Economic Environmental Dispatch Using Improved Cuckoo Search Algorithm

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ABSTRACT—This paper presents a new meta-heuristic search algorithm, termed Improved cuckoo search algorithm (ICSA). The canonical cuckoo search is an optimisation algorithm based on the brood parasitism of cuckoo species by laying their eggs in the collective nests of other host birds, though they may eradicate others’ eggs to rise the hatching probability of their own eggs. The new algorithm is implemented to solve economic environmental dispatch (EED) problem in power systems considering several practical constraints. The EED is to minimize both the operating fuel cost and emission level simultaneously while satisfying operational constraints and the load demand. The usefulness of the proposed algorithm has been tested on three and six-generator systems using MATLAB and the results were compared with other methods reported in recent literature. The simulation results demonstrate that the proposed algorithm outperforms earlier optimisation approaches.

Index Terms: Cuckoo search, Economic environmental dispatch, Meta-heuristic, Optimisation, Ramp rate limit

I. INTRODUCTION

The upsurge in ecological problems and volatile electricity prices around the globe have become a source of concern to power generation utilities. The production of electricity from remnant fuel releases some toxic substances, such as nitrogen oxides (NOx), carbon dioxide (CO2), and sulfur dioxide (SO2), into the atmosphere. In recent years, pollution reduction has attracted much attention due to the persistent public call for clean air. The passage of the U.S. Clean Air Act amendments of 1990, the Paris Agreement and the Kyoto Protocol have made environmental limitations an issue of great concern to utility managers [1]. Economic Environmental Dispatch (EED) is a multi-objective problem that seeks to minimise total emission and the total fuel cost which are conflicting simultaneously. When the fuel cost is minimised the emission may be high or when the emission is minimised the fuel cost may be inadmissibly high.

Over the past decades, researchers have used several methods and approaches to address the EED problem. In [2], Farag et al used linear programming techniques to optimise the multi-objective economic load dispatch problem.

The lambda-iteration method [3], enhanced Lagrangian neural network [4] and Balamurugan and Subramanian [5] have been used in solving the dispatch problem. However, it is realised that classical techniques become very difficult when dealing with increasingly complex dispatch problems, and are further restricted by their lack of efficiency and robustness in a number of real-world applications. Consequently, nature-inspired techniques and heuristics-based methods were tried to solve this problem. Differential Evolution (DE) [6], Tabu Search (TS) [7] and Particle Swarm Optimization (PSO) [8] have all been used to tackle the EED problem.

Yang and Deb [9], recently propounded a new meta-heuristic search algorithm, named cuckoo search algorithm (CSA) for solving optimisation problems inspired from the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds of other species. In the extant study, an improved version of the canonical cuckoo search algorithm has been used to solve EED problem considering several practical constraints. Viability of the proposed technique has been confirmed on three and six generator systems. The results obtained with the proposed method were analysed and compared with other optimisation results reported in literature.

The rest of this paper is ordered as follows. Section II provides a mathematical modelling of the economic environmental dispatch multi-objective optimisation problem. Section III introduces the canonical cuckoo search algorithm and the improved version as well. Experiments and results are demonstrated in Section IV. Finally, the paper is concluded in Section V.

II. MATHEMATICAL MODELLING OF THE PROBLEM

The main goal of EED problem is to find the optimum combination of load dispatch of generating units and minimises both emission and fuel cost while satisfying the total power demand and practical constraints. Hence, EED consists of two objective functions, which are emission and economic dispatches. Then these two functions are combined to solve the problem. The EED problem can be formulated as follows [10]:

\[ F_r = \min \ (EC, FC) \]  (1)
Where: $EC$ is the total emission of generators, $FC$ is the total fuel cost of generators and $F_T$ is the total generation cost of the system.

(a) **Fuel Cost Minimisation:** The objective function is to minimise the total fuel cost ($F_T$) ($$/h$$) considering a system with $N$ power generating units given by the following expression:

$$F_T = \sum_{j=1}^{N} C_j (P_j) = \sum_{j=1}^{N} a_j + b_j P_j + C_j P_j^2$$  \hspace{1cm} (2)

Where: $C_j$ is the cost function of $j$th generating unit, $a_j$, $b_j$, $C_j$ are the cost coefficients of $j$th power generation unit, $N$ is the total number of generating units and $P_j$ is the output of $j$th power generating unit.

(b) **Minimisation of emission:** The emission function can be presented as the sum of all types of emission from the thermal power plant (ton/h) such as $CO_2$, $NO_x$, and $SO_2$, with suitable weighting or pricing on each pollutant emitted. In the extant study, only one type of emission ($NO_x$) is taken into account without loss of generality. The amount of $NO_x$ emission is given as a function of generator output, that is, the sum of a quadratic and exponential function:

$$E(P_c) = \sum_{j=1}^{N} 10^{-2}(a_j + b_j P_j + C_j P_j^2) + \xi_j \exp(\lambda_j P_j)$$  \hspace{1cm} (3)

Where: $a_j$, $b_j$, $C_j$, $\xi_j$ and $\lambda_j$ are coefficients of the $j$th generator emission characteristics.

(c) **Problem Constraints:** The EED is subjected to two major constraints of the power system. Namely:

i. Equality and

ii. Inequality Constraints

i. **Power Balance Constraints:** In emission dispatch of power, the total power generated should exactly match with the load demand and losses which is represented by the following equation. It is a kind of equality constraint.

$$\sum_{j=1}^{N} P_j = P_D + P_{loss}$$  \hspace{1cm} (4)

Where: $P_D$ is the total system load demand, $P_j$ is the power output from $j$th generating unit, $P_{loss}$ is the network transmission loss and $N$ is the number of generating unit. $P_{loss}$ is calculated using B-coefficient as follows:

$$P_{loss} = \sum_{j=1}^{N} \sum_{k=1}^{N} P_j B_{jk} P_k + \sum_{j=1}^{N} B_{oj} P_j + B_{oo}$$  \hspace{1cm} (5)

Where: $B_{jk}$, $B_{oj}$, and $B_{oo}$ are loss coefficients of generating units.

ii. **Generator Constraints:** The output power of each generating unit is restricted by its upper ($P_{jmax}$) and lower ($P_{jmin}$) limits of actual power generation and is given by:

$$P_{jmin} \leq P_j \leq P_{jmax}$$  \hspace{1cm} (6)

**Ramp Rate Limits:** In practice, the power output of a generator is not promptly adjustable. The operating range of all such units is limited by their ramp rate limits during each dispatch period. So, the dispatch output of a generator should be restricted between the upper $UR_j$ and down $UD_j$ ramp rate constraints as expressed in Equation (7):

$$\max(P_{jmax} - DR_j, UR_j) \leq P_j \leq \min(P_{jmax}, P_j + UR_j)$$  \hspace{1cm} (7)

Here: $P_j^D$ represents the previous operating point of $j$th generator.

**Valve point loading effects:** The valve-point effects present undulations in the heat-rate curves and make the objective function nonconvex, discontinuous, and multimodal. For precise modeling of valve point loading effects, a rectified sinusoidal function [11] is added in the cost function given in Equation (2). The cost function of the $j$th unit with VPL effects can be written as [11]:

$$\sum_{j=1}^{N} \left[ \left( a_j + b_j P_j + C_j P_j^2 \right) + |e_j \sin(f_j (P_{jmin} - P_j))| \right]$$  \hspace{1cm} (8)

**Constraints due to prohibited operating zones:** The cost curves of practical generators are discontinuous as whole of the unit operating array is not always accessible for allocation. In other words, the generating units have prohibited operating zones due to some faults in the machines or their accessories such as pumps or boilers [12]. A unit with prohibited operating zones has discontinuous input-output characteristics. This feature can be included in the problem formulation as follows:

$$\begin{cases} P_{jmin} \leq P_j \leq P_{j1}^L \\ P_{j1}^U \leq P_j \leq P_{j1}^L \\ P_{j2}^U \leq P_j \leq P_{j1}^L \\ \vdots \\ P_{jk}^U \leq P_j \leq P_{j1}^L 
\end{cases}$$  \hspace{1cm} (9)

Where: $P_{j1}^U$ is the lower limit of $k$th prohibited zone; $P_{j1}^L$ is the upper limit of $(k-1)$th prohibited zone of the $j$th generator; $k$ is the index of prohibited zone of the $j$th generator and $j$ are the number of prohibited zones in $j$th generator curve.

### III. CANONICAL CUCKOO SEARCH

The canonical cuckoo search algorithm (CS) is a swarm intelligence form of algorithm inspired by the behaviors of
cuckoos, consisting of laying eggs, locating nests, and the Lévy flight. CS was established by [9]. With a simple structure and a few control parameters, CS has been extensively used in practical engineering optimization problems. The CS is based on the brood parasitism of cuckoo species by laying their eggs in the collective nests of other host birds, though they may eradicate others' eggs to increase the hatching probability of their own eggs. Some host birds do not behave sociable against burglars and engage in direct conflict with them. If a host bird notices the eggs are not their own, it will either throw these distant eggs away or merely abandon its nest and build a new nest elsewhere.

The CS algorithm comprises a population of nests or eggs. Each egg in a nest signifies a solution and a cuckoo egg denotes a new solution. If the cuckoo egg is very similar to the host’s, then this cuckoo egg is less expected to be exposed; thus, the fitness should be associated to the change in solutions. The better novel solution (cuckoo) is replaced with a solution which is not so good in the nest. In the simplest form, each nest has one egg. When generating new solutions for $x^{(r+1)}$, say cuckoo $j$ a Lévy flight is performed:

$$x_{j}^{(r+1)} = x_{j}^{r} + \alpha \odot \text{Lévy} (\lambda)$$  \hspace{1cm} (10)

where $\alpha > 0$ is the step size which should be linked to the scales of the problem of attention. In most cases, we can use $\alpha = 0$ (1). The product $\odot$ means entry-wise multiplications. Lévy flights principally offer a random walk while their random steps are drawn from a Lévy distribution for large steps:

$$\text{Lévy} \sim u = r^{-\lambda}, (1 < \lambda \leq 3)$$  \hspace{1cm} (11)

which has an infinite variance with an infinite mean. Here the consecutive jumps/steps of a cuckoo essentially form a random walk process which obeys a power-law step-length distribution with a heavy tail. There are three basic guidelines in CS.

1. Each cuckoo selects a random nest to lay an egg once.
2. Only the best nests with a high quality of eggs would be reserved to the ensuing generations.
3. A host cuckoo has a probability of $p_a \in [0,1]$ to spot the egg of another cuckoo in its own nest. Through the switching coefficient $p_a$, CS can subtly combine a global search and a local search.

The later assumption can be approximated by the fraction $P_a$ of the $n$ nests which are replaced by new ones (with new random solutions). With these three guidelines, the basic steps of the CS can be summarised as the pseudo-code as follows [13]:

a) Define the objective function $f(x)$, $x = (x_1, x_2, ..., x_d)^T$

b) Set $p_a$, $n$, and MaxGeneration parameters.

c) Generate initial population of $n$ available nests.

d) Move a cuckoo ($j$) randomly by Lévy flights.

e) Evaluate the fitness $f_j$.

f) Randomly choose a nest ($k$) among $n$ available nests.

g) If $f_j > f_k$ the replace $k$ by the new solution.

h) Abandon a fraction $P_a$ of worse nests and generate the same fraction of new nests at new position via Lévy flights.

i) Keep the best solutions (or nests with quality solutions).

j) Sort the solutions and find the best current solution.

k) If stopping criteria is not satisfied, increase generation number and go to step d.

l) Post process results and find the best solution among all.

**Improved Cuckoo Search**

In general, the parameter $\alpha$ in Lévy flight is the key factor to affect the convergence of CS. Due to the infinite variance and mean, the classical CS algorithm may have a premature search process. To overcome this problem, the tent map is used to generate a chaotic sequence for parameter $\alpha$. In that case, the algorithm hunts the new location in the locality of the current optimum position. Meanwhile, a new emotional acceptance standard is used to prevent the algorithm from getting trapped into local optima. In the ICS, two cuckoos’ emotions (positive and negative) can be described as follows:

$$e = -k \ln \left| \frac{F(x_j) - F(x_k)}{S_0} \right|$$  \hspace{1cm} (12)

IF $\alpha < e$ Then positive Else negative,

Where: $e$ represents the function of cuckoo’s emotion, $k$ is a constant, $S$ is the stimulus function, $S_0$ is a stimulus threshold, and $F$ is the objective function. It should be noted that $k$ is selected as 1 and $S = e^x$. Figure 1 depicts the Improved Cuckoo Search flow chart.

![Figure 1. Flow Chart for the Improved Cuckoo Search](image-url)
IV. EXPERIMENTS AND RESULTS

The proposed method has been applied to a test power system consists of three and 13 generators at 350 MW and 500 MW power demand respectively. Generation unit data has been taken from [14] [15]. Simulations were performed in MATLAB R2019a environment on a PC with a 3 GHz processor.

**Experiment One**

The IEEE 3-generator test system is considered to assess the potential of ICSA for solving the EED problem. The values of the fuel and emission coefficients of the IEEE 3-generator system is given in Table 1 and 2 respectively. The line data and bus data of the system are referenced in [14]. The load of the IEEE 3-generator system was set to 0.35 p.u on a 100MVA base. In order to verify how competitive, the proposed approach was, it was compared with the DE, GA and PSO which have been implemented and applied to the EED problem with impressive success.

<table>
<thead>
<tr>
<th>Generator</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>$P_{\text{min}}^0$</th>
<th>$P_{\text{max}}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1243.53</td>
<td>38.31</td>
<td>0.0354</td>
<td>35</td>
<td>210</td>
</tr>
<tr>
<td>2</td>
<td>1658.57</td>
<td>36.33</td>
<td>0.0211</td>
<td>130</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>1356.66</td>
<td>38.27</td>
<td>0.0180</td>
<td>125</td>
<td>315</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generator</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$P_{\text{min}}^0$</th>
<th>$P_{\text{max}}^0$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>40.2669</td>
<td>-0.5455</td>
<td>0.00683</td>
<td>35</td>
<td>210</td>
</tr>
<tr>
<td>2</td>
<td>42.8955</td>
<td>-0.5116</td>
<td>0.00461</td>
<td>130</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>42.8955</td>
<td>-0.5116</td>
<td>0.00461</td>
<td>125</td>
<td>315</td>
</tr>
</tbody>
</table>

B-Matrix for the 3-generator system

$$B_{ij} = \begin{bmatrix}
0.000071 & 0.000030 & 0.000025 \\
0.000030 & 0.000069 & 0.000032 \\
0.000025 & 0.000032 & 0.000080
\end{bmatrix}$$

**Experiment Two**

An IEEE 6-generator system is used for this experiment with a 500 MW power demand. Table 4. Depicts the various data of the system [15]. This case demonstrates the relationships between fuel cost, emission and system loss. This example is more complex than the previous case, because the size of the number of the generators. After two hundred independent optimisation runs, the best cost, emission and transmission losses obtained out of ten runs by ICSA are given in Table 6.

<table>
<thead>
<tr>
<th>Generator System Best Solutions for Experiment 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
</tr>
<tr>
<td>$P_{\text{G1}}$</td>
</tr>
<tr>
<td>$P_{\text{G2}}$</td>
</tr>
<tr>
<td>$P_{\text{G3}}$</td>
</tr>
<tr>
<td>Losses (MW)</td>
</tr>
<tr>
<td>Fuel Cost ($/h$)</td>
</tr>
<tr>
<td>Emission (ton/h)</td>
</tr>
<tr>
<td>Time (s)</td>
</tr>
</tbody>
</table>

From Table 3. It can be seen that the ICSA yielded superior results compared with DE, GA, and PSO in terms of better system losses, reduced fuel cost, lower emissions and least computational time. The convergence graph for the 3-generator system is shown in Figure 2.

![Figure 2. Economic Convergence graph for experiment 1](image)

![Figure 3. Comparison of all Four Methods used for 3-generator System](image)
Table 4. Generator cost coefficients of system (6-generator)

<table>
<thead>
<tr>
<th>Units</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(p_{\text{min}}^0)</th>
<th>(p_{\text{max}}^0)</th>
</tr>
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<tbody>
<tr>
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<td>756.7988</td>
<td>38.5390</td>
<td>0.1525</td>
<td>10</td>
<td>125</td>
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<tr>
<td>2</td>
<td>451.3251</td>
<td>46.1591</td>
<td>0.1059</td>
<td>10</td>
<td>150</td>
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<tr>
<td>3</td>
<td>1243.5311</td>
<td>38.3055</td>
<td>0.0354</td>
<td>35</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>1049.9977</td>
<td>40.3965</td>
<td>0.0280</td>
<td>35</td>
<td>225</td>
</tr>
<tr>
<td>5</td>
<td>1658.5696</td>
<td>36.3278</td>
<td>0.0211</td>
<td>130</td>
<td>325</td>
</tr>
<tr>
<td>6</td>
<td>1356.6592</td>
<td>38.2704</td>
<td>0.0180</td>
<td>125</td>
<td>315</td>
</tr>
</tbody>
</table>

Table 5. Emission coefficients of system (6-generator)

<table>
<thead>
<tr>
<th>Units</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(p_{\text{min}}^0)</th>
<th>(p_{\text{max}}^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.8583</td>
<td>0.3277</td>
<td>0.00419</td>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>13.8593</td>
<td>0.3277</td>
<td>0.00419</td>
<td>10</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>40.2669</td>
<td>-0.5455</td>
<td>0.00683</td>
<td>35</td>
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<td>-0.5455</td>
<td>0.00683</td>
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<td>225</td>
</tr>
<tr>
<td>5</td>
<td>42.8955</td>
<td>-0.5116</td>
<td>0.00461</td>
<td>130</td>
<td>325</td>
</tr>
<tr>
<td>6</td>
<td>42.8955</td>
<td>-0.5116</td>
<td>0.00461</td>
<td>125</td>
<td>315</td>
</tr>
</tbody>
</table>

\[ B \text{-Matrix for the 6-generator system} \]

\[
\begin{pmatrix}
0.000202 & -0.000286 & -0.000534 & -0.000565 & -0.000454 & -0.000103 \\
-0.000286 & 0.000343 & 0.000916 & -0.000307 & -0.000422 & 0.000147 \\
-0.000534 & 0.000016 & 0.000205 & 0.000831 & 0.000032 & -0.000270 \\
-0.000565 & -0.000307 & 0.000623 & 0.000112 & 0.000011 & -0.000295 \\
-0.000454 & -0.000422 & 0.000023 & 0.000113 & 0.000046 & -0.000153 \\
-0.000103 & 0.000147 & -0.000270 & -0.000295 & -0.000153 & 0.000098
\end{pmatrix}
\]

Table 6. Six-generator system best solutions

<table>
<thead>
<tr>
<th></th>
<th>DE</th>
<th>GA</th>
<th>PSO</th>
<th>ICSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_G^1)</td>
<td>57.27</td>
<td>57.55</td>
<td>58.04</td>
<td>57.93</td>
</tr>
<tr>
<td>(P_G^2)</td>
<td>44.39</td>
<td>44.58</td>
<td>43.21</td>
<td>43.88</td>
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<tr>
<td>(P_G^3)</td>
<td>77.03</td>
<td>76.90</td>
<td>75.17</td>
<td>74.54</td>
</tr>
<tr>
<td>(P_G^4)</td>
<td>84.69</td>
<td>84.63</td>
<td>84.15</td>
<td>83.20</td>
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<tr>
<td>(P_G^5)</td>
<td>131.90</td>
<td>132.11</td>
<td>134.09</td>
<td>133.81</td>
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<tr>
<td>(P_G^6)</td>
<td>129.15</td>
<td>128.92</td>
<td>128.57</td>
<td>128.92</td>
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<tr>
<td>Losses (MW)</td>
<td>24.42</td>
<td>24.30</td>
<td>23.5671</td>
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<tr>
<td>Emission (ton/h)</td>
<td>274.32</td>
<td>274.32</td>
<td>274.27</td>
<td>274.28</td>
</tr>
<tr>
<td>Time (s)</td>
<td>1.675</td>
<td>1.581</td>
<td>1.507</td>
<td>1.264</td>
</tr>
</tbody>
</table>

From Table 6, it is obvious that ICSA always produces better results than DE, GA, and PSO. Even though the emission produced by ICSA technique is higher than using PSO, the computational burden is less when using ICSA.
V. CONCLUSIONS

In this paper, an improved cuckoo search algorithm has been applied to solve EED problem of generating units considering the system practical constraints. The proposed method has provided the global solution in the three and six-generator systems and yielded better solution than the earlier studies reported in the literature. Future works will consider the integration of intermittent energy resources in the model. Also, larger system performance will be carried out on IEEE 118 and 300 bus systems using the proposed technique.

REFERENCES


