CHAPTER 5
APPLICATION AND COMPARISON OF MOGAs TO CEED PROBLEM WITH PROHIBITED OPERATING ZONES

5.1 INTRODUCTION

NSGA-II and MNSGA-II (NSGA-II + DCD + CE) are applied to solve the CEED problem with POZ constraint. The details of the algorithms have been discussed in Chapter 3. In order to assess the effectiveness and robustness of the implemented algorithms, three test systems i.e., IEEE 30-bus, IEEE 57-bus and IEEE 118-bus systems have been considered.

In this chapter, the results of CEED problem with POZ constraint are discussed. Simultaneous minimization of cost and emission is the main objective of this problem. The objective functions are subjected to power balance constraint and generator capacity limit constraint. In addition, POZ is also considered as a constraint in this problem. Newton-Raphson power flow method is used for the calculation of transmission line losses. Reference Pareto front is generated by conventional weighted sum method using RCGA for the performance comparison of NSGA-II and MNSGA-II.

The non-dominated solutions obtained by RCGA, NSGA-II and MNSGA-II are compared with each other. The multi-objective performance metrics such as convergence, spread and IGD are used to determine the closeness of Pareto front obtained by NSGA-II and MNSGA-II with reference Pareto front. Performance measures are based on the best, mean, worst and standard deviation.
TOPSIS method has also been used to determine the best compromise solution from the set of Pareto solutions. The algorithms are implemented in MATLAB version 7.11 and executed on a PC with Pentium-IV Intel (R) Core(TM) i3-2310M CPU operating at 2.10 GHz speed with 4 GB RAM.

5.2 TEST SYSTEM DESCRIPTION

Three test systems were considered as same as given in Section 4.2. The detailed fuel cost coefficients, emission coefficients, the minimum and maximum power limits and POZ data for IEEE 30-bus, IEEE 57-bus and IEEE 118-bus test systems are given in Appendix-1, Appendix-2 and Appendix-3 respectively.

5.3 PARAMETER SELECTION

The parameter settings of NSGA-II and MNSGA-II for solving CEED problem with POZ constraint are as follows: The population size and maximum number of iterations are fixed at 100 and 1000 respectively for all the test systems. The crossover probability ($P_c$) is fixed at 0.85 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.

5.4 SIMULATION RESULTS

Simulations are performed on IEEE 30-bus, IEEE 57-bus and IEEE 118-bus test systems for the demand of 283.4 MW, 1250.8 MW and 3668 MW respectively.

5.4.1 IEEE 30-bus System

In the standard IEEE 30-bus system, NSGA-II, MNSGA-II and RCGA techniques have been applied to solve the CEED problem. Extreme solutions for cost and emission obtained out of ten trial runs using NSGA-II
and MNSGA-II are given in Table 5.1 along with extreme solutions for cost and emission obtained using RCGA. The power generation dispatch values of six generating units corresponding to the extreme solutions are also given in Table 5.1. It satisfies the generator capacity limits. Losses are calculated using Newton-Raphson power flow method and presented in the same table. The total generation value minus losses is equal to the demand value and hence power balance constraint is satisfied. The power dispatch values obtained are not in the ranges of POZ. Thus POZ constraint is also not violated.

<table>
<thead>
<tr>
<th>Power generation / losses (MW)</th>
<th>RCGA</th>
<th>NSGA-II</th>
<th>MNSGA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost ($/hr)</td>
<td>Emission (ton/hr)</td>
<td>Cost ($/hr)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>11.519</td>
<td>40.186</td>
<td>10.157</td>
</tr>
<tr>
<td>$P_2$</td>
<td>30.597</td>
<td>45.811</td>
<td>40.001</td>
</tr>
<tr>
<td>$P_3$</td>
<td>59.991</td>
<td>54.525</td>
<td>57.132</td>
</tr>
<tr>
<td>$P_4$</td>
<td>98.315</td>
<td>40.738</td>
<td>96.494</td>
</tr>
<tr>
<td>$P_5$</td>
<td>51.448</td>
<td>54.432</td>
<td>48.688</td>
</tr>
<tr>
<td>$P_6$</td>
<td>35.000</td>
<td>51.005</td>
<td>34.388</td>
</tr>
<tr>
<td>Total Generation</td>
<td>286.870</td>
<td>286.697</td>
<td>286.860</td>
</tr>
<tr>
<td>Losses</td>
<td>3.470</td>
<td>3.297</td>
<td>3.460</td>
</tr>
<tr>
<td>Cost ($/hr)</td>
<td>608.128</td>
<td>643.505</td>
<td>609.330</td>
</tr>
<tr>
<td>Emission (ton/hr)</td>
<td>0.2201</td>
<td>0.1942</td>
<td>0.2183</td>
</tr>
<tr>
<td>Execution Time (seconds)</td>
<td>54027.485</td>
<td>1160.89</td>
<td>1177</td>
</tr>
</tbody>
</table>

From the Table 5.1, it can be observed that, MNSGA-II is capable of providing better result based on fuel cost compared to NSGA-II and RCGA for the CEED problem with POZ constraint. Execution time of NSGA-II and MNSGA-II is less, thus computationally more efficient than RCGA.
Best Pareto fronts obtained in the case of CEED without POZ using NSGA-II and MNSGA-II are shown in Figure 5.1 and in the case of CEED with POZ using RCGA, NSGA-II and MNSGA-II are shown in Figure 5.2. There are discontinuities in the Pareto front of Figure 5.2, because of POZ constraint is considered in the CEED problem.

![Figure 5.1 Pareto front of CEED without POZ using NSGA-II and MNSGA-II for IEEE 30-bus System](image1)

**Figure 5.1** Pareto front of CEED without POZ using NSGA-II and MNSGA-II for IEEE 30-bus System

![Figure 5.2 Comparison of NSGA-II, MNSGA-II and reference Pareto front of CEED with POZ for IEEE 30-bus system](image2)

**Figure 5.2** Comparison of NSGA-II, MNSGA-II and reference Pareto front of CEED with POZ for IEEE 30-bus system
The NSGA-II and MNSGA-II produce the Pareto front in a single simulation run but RCGA produces the Pareto-optimal front in multiple runs. Furthermore, the Pareto front generated using MNSGA-II is very close to the reference Pareto front obtained using RCGA. Using TOPSIS method to find the best compromise solution from the obtained Pareto front using MNSGA-II is shown in Figure 5.3.

![Figure 5.3 Best compromise solution of CEED with POZ for IEEE 30-bus system](image)

**Figure 5.3 Best compromise solution of CEED with POZ for IEEE 30-bus system**

The various performance metrics such as convergence, spread and IGD are calculated for IEEE 30-bus system and the values are given in Table 5.2. The performance measures are used to find the closeness between the Pareto fronts obtained from MOGAs and reference Pareto front. The detailed description of the performance metrics have been discussed in Chapter 3. From Table 5.2, it can be observed that, MNSGA-II is better than NSGA-II in most of the performance metrics values.
Table 5.2  Statistical comparison of performance metrics of CEED with POZ for IEEE 30-bus system

<table>
<thead>
<tr>
<th>Measure</th>
<th>Algorithm</th>
<th>Best</th>
<th>Worst</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>NSGA-II</td>
<td>0.0032</td>
<td>0.0047</td>
<td>0.0037</td>
<td>0.000518</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.0030</td>
<td>0.0040</td>
<td>0.0038</td>
<td>0.000167</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>NSGA-II</td>
<td>0.4579</td>
<td>0.5421</td>
<td>0.4998</td>
<td>0.0338</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.3676</td>
<td>0.5302</td>
<td>0.4440</td>
<td>0.0339</td>
</tr>
<tr>
<td>IGD</td>
<td>NSGA-II</td>
<td>0.0154</td>
<td>0.0226</td>
<td>0.0180</td>
<td>0.0028</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.0149</td>
<td>0.0192</td>
<td>0.0178</td>
<td>0.000890</td>
</tr>
</tbody>
</table>

5.4.2  IEEE 57-bus System

Simulations are performed on the standard IEEE 57-bus, seven generators test system by applying RCGA, NSGA-II and MNSGA-II. Two different cases are considered for the system. In case 1, POZ is not considered and it is considered as a constraint in the latter case. In both the cases, transmission line losses are included for the load demand of 1250.8 MW. Extreme solutions for cost and emission in the case of CEED with POZ are obtained out of ten trial runs using NSGA-II and MNSGA-II for IEEE 57-bus system and presented in Table 5.3. Extreme solutions for cost and emission obtained using RCGA method are also given in the same table. The IEEE 57-bus generated powers are shown in the first seven rows, the eighth row represent the total generation, the ninth row represent losses and the next two rows represent fuel cost and emission and the last row represent the execution time taken of all the methods. The power generation dispatch values are within the operating limits and out of multiple ranges of POZ. Thus the generator capacity limit and POZ constraints are satisfied. Losses are calculated through power flow method and subtracted from the total generation to meet the demand value and hence power balance constraint is also satisfied.
Table 5.3  Power generation schedule with power loss, extreme solution and execution time of CEED with POZ for IEEE 57-bus system

<table>
<thead>
<tr>
<th>Power generation / losses (MW)</th>
<th>RCGA</th>
<th>NSGA-II</th>
<th>MNSGA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost ($/hr)</td>
<td>Emission (ton/hr)</td>
<td>Cost ($/hr)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>537.065</td>
<td>200.025</td>
<td>516.419</td>
</tr>
<tr>
<td>$P_2$</td>
<td>10.000</td>
<td>84.995</td>
<td>34.647</td>
</tr>
<tr>
<td>$P_3$</td>
<td>20.000</td>
<td>115.003</td>
<td>26.229</td>
</tr>
<tr>
<td>$P_4$</td>
<td>10.000</td>
<td>96.726</td>
<td>10.001</td>
</tr>
<tr>
<td>$P_5$</td>
<td>376.400</td>
<td>300.003</td>
<td>374.042</td>
</tr>
<tr>
<td>$P_6$</td>
<td>10.000</td>
<td>99.999</td>
<td>10.537</td>
</tr>
<tr>
<td>$P_7$</td>
<td>319.001</td>
<td>370.001</td>
<td>310.621</td>
</tr>
<tr>
<td>Total Generation</td>
<td>1282.47</td>
<td>1266.75</td>
<td>1282.49</td>
</tr>
<tr>
<td>Losses</td>
<td>31.67</td>
<td>15.95</td>
<td>31.69</td>
</tr>
<tr>
<td>Cost ($/hr)</td>
<td><strong>3830.231</strong></td>
<td>6349.719</td>
<td><strong>4026.364</strong></td>
</tr>
<tr>
<td>Emission (ton/hr)</td>
<td>3.113</td>
<td><strong>2.011</strong></td>
<td>2.950</td>
</tr>
<tr>
<td>Execution Time (seconds)</td>
<td>36136.832</td>
<td>616.828</td>
<td>618.687</td>
</tr>
</tbody>
</table>

From the Table 5.3, it can be concluded that, obtained results based on extreme fuel cost and emission using MNSGA-II is better than NSGA-II and very close value when compared to RCGA. Execution time of MOGAs is approximately 10 minutes but RCGA has taken 10 hours to obtain the solutions. Thus MOGAs are computationally more efficient than RCGA.

Best Pareto fronts obtained in the case of CEED without POZ using NSGA-II and MNSGA-II and in the case of CEED with POZ using RCGA, NSGA-II and MNSGA-II are shown in figures 5.4 and 5.5 respectively. It can
be seen that, there are discontinuities present in the Pareto front of Figure 5.5, because of POZ constraint is considered for the CEED problem.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ceed_without_poz.pdf}
\caption{Pareto front of CEED without POZ using NSGA-II and MNSGA-II for IEEE 57-bus system}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ceed_with_poz.pdf}
\caption{Comparison of NSGA-II, MNSGA-II and reference Pareto front of CEED with POZ for IEEE 57-bus system}
\end{figure}
The NSGA-II and MNSGA-II produce the Pareto front in a single simulation run but RCGA produces the same in multiple runs. Furthermore, the Pareto front generated using MNSGA-II is very close to the reference Pareto front obtained using RCGA. TOPSIS method is used to determine best compromise solution from the obtained Pareto front as shown in Figure 5.6.

![Figure 5.6](image)

**Figure 5.6** Best compromise solution of CEED with POZ for IEEE 57-bus system

The three different performance metrics for the IEEE 57-bus system are calculated and the values given in Table 5.4. It can be observed that, most of the performance metrics values obtained by MNSGA-II are less than that of NSGA-II.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Algorithm</th>
<th>Best</th>
<th>Worst</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>NSGA-II</td>
<td>0.0151</td>
<td>0.0258</td>
<td>0.0224</td>
<td>0.0031</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.0126</td>
<td>0.0216</td>
<td>0.0154</td>
<td>0.0123</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>NSGA-II</td>
<td>0.3762</td>
<td>0.6253</td>
<td>0.4660</td>
<td>0.0899</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.1516</td>
<td>0.6226</td>
<td>0.3771</td>
<td>0.0146</td>
</tr>
<tr>
<td>IGD</td>
<td>NSGA-II</td>
<td>0.1051</td>
<td>0.1757</td>
<td>0.1335</td>
<td>0.0234</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.0662</td>
<td>0.1717</td>
<td>0.1281</td>
<td>0.0753</td>
</tr>
</tbody>
</table>
5.4.3 IEEE 118-bus System

Simulations are performed on the standard IEEE 118-bus, nineteen generators test system by applying RCGA, NSGA-II and MNSGA-II. In this system, POZ is considered as a constraint and transmission line losses are included for the load demand of 3668 MW.

Extreme solutions for cost and emission in the case of CEED problem with POZ constraint are obtained out of ten trial runs using NSGA-II and MNSGA-II. The same has been obtained using RCGA for IEEE 118-bus system as well and the results are given in Table 5.5. The obtained power generation values satisfy all the constraints considered in this problem. From Table 5.5, it can be observed that the obtained results using MNSGA-II is better than NSGA-II and RCGA. Execution time of the MNSGA-II and NSGA-II is very less, thus computationally more efficient than RCGA.

Best Pareto fronts obtained in the case of CEED without POZ using NSGA-II and MNSGA-II and in the case of CEED with POZ using RCGA, NSGA-II and MNSGA-II are shown in figures 5.7 and 5.8 respectively. There are discontinuities present in the Pareto front shown in Figure 5.8, because POZ constraint is considered for the CEED problem.

The NSGA-II and MNSGA-II produce the Pareto front in a single simulation run but RCGA produces the same in multiple runs. From the best Pareto front obtained using MNSGA-II shown in Figure 5.9, best compromise solution is determined using TOPSIS method.
Table 5.5  Power generation schedule with power loss, extreme solution and execution time of CEED with POZ for IEEE 118-bus system

<table>
<thead>
<tr>
<th>Power generation / Losses (MW)</th>
<th>RCGA</th>
<th>NSGA-II</th>
<th>MNSGA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost ($/hr)</td>
<td>Emission (ton/hr)</td>
<td>Cost ($/hr)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>653.0068</td>
<td>318.3101</td>
<td>652.0570</td>
</tr>
<tr>
<td>$P_2$</td>
<td>190.7422</td>
<td>376.9237</td>
<td>300.5014</td>
</tr>
<tr>
<td>$P_3$</td>
<td>83.8309</td>
<td>81.8151</td>
<td>66.8183</td>
</tr>
<tr>
<td>$P_4$</td>
<td>296.7857</td>
<td>289.139</td>
<td>232.6436</td>
</tr>
<tr>
<td>$P_5$</td>
<td>42.0419</td>
<td>383.992</td>
<td>101.1264</td>
</tr>
<tr>
<td>$P_8$</td>
<td>40.3225</td>
<td>234.3581</td>
<td>30.6023</td>
</tr>
<tr>
<td>$P_9$</td>
<td>46.5204</td>
<td>45.0646</td>
<td>32.0140</td>
</tr>
<tr>
<td>$P_{10}$</td>
<td>194.0858</td>
<td>197.6619</td>
<td>122.0069</td>
</tr>
<tr>
<td>$P_{11}$</td>
<td>196.1641</td>
<td>190.3700</td>
<td>88.3731</td>
</tr>
<tr>
<td>$P_{12}$</td>
<td>354.3593</td>
<td>355.0901</td>
<td>322.5816</td>
</tr>
<tr>
<td>$P_{13}$</td>
<td>397.0748</td>
<td>391.8275</td>
<td>383.3625</td>
</tr>
<tr>
<td>$P_{14}$</td>
<td>449.4249</td>
<td>169.5606</td>
<td>555.7721</td>
</tr>
<tr>
<td>$P_{15}$</td>
<td>1.5503</td>
<td>3.0641</td>
<td>2.9170</td>
</tr>
<tr>
<td>$P_{16}$</td>
<td>651.186</td>
<td>349.9718</td>
<td>662.4273</td>
</tr>
<tr>
<td>$P_{17}$</td>
<td>214.648</td>
<td>288.7042</td>
<td>217.1451</td>
</tr>
<tr>
<td>$P_{18}$</td>
<td>9.1038</td>
<td>48.3530</td>
<td>8.6953</td>
</tr>
<tr>
<td>$P_{19}$</td>
<td>9.8327</td>
<td>17.7370</td>
<td>33.0911</td>
</tr>
<tr>
<td>Total Generation</td>
<td>3860.372</td>
<td>3771.034</td>
<td>3838.9344</td>
</tr>
<tr>
<td>Losses</td>
<td>192.372</td>
<td>103.034</td>
<td>170.9344</td>
</tr>
<tr>
<td>Cost ($/hr)</td>
<td><strong>11979.866</strong></td>
<td><strong>17593.096</strong></td>
<td><strong>12862.488</strong></td>
</tr>
<tr>
<td>Emission (ton/hr)</td>
<td>11.7181</td>
<td><strong>5.7041</strong></td>
<td>13.0403</td>
</tr>
<tr>
<td>Execution Time (seconds)</td>
<td>63638.3</td>
<td>1781.688</td>
<td>1762.453</td>
</tr>
</tbody>
</table>
Figure 5.7  Pareto front of CEED without POZ using NSGA-II and MNSGA-II for IEEE 118-bus system

Figure 5.8  Comparison of NSGA-II, MNSGA-II and reference Pareto front of CEED with POZ for IEEE 118-bus system

Figure 5.9  Best compromise solution of CEED with POZ for IEEE 118-bus system
The performance metrics for the IEEE 118-bus test system are given in Table 5.6 and most of the performance metrics values obtained by MNSGA-II are less compared to the values obtained by NSGA-II.

**Table 5.6 Statistical comparison of performance metrics of CEED with POZ for IEEE 118-bus system**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Algorithm</th>
<th>Best</th>
<th>Worst</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>NSGA-II</td>
<td>0.0472</td>
<td>0.1106</td>
<td>0.0805</td>
<td>0.0231</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.0272</td>
<td>0.0835</td>
<td>0.0439</td>
<td>0.0231</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>NSGA-II</td>
<td>0.6617</td>
<td>0.8238</td>
<td>0.7294</td>
<td>0.0665</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.3862</td>
<td>0.7201</td>
<td>0.5559</td>
<td>0.1493</td>
</tr>
<tr>
<td>IGD</td>
<td>NSGA-II</td>
<td>0.1890</td>
<td>0.4424</td>
<td>0.3219</td>
<td>0.0922</td>
</tr>
<tr>
<td></td>
<td>MNSGA-II</td>
<td>0.1087</td>
<td>0.3341</td>
<td>0.1754</td>
<td>0.0926</td>
</tr>
</tbody>
</table>

**5.5 CONCLUSION**

NSGA-II and MNSGA-II have been applied to solve the CEED problem with POZ constraint. Reference Pareto front is generated by using RCGA based weighted sum method. The standard IEEE 30-bus, IEEE 57-bus and IEEE 118-bus are considered as the test systems. In all the test systems, simulation results reveal that the NSGA-II and MNSGA-II can identify the solutions in a single simulation run with less computational time compared to RCGA approach. MNSGA-II performs better than NSGA-II based on the extreme solutions. Best obtained Pareto front using MNSGA-II is very close to the reference Pareto front and significant improvement in the uniform distribution of non-dominated solutions compared to NSGA-II for all the test systems. The MADM procedure is followed for choosing the best compromise solution from the obtained Pareto solutions based on TOPSIS method. The performance of NSGA-II and MNSGA-II are compared with respect to various statistical performance measures such as convergence, spread and IGD. It is observed that MNSGA-II performs better when compared to NSGA-II in most of the performance metrics values.