NSGA-II Technique for Multi-objective Generation Dispatch of Thermal Generators with Nonsmooth Fuel Cost Functions

M. Rajkumar†, K. Mahadevan*, S. Kannan** and S. Baskar***

Abstract – Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied for solving Combined Economic Emission Dispatch (CEED) problem with valve-point loading of thermal generators. This CEED problem with valve-point loading is a nonlinear, constrained multi-objective optimization problem, with power balance and generator capacity constraints. The valve-point loading introduce ripples in the input-output characteristics of generating units and make the CEED problem as a nonsmooth optimization problem. To validate its effectiveness of NSGA-II, two benchmark test systems, IEEE 30-bus and IEEE 118-bus systems are considered. To compare the Pareto-front obtained using NSGA-II, reference Pareto-front is generated using multiple runs of Real Coded Genetic Algorithm (RCGA) with weighted sum of objectives. Comparison with other optimization techniques showed the superiority of the NSGA-II approach and confirmed its potential for solving the CEED problem. Numerical results show that NSGA-II algorithm can provide Pareto-front in a single run with good diversity and convergence. An approach based on Technique for Ordering Preferences by Similarity to Ideal Solution (TOPSIS) is applied on non-dominated solutions obtained to determine Best Compromise Solution (BCS).

Keywords: Combined Economic Emission Dispatch (CEED), Non-dominated Sorting Genetic Algorithm-II (NSGA-II), Pareto-optimal solutions, TOPSIS, Valve-point loading.

1. Introduction

Economic Dispatch (ED) is the process of allocating generation levels to the various generating units so that the system demand is fully met in the most economical way. The traditional ED has the objective of minimizing the fuel costs [1]. Operating at absolute minimum cost can no longer be the only criterion for dispatching electric power due to the increasing environmental pollution caused by the fossil-fueled electric power plants. It forces the utilities to modify their design to reduce pollution and atmospheric emissions of the thermal power plants [2]. Hence, it is necessary to minimize both emission and cost. However, minimizing the emission and cost are usually two conflicting objectives. Thus, it is not possible to minimize both of them simultaneously and some form of conflicting resolution must be adopted to arrive at a solution [3].

Several Economic Emission Dispatch (EED) strategies have appeared in the literature over the years. Lagrange relaxation method [4], weighted sum method [5], ε-constrained algorithm [6], Linear programming method, [7], Goal programming technique [8] are used to solve the EED problem. However, these classical methods are highly sensitive and frequently converge at local optimum solution and computational time increases with the increase of the dimensionality of the problem.

Later, the use of heuristic optimization approaches such as Genetic Algorithm (GA) [9], Evolutionary Programming (EP) [10] and Differential Evolution (DE) [11] are used to solve the multi-objective constrained optimization problem. Prabakar et al have applied modified price penalty factor method to Combined Economic Emission Dispatch (CEED) problem and converted into single objective problem [12]. Recently, the multi-objective evolutionary algorithms (MOEAs) are used to eliminate many difficulties in the classical methods [13]. Because, population of solutions is used in their search and multiple Pareto-optimal solutions can be found in one single simulation run. Some of the popular MOEAs are Non-dominated Sorting Genetic Algorithm (NSGA), Niched Pareto Genetic Algorithm, Strength Pareto Evolutionary Algorithm (SPEA), NSGA-II, Pareto Archived Evolution Strategy etc. [14]. Abido has applied NSGA [15], SPEA [16] and Multi-objective Particle Swarm Optimization (MOPSO) [17] approaches for solving the multi-objective CEED problem. NSGA suffers from computational complexity, non-elitist approach and the need to specify a sharing parameter. An improved version of NSGA known as NSGA-II, which resolves CEED problems and uses elitism to create a diverse Pareto-
optimal front, has been subsequently presented [18-21]. In addition, TOPSIS method is employed to choose the BCS, which will be useful to the decision maker [20, 21]. Wu et al proposed multi-objective DE (MODE) algorithm with elitist archive and crowding entropy based diversity measure to solve the environmental/economic power dispatch problem [22]. The premature convergence using MODE algorithm is overcome by enhanced MODE (EMODE) algorithm to solve EED problem by Youlin Lu et al [23]. Though researchers have used several methods for solving single objective ED problem and multi-objective EED problem, but they do not considered valve-point loading effect [1-23].

In general, discontinuity may also be observed in thermal power plants due to valve-point loading. In reality, due to valve-point effect, the cost function is nonsmooth and nonmonotonically increasing and conventional methods such as Lambda-iteration, Gradient method and Newton method have failed to obtain global optimum solution. Hence, stochastic methods such as GA [24], EP [25], Improved EP [26], PSO [27] and DE [28] have been used to solve the ED problem with valve-point loading effect by adding the rectified sinusoidal contribution to the conventional quadratic cost function.

Though researchers considered valve-point effect in the single objective ED problem [24-28], very few works are reported with the consideration of valve-point effect for the CEED problem. Basu [29] analyzed the interactive fuzzy satisfying based simulated annealing technique for CEED problem with nonsmooth fuel cost and emission level functions. The major advantage of this method is obtaining a compromising solution in the presence of conflicting objectives. However, the longer execution time is the drawback of this method. Hemamalini et al have applied PSO algorithm to solve emission constrained ED problem with valve-point loading effect. However, this formulation does require the knowledge of the relative importance of each objective and has a severe difficulty in getting the trade-off relations between cost and emission [30]. MODE algorithm has been applied by Basu, for solving EED problems with valve-point loading and extreme points obtained are compared with Partial DE, NSGA-II and SPEA-2 for different test systems. However, the selection of BCS from the estimated Pareto-optimal set is not considered [31]. Also, the transmission line losses are calculated through B_{min} coefficients [29-31].

In this paper, NSGA-II algorithm is used to solve CEED problem with valve-point effect. Pareto-front obtained by the NSGA-II is compared with reference Pareto-front found by RCGA. In addition, the transmission line losses are calculated through load flow solutions and BCS is obtained by TOPSIS method, which will be useful to the decision maker. The rest of this paper is organized as follows: Section 2 describes the CEED problem formulation. Implementation of NSGA-II for the CEED problem is explained in Section 3. Section 4 incorporates TOPSIS decision approach to determine the BCS. The simulation results of various test cases are presented in Section 5 and Section 6 concludes.

2. Problem Formulation

The multi-objective CEED problem with its constraints is formulated as a nonlinear constrained problem as follows.

subject to power balance and generation capacity constraints, where,

\[
F\left(P_g\right): \text{Total fuel cost ($/hr)},
\]

\[
E\left(P_g\right): \text{Total emission (ton/hr)}.
\]

2.1 Objective functions

The fuel cost function or input-output characteristics of the generator may be obtained from design calculations or from heat rate tests. For large steam turbine generators, the input-output characteristics are not always smooth. Large steam turbine generators will have a number of steam admission valves that are opened in sequence to obtain ever-increasing output of the unit. These “valve-points” are illustrated in Fig. 1.

Ignoring the valve-point loading effects, some inaccuracy would result in the generation dispatch. Therefore, the fuel costs of generators are usually approximated by second-order polynomial when the traditional techniques are used.

The assumptions made the problem easier to solve. However, the loss of accuracy induced by these approximations is not desirable. To model the effects of nonsmooth fuel cost functions, a recurring rectified sinusoidal contribution is added to the second order polynomial functions to represent the input-output Eq. (2) as follows. The total fuel cost in terms of real power output can be expressed as [24],

![Incremental fuel cost curve of turbine unit](image)
The total emission of atmospheric pollutants such as Sulphur Oxides (SO$_2$) and Nitrogen Oxides (NO$_x$) from a fossil-fired thermal generating unit depends upon the amount of power generated by each unit. For simplification, the total emission generated can be approximately modeled as a direct sum of a quadratic function and an exponential term of the active power output of the generating units and is expressed in the following form [29]:

$$E(P_g) = \sum_{i=1}^{N} \alpha_i + \beta_i P_g + \gamma_i P_g^2 + \eta_i \exp(\delta_i P_g)$$

where,

$$E(P_g): \text{Total emission (ton/hr)}$$

$$\alpha_i, \beta_i, \gamma_i, \eta_i, \delta_i: \text{Emission coefficients of generator } i.$$

### 2.2 Constraints

#### Generation capacity constraint:
For stable operation, real power output of each generator is restricted by lower and upper limits as follows:

$$P_{g_i}^{\text{min}} \leq P_{g_i} \leq P_{g_i}^{\text{max}}, \quad i=1,\ldots,N$$

where,

$$P_{g_i}^{\text{min}}, P_{g_i}^{\text{max}}: \text{Minimum and maximum power generated}.$$  

#### Power balance constraint:
The total power generated must supply the total load demand and the transmission losses [19].

$$\sum_{i=1}^{N} P_{g_i} - P_d - P_{\text{loss}} = 0$$

where,

$$P_d: \text{Total load demand},$$

$$P_{\text{loss}}: \text{Transmission losses}.$$  

The real power loss $P_{\text{loss}}$ can be calculated from Newton-Raphson load flow solution, which gives all bus voltage magnitudes and angles; it can be described as follows [22]:

$$P_{\text{loss}} = \sum_{k=1}^{N} g_k \left[ V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j) \right]$$

where,

$$i \text{ and } j \text{ are the total number of buses ( } i \neq j),$$

$$k \text{ is the } k^{\text{th}} \text{ network branch that connects bus } i \text{ to bus } j,$$

$$N_i \text{ is the number of transmission lines,}$$

$$V_i \text{ and } V_j \text{ are the voltage magnitudes at bus } i \text{ and } j,$$

$$g_k \text{ is the transfer conductance between bus } i \text{ and } j,$$

$$\theta_i \text{ and } \theta_j \text{ are the voltage angles at bus } i \text{ and } j \text{ respectively.}$$

### 3. Implementation of NSGA-II

The NSGA-II algorithm and its computational flow are described in this section.

#### 3.1 NSGA-II

NSGA-II is a fast and elitist multi-objective evolutionary algorithm (MOEA) and implements elitism for multi-objective search, using an elitism-preserving approach. Elitism enhances the convergence properties towards the true Pareto-optimal set. A parameter-less diversity preserving mechanism is adopted. Diversity and spread of solutions are guaranteed without the use of sharing parameters. In this paper, NSGA-II uses simulated binary crossover and polynomial mutation for solving the problem. The crowding comparison operator, guides the selection process towards a uniformly spread Pareto-frontier [18].

#### 3.2 Computational flow

**Step1:** Initially, a random parent population of size $N$ is created.

**Step2:** The population is sorted based on the non-domination. Each population is assigned a rank equal to its non-domination level or front number (1 is the best level, 2 is the next best level, and so on). Calculate the crowding distance (CD) of populations in each non-domination level and sort populations in descending order of CD.

**Step3:** Select two individuals at random. Compare their front number and CD. Select the better one and copy it to the mating pool.

**Step4:** The Simulated Binary Crossover (SBX) and polynomial mutation have been used to create offspring population of size $N$.

**Step5:** Combine the parent population and child population.

**Step6:** The combined population is sorted according to non-domination and crowding distance. Since all parent and offspring population members are included, elitism is ensured.

**Step7:** The process can be stopped after a fixed number of iterations. If the criterion is not satisfied then the
Fig. 2. Computational flow of NSGA-II

4. TOPSIS Method

In general, the result of MOEAs is a set of non-dominated front. From the best obtained Pareto-front, it is usually required to select one solution for implementation. A multi attribute decision making (MADM) approach is adopted to rank the obtained NSGA-II solutions and the BCS is calculated in a deterministic environment with a single decision maker. From the decision maker’s perspective, the choice of a solution from all Pareto-optimal solutions is called a posteriori approach and it requires a higher level decision making approach, which is to determine the best solution among a finite set of Pareto-optimal solutions with respect to all relevant attributes. In this paper, MADM technique based on TOPSIS is employed in posterior evaluation of Pareto-optimal solutions to choose the best one among them. The concept of TOPSIS is described as: In the absence of a natural course of action for overall summary measure and ranking, the most preferred alternative should not only have the shortest distance from the positive ideal solution, but also have the longest distance from the negative ideal solution. Almost all MADM methods require predetermined information on the relative importance of the attributes, which is usually given by a set of normalized weights. The weights of two objectives are calculated by Shannon’s entropy method. The entropy method is based on information theory, which assigns a small weight to an attribute if it has similar attribute values across alternatives, because such attribute does not help in differentiating alternatives [20, 21].

The classical MADM model is described as follows:
Let $R = R_{ij}$ ($i = 1, 2, ..., n$ (no. of Pareto-optimal solutions), $j = 1, 2, ..., m$ (no. of objectives)) is the $n \times m$ decision matrix, where $R_{ij}$ is the performance rating of alternative $X_i$ (Pareto-optimal solutions) with respect to attribute $A_j$ (objective function values).

To determine objective weights by the entropy measure, the decision matrix needs to be normalized for each objective $A_j$ as

$$p_{ij} = \frac{R_{ij}}{\sum_{p=1}^{n} R_{pj}}$$

(7)

As a consequence, a normalized decision matrix representing the relative performance of the alternatives is obtained as

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\
p_{21} & p_{22} & \cdots & p_{2m} \\
& \vdots & \ddots & \vdots \\
p_{n1} & p_{n2} & \cdots & p_{nm} \end{bmatrix}$$

(8)

The amount of decision information contained in Eq. (8) and emitted from each attribute $A_j (j = 1, 2, ..., m)$ can thus be measured by the entropy value $e_j$ as

$$e_j = \frac{1}{\ln n} \sum_{p=1}^{n} p_{pj} \ln p_{pj}$$

(9)

The degree of divergence $d_j$ of the average intrinsic
information contained by each attribute $A_j$ ($j = 1, 2, ..., m$) can be calculated as

$$d_j = 1 - e_j$$

The objective weight for each attribute $A_j$ ($j = 1, 2, ..., m$) is thus given by

$$w_j = \frac{d_j}{\sum_{k=1}^{m} d_k}$$

The weighted normalized value $v_i$ is calculated as

$$v_i = w_i p_i$$

After determining performance ratings of the alternatives and objective weights of the attributes, the next step is to aggregate them to produce an overall performance index for each alternative. This aggregation process is based on the positive ideal solution ($A^+$) and the negative ideal solution ($A^-$), which are defined, respectively by

$$A^+ = (\max(v_{j1})\max(v_{j2})... \max(v_{jm})) = (v_{1}^+, v_{2}^+, ..., v_{m}^+)$$

$$A^- = (\min(v_{j1})\min(v_{j2})... \min(v_{jm})) = (v_{1}^-, v_{2}^-, ..., v_{m}^-)$$

Separation between alternatives can be measured by the $n$-dimensional Euclidean distance. The separation of each alternative from the ideal solution is given as

$$d_j = \left\{ \sum_{i=1}^{n} (v_{ij} - v_i^+) \right\}^{\frac{1}{2}}, \quad j = 1, 2, ..., n$$

Similarly, the separation from the negative ideal solution is given as

$$d_j = \left\{ \sum_{i=1}^{n} (v_{ij} - v_i^-) \right\}^{\frac{1}{2}}, \quad j = 1, 2, ..., n$$

The relative closeness to the ideal solution of alternative $X_j$ with respect to $A^+$ is defined as

$$C_j = \frac{d_j}{d_j^* + d_j^-}$$

Since $d^- \geq 0$ and $d^+ \geq 0$, then clearly, $C_j \in [0,1]$. Choose an alternative with maximum $C_j$ or rank alternatives according to $C_j$ in descending order. It is clear that an alternative $X_j$ is closer to $A^+$ than to $A^-$ as $C_j$ approaches 1 [20, 21].

5. Simulation Results and Discussion

The RCGA and NSGA-II algorithms are coded in MATLAB version 7.11 on a PC with Pentium-IV Intel (R) Core(TM) 13-2310M CPU operating at 2.10 GHz speed with 4 GB RAM.

5.1 Description of the test systems

The standard IEEE 30-bus system consists of six generating units with a demand of 283.4 MW and IEEE 118-bus system is composed of 19 generating units with a demand of 3668 MW are taken as test systems, to verify the effectiveness of NSGA-II. The detailed fuel cost coefficients, emission coefficients, the lower and the upper power limits are taken from [12, 26 and 30]. The bus data and the line data are taken from [32]. MATPOWER software is used for power flow calculations [32].

5.2 Parameter settings

The parameter settings of NSGA-II for solving CEED problem is as follows: In general, the population size of six times the number of decision variables is considered. For IEEE 30-bus system, the population size and iteration are set as 40 and 200 respectively. For IEEE 118-bus system, the population size and maximum iteration number are set as 100 and 500 respectively. The crossover probability ($P_c$) is varied between 0.8 to 0.9 and other parameters such as mutation probability ($P_m$), crossover index ($\eta_c$) and mutation index ($\eta_m$) are selected as $1/n$ (where $n$-number of variables), 5 and 15 respectively [14].

5.3 Generation of reference Pareto-front

To compare the performance of NSGA-II, a reference Pareto-front obtained by using multiple runs of Real Coded Genetic Algorithm (RCGA) with weighted sum approach is considered. In reference Pareto-front generation, CEED problem is treated as single objective optimization problem by linear combination of objectives as follows:

$$\text{Minimize } C = w f_1 + (1-w) f_2$$

where,

- $w$ is a weighing factor and the sum of weighting factor must be 1.
- $f_1$ is the cost objective and $f_2$ is the emission objective.

To get 50 non-dominated solutions, the algorithm is applied 50 times with varying weight factors as a uniform random number varying between 0 and 1 in each trial. Different population sizes and iteration numbers are selected depending upon the number of decision variables [20].
5.4 IEEE 30-bus system

In this case, the NSGA-II and RCGA have been applied to solve CEED problem for the standard IEEE 30-bus system. The single line diagram of this system is given in [19]. The power system is interconnected by 41 transmission lines and the total system demand for the 21 load buses is 283.4 MW. Extreme solutions for cost and emission are obtained using NSGA-II and PSO respectively and reported in Table 1 and Table 4. Referring to Table 1, PSO algorithm as reported in the literature [30], able to give better results compared to other methods but it needs weight factors to convert multi-objective problem into single objective algorithm and also multiple runs are required to obtain the Pareto-optimal solutions. From the

Table 1. Comparative result of Extreme solution for cost - IEEE 30-bus system in the case of CEED without Valve-point effect

<table>
<thead>
<tr>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Cost ($/hr$)</th>
<th>Corresponding Emission (ton/hr)</th>
<th>Execution Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSGA-II</td>
<td>0.116</td>
<td>0.305</td>
<td>0.597</td>
<td>0.982</td>
<td>0.512</td>
<td>0.356</td>
<td>0.035</td>
<td>608.125</td>
<td>0.2200</td>
<td>98.359</td>
</tr>
<tr>
<td>RCGA</td>
<td>0.115</td>
<td>0.306</td>
<td>0.599</td>
<td>0.982</td>
<td>0.513</td>
<td>0.355</td>
<td>0.035</td>
<td>608.124</td>
<td>0.2199</td>
<td>4518</td>
</tr>
<tr>
<td>PSO[30]</td>
<td>0.128</td>
<td>0.270</td>
<td>0.555</td>
<td>1.005</td>
<td>0.454</td>
<td>0.445</td>
<td>0.025</td>
<td>606.600</td>
<td>0.2207</td>
<td>--</td>
</tr>
<tr>
<td>NSGA[15]</td>
<td>0.117</td>
<td>0.317</td>
<td>0.544</td>
<td>0.945</td>
<td>0.549</td>
<td>0.396</td>
<td>0.034</td>
<td>608.245</td>
<td>0.21664</td>
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<tr>
<td>SPEA[16]</td>
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<td>0.582</td>
<td>0.985</td>
<td>0.529</td>
<td>0.358</td>
<td>0.034</td>
<td>607.807</td>
<td>0.22015</td>
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</table>

Table 2. Comparative result of Extreme solution for emission - IEEE 30-bus system in the case of CEED without Valve-point effect

<table>
<thead>
<tr>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Emission (ton/hr)</th>
<th>Corresponding Cost ($/hr$)</th>
<th>Execution Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSGA-II</td>
<td>0.358</td>
<td>0.465</td>
<td>0.541</td>
<td>0.392</td>
<td>0.576</td>
<td>0.534</td>
<td>0.033</td>
<td>0.1942</td>
<td>643.4214</td>
<td>98.359</td>
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<tr>
<td>RCGA</td>
<td>0.411</td>
<td>0.463</td>
<td>0.544</td>
<td>0.390</td>
<td>0.544</td>
<td>0.515</td>
<td>0.033</td>
<td>0.1942</td>
<td>645.7119</td>
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<td>PSO[30]</td>
<td>0.371</td>
<td>0.467</td>
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<td>0.522</td>
<td>0.578</td>
<td>0.034</td>
<td>0.1945</td>
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<td>0.411</td>
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<td>0.581</td>
<td>0.530</td>
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<td>0.1943</td>
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<tr>
<td>SPEA[16]</td>
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<td>0.453</td>
<td>0.553</td>
<td>0.408</td>
<td>0.547</td>
<td>0.501</td>
<td>0.031</td>
<td>0.1942</td>
<td>642.603</td>
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Table 3. Comparative result of Extreme solution for cost of IEEE 30-bus system in the case of CEED with Valve-point effect

<table>
<thead>
<tr>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
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<tr>
<td>NSGA-II</td>
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<td>0.307</td>
<td>0.594</td>
<td>0.982</td>
<td>0.516</td>
<td>0.354</td>
<td>0.035</td>
<td>611.057</td>
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<td>96.5780</td>
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<tr>
<td>RCGA</td>
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<td>0.306</td>
<td>0.598</td>
<td>0.982</td>
<td>0.513</td>
<td>0.355</td>
<td>0.035</td>
<td>611.057</td>
<td>0.2140</td>
<td>4500</td>
</tr>
<tr>
<td>PSO[30]</td>
<td>0.099</td>
<td>0.363</td>
<td>0.484</td>
<td>0.874</td>
<td>0.664</td>
<td>0.390</td>
<td>0.039</td>
<td>626.96</td>
<td>0.21392</td>
<td>--</td>
</tr>
<tr>
<td>NSGA[15]</td>
<td>0.389</td>
<td>0.443</td>
<td>0.557</td>
<td>0.404</td>
<td>0.564</td>
<td>0.509</td>
<td>0.033</td>
<td>0.1942</td>
<td>645.2848</td>
<td>96.5780</td>
</tr>
<tr>
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<td>0.463</td>
<td>0.544</td>
<td>0.389</td>
<td>0.544</td>
<td>0.516</td>
<td>0.033</td>
<td>0.1947</td>
<td>648.5656</td>
<td>4500</td>
</tr>
<tr>
<td>PSO[30]</td>
<td>0.379</td>
<td>0.392</td>
<td>0.499</td>
<td>0.534</td>
<td>0.573</td>
<td>0.487</td>
<td>0.031</td>
<td>0.19567</td>
<td>659.44</td>
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Table 4. Comparative result of Extreme solution for emission of IEEE 30-bus system in the case of CEED with Valve-point effect

<table>
<thead>
<tr>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
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<th>$P_4$</th>
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<td>0.516</td>
<td>0.033</td>
<td>0.1947</td>
<td>648.5656</td>
<td>4500</td>
</tr>
<tr>
<td>PSO[30]</td>
<td>0.379</td>
<td>0.392</td>
<td>0.499</td>
<td>0.534</td>
<td>0.573</td>
<td>0.487</td>
<td>0.031</td>
<td>0.19567</td>
<td>659.44</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 5. Extreme solution for cost - IEEE 118-bus system in the case of CEED without Valve-point effect
Tables 2 to 4, it can be concluded that, the NSGA-II is capable of providing better results compared to other methods for the CEEED problem and it can be observed that the inaccuracy in the resulting dispatch when the valve-point loading effects are ignored. The execution time is also short using NSGA-II, thus computationally more efficient than RCGA. Best Pareto-front obtained in the problems of CEEED with valve-point effect and without valve-point effect using NSGA-II and RCGA are shown in Fig. 3. The NSGA-II produces the Pareto-optimal front in a single simulation run and it is clear that the solutions are diverse and well distributed. Furthermore, the Pareto-front generated using NSGA-II and multiple runs Pareto-front obtained using RCGA are almost identical.

5.5 IEEE 118-bus system

Simulations are conducted on the standard IEEE 118-bus, 19 generators-test system applying RCGA and NSGA-II. Two different cases are considered for the study. In the first case, valve-point effect is not considered but in the second case the cost function is modeled as a quadratic function summed with a sine term to include valve-point effect. In both cases, transmission line losses are included for the load demand of 3668 MW. Extreme solutions for cost and emission are obtained out of ten trial runs using NSGA-II for IEEE 118-bus system in the problem of CEEED without valve-point effect are reported in Tables 5 and 6 respectively and in the problem of CEEED with valve-point

Table 6. Extreme solution for emission - IEEE 118-bus system in the case of CEEED without Valve-point effect

<table>
<thead>
<tr>
<th>System</th>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Emission (ton/hr)</th>
<th>Corresponding Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEE118</td>
<td>NSGA-II</td>
<td>314.74</td>
<td>396.63</td>
<td>82.989</td>
<td>299.49</td>
<td>395.52</td>
<td>8.837</td>
<td>22.667</td>
<td>5495</td>
<td>17993.47</td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>310.33</td>
<td>425.52</td>
<td>89.922</td>
<td>299.99</td>
<td>399.99</td>
<td>1.666</td>
<td>18.706</td>
<td>5488</td>
<td>18227.58</td>
</tr>
<tr>
<td></td>
<td>Execution Time (sec)</td>
<td>340.86</td>
<td>386.81</td>
<td>174.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>236.20</td>
<td>49.480</td>
<td>199.66</td>
<td>198.92</td>
<td>340.86</td>
<td>386.81</td>
<td>174.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>239.99</td>
<td>49.989</td>
<td>199.95</td>
<td>199.99</td>
<td>291.42</td>
<td>399.83</td>
<td>167.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Execution Time (sec)</td>
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<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>4.895</td>
<td>303.70</td>
<td>276.89</td>
<td>38.283</td>
<td>39.801</td>
<td>---</td>
<td>---</td>
<td>874.859</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>1.645</td>
<td>307.753</td>
<td>292.74</td>
<td>49.988</td>
<td>26.841</td>
<td>---</td>
<td>---</td>
<td>31806.157</td>
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</tr>
</tbody>
</table>

Table 7. Extreme solution for cost - IEEE 118-bus system in the case of CEEED with Valve-point effect

<table>
<thead>
<tr>
<th>System</th>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Cost ($/hr)</th>
<th>Corresponding Emission (ton/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEE118</td>
<td>NSGA-II</td>
<td>641.52</td>
<td>53.23</td>
<td>88.876</td>
<td>298.95</td>
<td>40.559</td>
<td>7.292</td>
<td>14.659</td>
<td>12002.2</td>
<td>13.633</td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>650.98</td>
<td>300.00</td>
<td>19.997</td>
<td>249.992</td>
<td>40.001</td>
<td>1.003</td>
<td>22.996</td>
<td>11994.4</td>
<td>11.314</td>
</tr>
<tr>
<td></td>
<td>Execution Time (sec)</td>
<td>383.12</td>
<td>398.262</td>
<td>582.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>31.255</td>
<td>47.663</td>
<td>186.136</td>
<td>183.536</td>
<td>383.12</td>
<td>398.262</td>
<td>582.43</td>
<td>599.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>30.002</td>
<td>49.998</td>
<td>100.199</td>
<td>159.993</td>
<td>324.994</td>
<td>399.999</td>
<td>599.94</td>
<td>599.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Execution Time (sec)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>4.204</td>
<td>624.500</td>
<td>259.765</td>
<td>5.353</td>
<td>14.089</td>
<td>---</td>
<td>---</td>
<td>846.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>1.645</td>
<td>699.995</td>
<td>202.635</td>
<td>5.000</td>
<td>4.005</td>
<td>---</td>
<td>---</td>
<td>31938.32</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Extreme solution for emission - IEEE 118-bus system in the case of CEEED with Valve-point effect

<table>
<thead>
<tr>
<th>System</th>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Emission (ton/hr)</th>
<th>Corresponding Cost ($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEE118</td>
<td>NSGA-II</td>
<td>334.05</td>
<td>368.85</td>
<td>83.496</td>
<td>295.56</td>
<td>396.76</td>
<td>8.555</td>
<td>22.539</td>
<td>5622</td>
<td>181547.76</td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>301.09</td>
<td>450.14</td>
<td>89.98</td>
<td>299.92</td>
<td>399.89</td>
<td>9.877</td>
<td>22.998</td>
<td>5517</td>
<td>18322.43</td>
</tr>
<tr>
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<td>Execution Time (sec)</td>
<td>291.99</td>
<td>324.994</td>
<td>181.75</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>NSGA-II</td>
<td>236.27</td>
<td>47.616</td>
<td>192.93</td>
<td>197.27</td>
<td>310.32</td>
<td>396.01</td>
<td>181.75</td>
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<td></td>
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<tr>
<td></td>
<td>RCGA</td>
<td>239.99</td>
<td>9.966</td>
<td>199.97</td>
<td>199.94</td>
<td>268.03</td>
<td>393.46</td>
<td>159.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Execution Time (sec)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>3.194</td>
<td>341.43</td>
<td>292.58</td>
<td>48.966</td>
<td>12.879</td>
<td>---</td>
<td>---</td>
<td>846.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCGA</td>
<td>4.977</td>
<td>450.00</td>
<td>224.95</td>
<td>49.99</td>
<td>9.979</td>
<td>---</td>
<td>---</td>
<td>31938.32</td>
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</tr>
</tbody>
</table>

Table 9. Best compromise solution for IEEE 30-bus and IEEE 118-bus system in the case of CEEED with Valve-point effect

<table>
<thead>
<tr>
<th>System</th>
<th>Method</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$P_5$</th>
<th>$P_6$</th>
<th>$P_7$</th>
<th>Cost ($/hr)</th>
<th>Emission (ton/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEE30</td>
<td>NSGA-II</td>
<td>0.30946</td>
<td>0.45906</td>
<td>0.34585</td>
<td>0.49112</td>
<td>0.55347</td>
<td>0.50429</td>
<td>---</td>
<td>6357946</td>
<td>0.1948</td>
</tr>
<tr>
<td></td>
<td>PSO[30]</td>
<td>0.14099</td>
<td>0.34415</td>
<td>0.67558</td>
<td>0.83971</td>
<td>0.49043</td>
<td>0.39797</td>
<td>---</td>
<td>63965</td>
<td>0.21105</td>
</tr>
<tr>
<td>IEE118</td>
<td>NSGA-II</td>
<td>348.31</td>
<td>367.56</td>
<td>89.299</td>
<td>296.83</td>
<td>361.70</td>
<td>9.825</td>
<td>21.179</td>
<td>17374.43</td>
<td>5.767</td>
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<tr>
<td></td>
<td>Execution Time (sec)</td>
<td>238.42</td>
<td>195.93</td>
<td>195.88</td>
<td>337.58</td>
<td>389.70</td>
<td>182.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NSGA-II</td>
<td>1.619</td>
<td>310.875</td>
<td>281.737</td>
<td>49.887</td>
<td>39.032</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

748
Effect are reported in Tables 7 and 8 respectively. Extreme solutions for cost and emission are obtained using RCGA also reported in Tables 5 to 8 and it can be observed that the inaccuracy in the resulting dispatch when the valve-point loading effects are ignored. Execution time of the NSGA-II is very less, thus computationally more efficient than RCGA. Best Pareto-front obtained in the cases of CEED with valve-point effect and without valve-point effect using NSGA-II and RCGA are shown in Fig. 4. The NSGA-II produces the Pareto-optimal front in a single simulation run but RCGA produces the Pareto-front in multiple runs. Furthermore, the Pareto-front generated using NSGA-II and multiple runs Pareto-front obtained using RCGA are almost identical.

5.6 Best Compromise Solution (BCS)

From the estimated Pareto-optimal set, it is usually required to choose one of them for implementation. Moreover, the choice of one solution over the other requires additional knowledge about the CEED problem. MADM technique is commonly used to evaluate the Pareto-optimal solutions and choose the best one Table 1 Comparative result of Extreme solution for cost - IEEE 30-bus system in the case of CEED without Valve-point effect among them. A large number of methods have been developed for solving multiple attribute problems. The concept of TOPSIS from the decision maker’s perspective, the choice of a solution from all Pareto-optimal solutions, which is to determine the best solution among a finite set of Pareto-optimal solutions with respect to all relevant attributes is used in this work. This procedure has been applied to NSGA-II results and the BCS is arrived. Table 9 gives the BCS value of IEEE 30-bus and IEEE 118-bus systems. It can be noticed that, NSGA-II is capable of providing better results in the BCS compared to PSO algorithm for IEEE 30-bus system.

Figs. 5 and 6 show the position of BCS on Pareto-front obtained using NSGA-II for the CEED problem of with valve-point effect in IEEE 30-bus and IEEE 118-bus system respectively.

6. Conclusion

In this paper, RCGA and NSGA-II have been applied to solve the CEED problem with complexities of valve-point loading effect and transmission line losses. The problem has been formulated as multi-objective optimization problem with competing fuel cost and emission objectives. By means of stochastically searching multiple points at one time and considering trial solutions of successive iterations,
the NSGA-II avoids entrapping in local optimal solutions than conventional methods. The NSGA-II was tested for the IEEE 30-bus and IEEE 118-bus systems and compared with the generated reference Pareto-front by RCGA. In all the cases, valve-point loading effect is included. Simulation results reveal that the NSGA-II can identify the Pareto-optimal front with a good diversity for the CEED problems of with and without valve-point effect. Moreover, the solutions are obtained in a single simulation run with less computational time. The MADM procedure is followed for choosing the BCS from the obtained Pareto-optimal solutions based on TOPSIS.

References


M. Rajkumar was born in Tirunelveli, Tamilnadu, India, on August 1975. He received the B.E. degree in Electrical and Electronics Engineering from National Engineering College, Kovilpatti, Tamilnadu, India, in 1999 and M.E. degree in Power Systems from Arulmigu Kalasalingam College of Engineering Krishnankoil, Tamilnadu, India, in 2004. He has presented various papers in the National and International conferences. His current research interests include Power system optimization and evolutionary computation technique. He is currently an Associate Professor in the department of Electrical & Electronics Engineering, National College of Engineering, Maruthakulam, Tirunelveli, 627 151, Tamilnadu, India. He is a member of IET and life member of ISTE.

His fields of interest are Power System Operation and Control and Evolutionary Computation. Currently, he is Professor of Electrical & Electronics Engineering, PSNA College of Engineering & Technology, Dindigul, Tamilnadu, India.

Dr. S. Kannan received his B.E., M.E., and Ph.D Degrees from Madurai Kamaraj University, Tamilnadu, India in 1991, 1998 and 2005 respectively. His research interests include Power System Deregulation and Evolutionary Computation. He was a visiting scholar in Iowa State University, USA (October 2006-September 2007) supported by the Department of Science and Technology, Government of India with BOYSCAST Fellowship. He is Professor and Head of Electrical and Electronics Engineering Department, Kalasalingam University, Krishnankoil, Tamilnadu, India, where he has been since July 2000. He is a Sr. Member of IEEE, Fellow of IE (I), Sr. Member in CSI, Fellow in IETE, Life member SSI and Life member of ISTE.

Dr. S. Baskar received the B.E., and the PhD Degrees from Madurai Kamaraj University, Madurai, Tamilnadu, India, in 1991 and 2001 respectively and the M.E., degree from Anna University, India, in 1993. He did his post-doc research in Evolutionary Optimization at NTU, Singapore. His research interests include the development of new Evolutionary Algorithm and applications to engineering optimization problems. He is the reviewer for IEEE Transactions on Evolutionary Computation. He has published over 50 papers in journals in the area of Evolutionary Optimization and applications. He is Professor in the department of Electrical & Electronics Engineering, Thiagarajar College of Engineering, Madurai, Tamilnadu, India. He is a Sr. Member of IEEE, Fellow of Institution of Engineers (India) and Life member of the Indian Society for Technical Education. He was the recipient of the Young Scientists BOYSCAST Fellowship during 2003-2004 supported by the Department of science and Technology, Government of India.

Dr. K. Mahadevan was born in Thirumangalam, Tamilnadu, India. He graduated in Electrical and Electronics Engineering in 1993 and Post graduated in Industrial Engineering in 1997 and PhD in 2006 from Madurai Kamaraj University, Tamilnadu, India.