than two objective functions. Moreover, simulation results obviously demonstrate the capabilities of the proposed algorithm to generate a set of non-dominated feasible solutions.

### Table 11 Optimal results of IEEE 300-bus power system for different cases.

<table>
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<tr>
<th>Case:</th>
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<th>DV</th>
<th>Case: Ploss+L_index+DV</th>
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<td>-</td>
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</table>

### Fig. 16 Pareto-optimal solutions obtained for IEEE 300-bus power system; a) Case: Ploss+L_index and b) Case: Ploss+L_index+DV.

### 6 Conclusion

In this paper, a multiobjective optimal power flow problem (MOOPF) with four conflicting objectives; fuel cost, total emission, real power losses and magnitude voltage deviation under different constraints was solved using a recently developed MOALO algorithm. The proposed MOALO was applied to several cases studies in four power systems; namely IEEE 30-bus, IEEE 57-bus, IEEE 118-bus, IEEE 300-bus test systems and the Algerian network DZ 114-bus. The simulation results indicated that the proposed approach successfully achieved the goal of finding the best global settings of the control variables. The results obtained were compared with those obtained from two other algorithms namely MOMICA and MODA. The outcomes of the comparison confirm the effectiveness and the superiority of the proposed MOALO method in solving the optimal power flow (OPF) for small, medium and large scale electrical networks. Furthermore, MOALO has the ability more than the other algorithms (MOMICA, MODA) in solving the problems with more than two objective functions. Moreover, simulation results obviously demonstrate the capabilities of the proposed algorithm to generate a set of non-dominated feasible solutions.

### Acknowledgement

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### References


Optimal Power Flow With Four Conflicting Objective Functions   

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