CHAPTER 6

MULTI-OBJECTIVE OPD PROBLEM WITH
MULTI LINE FACTS DEVICES

6.1 INTRODUCTION

The Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) are new versatile and FACTS devices for power systems operating conditions. However, the UPFC is not attractive for complex transmission systems and there is a need to connect every transmission line for providing power flow control. In addition, it is not suitable for load varying conditions. Among the FACTS controllers, the IPFC is one of the most powerful, flexible controllers for active and reactive power flows. The IPFC scheme provides compensation and power flow management in multi-line transmission systems.

Interline Power Flow Controller (IPFC) was introduced by Gyugyi et al (1999) and IPFC power flow control concept was introduced by Yanki Zhang et al (2006) and El-Saddek et al (2009). The IPFC device is a back-to-back connection of (normally two) inverters that are connected in series with different lines of power system network. The IPFC is able to provide effective power flow control in multi-line transmission systems, in addition to transfer of real power and compensate reactive power for each individual line independently. This is used to equalize both real and reactive power flow between the lines. The transfer power demand from overloaded to under loaded lines compensates against resistive voltage drops, and increase the
effectiveness of the system during load varying conditions and dynamic disturbances.

The IPFC employs the Voltage-Sourced Converter (VSC) as a basic building block. Zhang (2003), Nareshbabu et al. (2010), Venkatesh Kumar & Gomathi (2010) and Khalid Mohamed et al. (2010) have investigated the IPFC controllers and the power injection model. In this chapter, the advancement of the IPFC scheme is proposed to provide the active and reactive power flows on simultaneous compensation of transmission lines. The focus of the proposed RBFA for solution of Multi-Objective OPD problem incorporating Multi-line FACTS devices, seek the optimal parameters. The results of various IEEE standard bus systems with IPFC are presented to use in optimal power dispatch environment.

6.2 PROBLEM FORMULATION

The multi-objective OPD problem is solved by inclusion of optimal parameters of IPFC for power system secure operation. The OPD problem with sizing of IPFC is formulated as a multi-objective optimization problem. The operating state performance of a power system is the effective placement of controls with optimal solution of all the objectives considered in the OPD problem. The main objectives are minimizing the transmission line losses, enhancing the voltage profile, optimal location and enhancing the optimal power flow. The entire set of power flow equations are solved simultaneously with minimization of the total capacity of IPFC required during critical conditions of transmission lines. The Newton-Raphson load flow algorithm is introduced to include the IPFC devices into the network simulation.

6.2.1 Objectives Functions

The multi-objective OPD problem with IPFC consists of minimizing the cost of operation, power loss, voltage profile optimization,
reactive power injection and voltage deviation. The objectives are constructed and detailed in Chapter 4 and section 4.2.3 in Equation (4.2) to (4.6). In this chapter, the IPFC operation and power losses are considered for detail analysis.

**IPFC operation**

The handling of IPFC capacity and injection model of the network is important factors for enhancing the power flow control. The enhancement is based on where the location is made and optimal parameters of the IPFC, the capacity handling are given in the Equation (6.1), (6.2) and (6.3).

\[
\text{Minimize } F \times \begin{pmatrix} \text{PQ}_1^2 & \text{PQ}_2^2 \end{pmatrix} \\
\text{h}_1(x) = 0 \\
\text{g}(x) \leq 0
\] (6.1)

**Power Loss**

The foremost problem connected with the power system network is power loss. The power loss minimization is expressed in the Equation (6.4).

**Minimize the \( P_{\text{loss}} \)**

\[
P_{\text{loss}} = \left( V_i G_{ik} | V_i | V_i G_{ik} \cos \beta_{ik} + B_{ik} \sin \beta_{ik} + V_i G_{ik} \cos \beta_{ik} + B_{ik} \sin \beta_{ik} + V_i G_{ik} \cos \beta_{ik} + B_{ik} \sin \beta_{ik} \right)
\]

Where

- \( I_k \) - number of transmission lines
- \( V_i, V_k \) - voltages at the end buses \( i \) and \( k \)
- \( V_{\text{slk}} \) - series injected voltage source of \( k \)th line.
\( G_{IK}, B_{IK} \) - transfer conductance and susceptance of buses \( I \) and \( K \).

PQ - capacity of each VSC of IPFC.

\( h(x) \) - equality constraints such as bus power flow equations under the IPFC operating and control.

\( g(x) \) - inequality constraints such as thermal line constraints and voltage limitation.

\( e \) and \( f \) - The real part and imaginary part of bus voltage, \( x = e, f \).

### 6.2.2 Constraints of MO-OPD Problem

The MO-OPD problem with IPFC devices consists of equality constraints and a set of inequality constraints.

#### Equality Constraints

While solving the optimization problem, power balance equations are taken as equality constraints. The power balance equations are typical equality constraints and is formulated in the Equations (6.5) and (6.6).

\[
P_{k}^{net} - P_{k}^{col} = 0 \quad k \quad m, n \quad (6.5)
\]

\[
Q_{k}^{net} - Q_{k}^{col} = 0 \quad k \quad m, n \quad (6.6)
\]

In IPFC, active power supplied to one converter is equal to the active power demanded by the other.

#### Inequality Constraints

These constraints represent the system operating constraints as follows and the inequality constraint of OPD problems are generating operating limit, state variable limit and control variable limit. The inequality
constraints of the power system consist of the upper and lower limits of active power generation, reactive power generations, bus voltages, line loading limits and tap setting transformers.

\[
P_{g_{\min}} \quad P_{g} \quad P_{g_{\max}} \quad i \quad N_{g} \quad (6.7)
\]

\[
Q_{g_{\min}} \quad Q_{g} \quad Q_{g_{\max}} \quad i \quad N_{g}
\]

\[
T_{k_{\min}} \quad T_{k} \quad T_{k_{\max}} \quad i \quad N_{t}
\]

\[
V_{i_{\min}} \quad V_{i} \quad V_{i_{\max}} \quad i \quad N_{t}
\]

\[
S_{i} \quad S_{i_{\max}} \quad i \quad N_{i}
\]

**Operating Constraints for IPFC**

In the IPFC device, the operating constraints are Voltage injected by VSC with controllable magnitude, \(V_{\text{slk}}\) and angle, \(\theta_{\text{slk}}\) are given by the Equations (6.8) and (6.9). The injected voltage magnitude and the angle limits of control parameters of VSCs are \(0.0 < V_{\text{inj}} < 0.15\) and \(\pi/2 < \theta_{\text{inj}} < \pi/2\) respectively.

\[
V_{\text{slk}_{\min}} \quad V_{\text{slk}} \quad V_{\text{slk}_{\max}} \quad k \quad m, n \quad (6.8)
\]

\[
V_{\text{slk}_{\min}} \quad V_{\text{slk}} \quad V_{\text{slk}_{\max}} \quad k \quad m, n \quad (6.9)
\]

Line current magnitude through series VSC is given by the Equation (6.10)

\[
I_{\text{lk}_{\min}} \quad I_{\text{lk}} \quad I_{\text{lk}_{\max}} \quad k \quad m, n \quad (6.10)
\]

Series injected power through VSC is given by the Equation (6.11)

\[
|S_{\text{slk}}| \quad S_{\text{slk}_{\max}} \quad k \quad m, n \quad (6.11)
\]
Voltage Stability Constraints

Voltage Stability includes voltage stability constraints in the objective function by the Equation (6.12).

\[
\nu = \begin{cases} 
0 & \text{if } 0.9 \leq V_b \leq 1.1 \\
0.9 & \text{if } V_b < 0.9 \\
1.1 & \text{if } V_b > 1.1 
\end{cases}
\]  
(6.12)

Where, \( P_k^{\text{net}}, Q_k^{\text{net}} \) - net scheduled active and reactive power at node \( k \)
\( P_k^{\text{cal}}, Q_k^{\text{cal}} \) - calculated active and reactive powers at node \( k \)
\( Q_{gi} \) - the reactive power output of compensators
\( S_{4ik} \) - complex power injected into line by series VSC
\( N_g \) - total number of generators buses
\( P_{Gi}^{\text{min}} \) and \( P_{Gi}^{\text{max}} \) - minimum and maximum limits of real power generation
\( Q_{Gi}^{\text{min}} \) and \( Q_{Gi}^{\text{max}} \) - minimum and maximum limits of reactive power generation
\( V_{Gi}^{\text{min}} \) and \( V_{Gi}^{\text{max}} \) - minimum and maximum limits of Generator Bus Voltages
\( V_{li}^{\text{min}} \) and \( V_{li}^{\text{max}} \) - minimum and maximum limits of Load Bus Voltages
\( V_b \) - Voltage at any desired bus \( b \)
\( S_i \) - transmission line loading
\( N_i \) - number of Transformers
\( T_k \) - transformer tap settings at the \( k^{th} \) bus
\( Q_C \) - Switchable VAR compensation in MVAR
$N_c$ - number of Switchable VAR sources

$X_L$ - Line Reactance

$nb$ - the number of buses ($i=1, ... , nb$)

$P_{Di}$ and $Q_{Di}$ - the real and reactive power demand

$G_{ij}$ and $B_{ij}$ - the transfer conductance and susceptance between bus $i$ and bus $j$ respectively.

### 6.3 OPERATING PRINCIPLE OF INTERLINE POWER FLOW CONTROLLER

The IPFC comprises of Static Synchronous Series Compensators (SSSC) with a common DC link and each SSSC contains a VSC that is in series with the transmission line through a coupling transformer. The voltage injection with controllable magnitude and phase angle is fed into the transmission system with the help of VSCs. The compensation to the transmission line is based on common DC link by providing control of series reactive compensation and real power control own transmission line. Here, the IPFC concept is proposed to MO-OPD problem in complex transmission systems and its providing compensation to number of transmission lines.

![Simple Connection diagram of IPFC](image)

**Figure 6.1 Simple Connection diagram of IPFC**

The IPFC is able to transfer real power between multi lines in addition to compensation of the reactive power for each individual line.
independently. The simple schematic connection diagram of IPFC with two converter scheme is given in the Figure 6.1.

6.4 IMPLEMENTATION OF RBFA AND OTHER ALGORITHMS

The steps for the implementation of RBFA and various algorithms are the same as for the MO-OPD with FACTS devices as explained in the Chapter 4 and section 4.3. However, Initialization, the fitness function and stopping criteria differ (IPFC parameters) which are described below.

Initialization

In the Multi-Objective OPD problem, the optimization is based on control variables. The load flow data, IPFC data and IPFC and control variables are represented as initial variables. The voltages magnitudes and phase angles at buses j, k and i. i.e., \( V_{i}, V_{j}, V_{k} \) are considered. Initial values of RBFA and other algorithms are IPFC control variables \( V_{ser1}^{0}, V_{ser2}^{0}, V_{ser3}^{0} \) and power generation \( (P_{u,i}) \) of units.

Fitness function calculation

In this, the IPFC state variables are incorporated in the Jacobian matrix. In this unified solution of MO-OPD problem, the IPFC state variables are adjusted simultaneously with the control variables of network. The interaction of network variables and the IPFC controls are to accomplish the specified controls of power flow. The fitness function based on the solution of power flow with injecting the IPFC control variables is given in the Equation (6.13).

\[
\begin{bmatrix} f & x \end{bmatrix} J X \tag{6.13}
\]
Where, \([f(x)]\) is the power mismatch, described in (6.14) and \(x\) is the solution vector (6.15) and \([J]\) is the Jacobian matrix (6.16). The power mismatch is modified with the help of jacobian analysis and incorporation of IPFC mathematical modeling.

\[
\begin{bmatrix}
 f \\
x
\end{bmatrix} = \begin{bmatrix}
P_i & P_j & P_k & Q_i
\end{bmatrix}^T
\]  \hspace{1cm} (6.14)

\[
\begin{bmatrix}
P_{ref1} & P_{ref2} & P_{ref1} & P_{ref2} & P_{ref1} & P_{ref2} & P_{ref1} & P_{ref2} & Q_{ref} & Q_{ref}
\end{bmatrix}^T
\]

\[
x = \begin{bmatrix}
V_{ser2} \\
V_{ser1}
\end{bmatrix} \hspace{1cm} (6.15)
\]

\[
J = \begin{bmatrix}
P_i & P_j & P_k & P_i \\
V_{ser2} & V_{ser1} & V_{ser2} & V_{ser1} \\
P_j & P_j & P_j & P_j \\
V_{ser2} & V_{ser1} & V_{ser2} & V_{ser1} \\
P_k & P_k & P_k & P_k \\
Q_i & Q_i & Q_i & Q_i \\
V_{ser2} & V_{ser1} & V_{ser2} & V_{ser1}
\end{bmatrix}
\]  \hspace{1cm} (6.16)

After solving the Equation (6.13), it is possible to update the values of the IPFC control variables using the Equation (6.16).

**Stopping Criteria**

A set of analytical equations have been derived to provide the initial conditions of IPFC and calculating the limit violations. The algorithm converges according to the power mismatch tolerance. If the maximal absolute mismatch is less than a given tolerance. In each iteration, check on convergence that causes the required mismatch and the stopping criteria is
then enabled. It is possible for the convergence results to determine the IPFC parameters and ratings, expressed in the Equation (6.17).

\[ X^1 \quad X^0 \quad X \quad (6.17) \]

Where, \( X \) represents the control variables of the IPFC and is mentioned as \( V_{sir1}, V_{sir2}, V_{sir2} \) and \( V_{sir2} \).

6.5 RESULTS AND DISCUSSIONS

In the present research, focus is on the performance of multiline FACTS (IPFC) devices incorporated with MO-OPD problem and its solution by proposed RBFA algorithm and other algorithms. The various IEEE standard systems such as IEEE 30 bus system, IEEE 57 bus system, New England IEEE 39 bus system, IEEE 9 bus system and IEEE 6 bus system are used. The proposed method is compared with the other (ACO, BFA and MBFA) algorithms. The improvement of voltage profile and the reduction of loss are obtained by optimal parameters (VSCs of IPFC used) IPFC and optimal solution of OPD problem. This study gives details about the IEEE 30 bus system with IPFC performance in power systems with load varying conditions.

6.5.1 IEEE 30 Bus system

The bus data of this system are presented in the Appendix A 1.1. The results of the case studies are compared without IPFC, with IPFC in two sectors and with IPFC in four sectors. The VSCs of the IPFC control of active power flow and reactive power flow of lines are 1-2, 1-3, 27-30 and 29-30. The power flow equation results are also important while considering the long term studies and it is necessary to monitor the active and reactive power dispatch with increase of active and reactive power load. In order to investigate the optimal dispatch power system, the multiline FACTS devices
are installed in IEEE 30 bus system for two different cases (Case A and Case B).

**Case A- IEEE 30 bus system** IPFC is installed for controlling the active power flow in 1-2 and active and reactive power flow in 1-3 lines. In this case, Power flow analysis for IEEE 30 bus power system with Multiline FACTS devices and the optimal parameters of IPFC and simulation is performed on IEEE 30 bus system under different operating conditions.

The voltage profile, generation cost, total system and line losses are reported in the Table 6.1. Based on critical identification and power flow analysis, IPFC model is connected between the lines 1-2 and 1-3 of IEEE 30 bus system. The results of the injected voltage magnitudes $V_{in}$ (p.u) and the angles $\theta_{in}$ (rad) of VSCs of the IPFC and transmission line losses of RBFA and other algorithms are reported in the Table 6.2.

Using RBFA algorithms, it is observed that the simulation result shows the line losses are reduced with the optimal parameters of IPFC. The effectiveness of the RBFA is the tuning of IPFC parameters and MO-OPD problem, the results show enhancement in voltage profile, the line losses 1-2, and 1-3 are 0.019 MW, 0.012 MW respectively, loss reduction is 8.639MW, and it is much better than the other algorithms. The individual bus performance measure and voltage profile of case A is given in the Figure 6.2.

Using other algorithms, the minimum line loss is 0.069MW in the line 1-2 using MBFA algorithm, the comparison of the results of line losses show that the MBFA is better than to ACO and BFA algorithms.

In Case A, the IPFC installed is in two sectors. Therefore, with the identification of optimal parameters and tuning of optimal parameters of IPFC gives enhancement voltage profile, reduction in line losses and power transfer
capability is improved. It is obtained that line losses are reduced in the RBFA and it is compared with the other algorithms loss reduction. The ever increasing load demand is in need different controls for secure operation of power system. For the power system, it is necessary to consider both active and reactive loading. Therefore, the following case B deals, IPFC devices against various operating conditions of power system.

### Table 6.1 The Case A- Results of IEEE 30 Bus system using RBFA method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimized Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus number</td>
<td>Voltage magnitude(p.u)</td>
</tr>
<tr>
<td>1</td>
<td>1.0400</td>
</tr>
<tr>
<td>2</td>
<td>1.0430</td>
</tr>
<tr>
<td>5</td>
<td>1.0100</td>
</tr>
<tr>
<td>8</td>
<td>1.0100</td>
</tr>
<tr>
<td>11</td>
<td>1.0820</td>
</tr>
<tr>
<td>13</td>
<td>1.0710</td>
</tr>
<tr>
<td>From bus to bus</td>
<td>Line losses in MW</td>
</tr>
<tr>
<td>1-2</td>
<td>0.019</td>
</tr>
<tr>
<td>1-3</td>
<td>0.012</td>
</tr>
<tr>
<td>Total line losses in MW</td>
<td>8.639</td>
</tr>
</tbody>
</table>

Optimal parameters of IPFC and losses results with RBFA method

<table>
<thead>
<tr>
<th>Line</th>
<th>1-2</th>
<th>1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{inj}) (p.u)</td>
<td>0.058</td>
<td>0.044</td>
</tr>
<tr>
<td>(\theta_{inj}) (rad)</td>
<td>1.028</td>
<td>0.942</td>
</tr>
<tr>
<td>Line loss (MW)</td>
<td>0.019</td>
<td>0.012</td>
</tr>
<tr>
<td>Total line losses (MW)</td>
<td>8.639</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bus number</th>
<th>Generation cost($/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus number</td>
<td>MBFA</td>
</tr>
<tr>
<td>Total generation cost ($/hr)</td>
<td>801.8246</td>
</tr>
</tbody>
</table>
Table 6.2 The Case-A Comparison of IPFC Parameters Results in IEEE 30 Bus system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Optimization techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBFA</td>
</tr>
<tr>
<td>Line</td>
<td>1-2</td>
</tr>
<tr>
<td>( V_{\text{ref}} ) (p.u)</td>
<td>0.064</td>
</tr>
<tr>
<td>( \theta_{\text{ref}} ) (rad)</td>
<td>1.400</td>
</tr>
<tr>
<td>Line losses (MW)</td>
<td>0.069</td>
</tr>
</tbody>
</table>

Figure 6.2 Voltage profile of IEEE 30 Bus system in case A using RBFA

Case B- IEEE 30 bus system IPFC is installed to control the active power flow in bus 1 to 2, the reactive power flow in bus 27 to 30 lines and the active and reactive power flow model in 29 to 30.
In Case B, Power flow analysis is carried out for IEEE 30 bus system with IPFC installation in different locations. The ACO, BFA and MBFA and the proposed RBFA techniques are considered to apply for minimizing the transmission losses and improving the voltage stability of IEEE 30-bus power system and find out the optimal parameters of IPFC.

In this case, the IPFC devices are installed in the section 1-2, bus 1-3, 27-30 and 29-30 lines. The voltage profile optimization of IEEE 30 bus system with installation of IPFC is reported in the Table 6.3. The voltage profile results of the RBFA algorithm and other algorithms are given in the same Table. The Table 6.4 shows the IPFC location, active power line losses under specified constraints and voltage magnitudes and angles of VSCs of IPFC. The results of line losses in IPFC installed sectors are also detailed in the same Table.

The details of control parameters and optimal parameters of IPFC are reported in the Table 6.5. The convergence characteristics of generation cost, losses and comparison of optimal values of RBFA and other algorithms are reported in the Table 6.6.

Using RBFA algorithms in Case-B, the maximum line reduction in IEEE 30 bus system is 2.948 MW and a generation cost of $801.8442$/hr has been obtained for RBFA algorithms. Using four IPFC at transmission lines with optimal placement and the results, line loss reduction, 24 seconds of computation time and results converge at minimum number of iterations 25, which is presented in the Table 6.4. The voltage at critical buses is enhanced during load varying conditions. The Figure 6.3 shows the convergence characteristics of IEEE 30 bus system with IPFC for RBFA algorithm.

Using the other algorithms in Case-B, the critical buses are bus 26 and bus 30. The voltage profile is within the limits during load varying
conditions but voltage profile improvement in other algorithms is not much as compared to RBFA algorithm.

Table 6.3 Voltage Profile of IEEE 30 Bus system - Case B

<table>
<thead>
<tr>
<th>Method</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>Case A RBFA</th>
<th>Case B RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1.084</td>
<td>1.084</td>
<td>1.083</td>
<td>1.0200</td>
<td>1.0400</td>
</tr>
<tr>
<td>V2</td>
<td>1.064</td>
<td>1.063</td>
<td>1.062</td>
<td>1.0130</td>
<td>1.0430</td>
</tr>
<tr>
<td>V3</td>
<td>1.050</td>
<td>1.050</td>
<td>1.049</td>
<td>1.0100</td>
<td>1.0200</td>
</tr>
<tr>
<td>V4</td>
<td>1.043</td>
<td>1.042</td>
<td>1.042</td>
<td>1.0008</td>
<td>1.0108</td>
</tr>
<tr>
<td>V5</td>
<td>1.032</td>
<td>1.030</td>
<td>1.030</td>
<td>1.0000</td>
<td>1.0100</td>
</tr>
<tr>
<td>V6</td>
<td>1.037</td>
<td>1.036</td>
<td>1.035</td>
<td>1.0001</td>
<td>1.0101</td>
</tr>
<tr>
<td>V7</td>
<td>1.027</td>
<td>1.025</td>
<td>1.025</td>
<td>1.0023</td>
<td>1.0023</td>
</tr>
<tr>
<td>V8</td>
<td>1.038</td>
<td>1.033</td>
<td>1.033</td>
<td>1.0100</td>
<td>1.0100</td>
</tr>
<tr>
<td>V9</td>
<td>1.028</td>
<td>1.019</td>
<td>1.022</td>
<td>1.0402</td>
<td>1.0402</td>
</tr>
<tr>
<td>V10</td>
<td>1.014</td>
<td>1.010</td>
<td>1.013</td>
<td>1.0231</td>
<td>1.0231</td>
</tr>
<tr>
<td>V11</td>
<td>1.055</td>
<td>1.056</td>
<td>1.056</td>
<td>1.0820</td>
<td>1.0500</td>
</tr>
<tr>
<td>V12</td>
<td>1.019</td>
<td>1.018</td>
<td>1.019</td>
<td>1.0503</td>
<td>1.0503</td>
</tr>
<tr>
<td>V13</td>
<td>1.032</td>
<td>1.035</td>
<td>1.035</td>
<td>1.0710</td>
<td>1.0430</td>
</tr>
<tr>
<td>V14</td>
<td>1.010</td>
<td>1.008</td>
<td>1.010</td>
<td>1.0330</td>
<td>1.0330</td>
</tr>
<tr>
<td>V15</td>
<td>1.011</td>
<td>1.009</td>
<td>1.011</td>
<td>1.0263</td>
<td>1.0263</td>
</tr>
<tr>
<td>V16</td>
<td>1.011</td>
<td>1.009</td>
<td>1.011</td>
<td>1.0315</td>
<td>1.0315</td>
</tr>
<tr>
<td>V17</td>
<td>1.011</td>
<td>1.007</td>
<td>1.010</td>
<td>1.0202</td>
<td>1.0202</td>
</tr>
<tr>
<td>V18</td>
<td>1.003</td>
<td>1.001</td>
<td>1.004</td>
<td>1.0128</td>
<td>1.0218</td>
</tr>
<tr>
<td>V19</td>
<td>1.002</td>
<td>1.000</td>
<td>1.003</td>
<td>1.0080</td>
<td>1.0080</td>
</tr>
<tr>
<td>V20</td>
<td>1.007</td>
<td>1.005</td>
<td>1.008</td>
<td>1.0110</td>
<td>1.0110</td>
</tr>
<tr>
<td>V21</td>
<td>1.006</td>
<td>1.002</td>
<td>1.005</td>
<td>1.0102</td>
<td>1.0102</td>
</tr>
<tr>
<td>V22</td>
<td>1.007</td>
<td>1.002</td>
<td>1.006</td>
<td>1.0147</td>
<td>1.0147</td>
</tr>
<tr>
<td>V23</td>
<td>1.010</td>
<td>1.006</td>
<td>1.009</td>
<td>1.0106</td>
<td>1.0106</td>
</tr>
<tr>
<td>V24</td>
<td>1.002</td>
<td>0.997</td>
<td>1.001</td>
<td>1.0033</td>
<td>1.0033</td>
</tr>
<tr>
<td>V25</td>
<td>1.006</td>
<td>0.996</td>
<td>1.002</td>
<td>1.0125</td>
<td>1.0175</td>
</tr>
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<td>V26</td>
<td>0.978</td>
<td>0.988</td>
<td>1.004</td>
<td>1.0018</td>
<td>1.0019</td>
</tr>
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<td>V27</td>
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<td>1.012</td>
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<td>1.0240</td>
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<td>1.032</td>
<td>1.031</td>
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<td>1.0091</td>
</tr>
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<td>1.002</td>
<td>1.009</td>
<td>1.0076</td>
<td>1.0076</td>
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<td>0.997</td>
<td>0.996</td>
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**Table 6.4 Comparison of the Results of IEEE 30 Bus system- Case B**

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<thead>
<tr>
<th>Parameters</th>
<th>RBFA Results</th>
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<tbody>
<tr>
<td>Location Line</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td>27-30</td>
</tr>
<tr>
<td></td>
<td>29-30</td>
</tr>
<tr>
<td>(V_{th} ) (pu)</td>
<td>0.0439</td>
</tr>
<tr>
<td></td>
<td>0.0842</td>
</tr>
<tr>
<td></td>
<td>0.0924</td>
</tr>
<tr>
<td></td>
<td>0.0863</td>
</tr>
<tr>
<td>(\theta_{th} ) (rad)</td>
<td>1.0877</td>
</tr>
<tr>
<td></td>
<td>0.9819</td>
</tr>
<tr>
<td></td>
<td>0.9750</td>
</tr>
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<td></td>
<td>0.859</td>
</tr>
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<td>Line losses (MW)</td>
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<tr>
<td></td>
<td>0.006</td>
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<td></td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>0.006</td>
</tr>
<tr>
<td>Total losses (MW)</td>
<td><strong>2.948</strong></td>
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<table>
<thead>
<tr>
<th>Parameters</th>
<th>IPFC</th>
<th>IPFC with indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location Lines</td>
<td>1-2 and 1-3</td>
<td>1-2, 1-3, 27-30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27-30 and 29-30</td>
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<tr>
<td>Total generation (MW)</td>
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<td>292.6242</td>
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<tr>
<td></td>
<td></td>
<td>292.5142</td>
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<tr>
<td>Total generation cost ($/hr)</td>
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<td><strong>801.8442</strong></td>
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<td></td>
<td><strong>801.8442</strong></td>
</tr>
<tr>
<td>Total line losses (MW)</td>
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<td><strong>2.948</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>2.948</strong></td>
</tr>
<tr>
<td>Simulation time (sec)</td>
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<td>24</td>
</tr>
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<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>No. of Iterations</td>
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<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28</td>
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</table>

**Table 6.5 IPFC Control Parameter and Optimal Parameter using RBFA-CASE B**

<table>
<thead>
<tr>
<th>Bus number</th>
<th>Control parameter</th>
<th>Optimal parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
<td>Vsh (pu)</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.0460</td>
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<tr>
<td>1</td>
<td>3</td>
<td>0.0460</td>
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<tr>
<td>27</td>
<td>30</td>
<td>0.0460</td>
</tr>
<tr>
<td>29</td>
<td>30</td>
<td>0.0460</td>
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</table>
Table G6: Results of Convergence of IEEE 30 Bus system in Case B

<table>
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<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>Case A RBFA</th>
<th>Case B RBFA</th>
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</thead>
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<tr>
<td>1</td>
<td>P_1</td>
<td>170.84</td>
<td>170.67</td>
<td>170.16</td>
<td>170.98</td>
<td>170.15</td>
</tr>
<tr>
<td>2</td>
<td>P_2</td>
<td>48.11</td>
<td>49.335</td>
<td>48.345</td>
<td>48.745</td>
<td>48.836</td>
</tr>
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<td>5</td>
<td>P_11</td>
<td>11.402</td>
<td>12.422</td>
<td>11.423</td>
<td>12.14</td>
<td>12.158</td>
</tr>
<tr>
<td>6</td>
<td>P_13</td>
<td>12</td>
<td>12</td>
<td>12.071</td>
<td>12</td>
<td>12</td>
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<tr>
<td>7</td>
<td>V_1</td>
<td>1.024</td>
<td>1.043</td>
<td>1.030</td>
<td>1.0200</td>
<td>1.0400</td>
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<tr>
<td>8</td>
<td>V_2</td>
<td>1.006</td>
<td>1.032</td>
<td>1.043</td>
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<td>1.0430</td>
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<td>9</td>
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<td>1.010</td>
<td>1.0000</td>
<td>1.0100</td>
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<td>10</td>
<td>V_8</td>
<td>0.980</td>
<td>0.987</td>
<td>1.010</td>
<td>1.0100</td>
<td>1.0100</td>
</tr>
<tr>
<td>11</td>
<td>V_11</td>
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<td>1.019</td>
<td>1.082</td>
<td>1.0820</td>
<td>1.0300</td>
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<tr>
<td>12</td>
<td>V_13</td>
<td>1.023</td>
<td>1.070</td>
<td>1.071</td>
<td>1.0710</td>
<td>1.0430</td>
</tr>
<tr>
<td>13</td>
<td>T_6.9</td>
<td>0.9881</td>
<td>1.0155</td>
<td>1.0290</td>
<td>1.0223</td>
<td>1.0165</td>
</tr>
<tr>
<td>14</td>
<td>T_6.10</td>
<td>0.9594</td>
<td>0.9940</td>
<td>1.0337</td>
<td>1.0199</td>
<td>1.0261</td>
</tr>
<tr>
<td>15</td>
<td>T_4.12</td>
<td>0.9802</td>
<td>1.0320</td>
<td>1.0298</td>
<td>1.0286</td>
<td>1.0277</td>
</tr>
<tr>
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<td>T_28.27</td>
<td>0.9865</td>
<td>0.9930</td>
<td>1.0274</td>
<td>1.0176</td>
<td>1.0152</td>
</tr>
<tr>
<td>17</td>
<td>Q_C10</td>
<td>0.692</td>
<td>3.05</td>
<td>1.725</td>
<td>1.453</td>
<td>1.453</td>
</tr>
<tr>
<td>18</td>
<td>Q_C12</td>
<td>0.046</td>
<td>2.89</td>
<td>3.429</td>
<td>3.769</td>
<td>3.769</td>
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<tr>
<td>19</td>
<td>Q_C15</td>
<td>0.285</td>
<td>2.79</td>
<td>2.980</td>
<td>1.027</td>
<td>1.027</td>
</tr>
<tr>
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<td>4.73</td>
<td>2.855</td>
<td>2.060</td>
<td>2.060</td>
</tr>
<tr>
<td>21</td>
<td>Q_C20</td>
<td>0.208</td>
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<td>2.038</td>
<td>2.756</td>
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<tr>
<td>22</td>
<td>Q_C21</td>
<td>0.000</td>
<td>7.47</td>
<td>2.366</td>
<td>2.332</td>
<td>2.332</td>
</tr>
<tr>
<td>23</td>
<td>Q_C23</td>
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<td>3.09</td>
<td>3.435</td>
<td>1.089</td>
<td>1.089</td>
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<tr>
<td>24</td>
<td>Q_C24</td>
<td>0.938</td>
<td>3.05</td>
<td>3.057</td>
<td>0.355</td>
<td>0.355</td>
</tr>
<tr>
<td>25</td>
<td>Q_C29</td>
<td>0.269</td>
<td>0.290</td>
<td>2.484</td>
<td>4.028</td>
<td>4.028</td>
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<tr>
<td></td>
<td>Total loss (MW)</td>
<td>8.424</td>
<td>8.278</td>
<td>8.639</td>
<td>3.382</td>
<td>2.948</td>
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<tr>
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<td>Total cost ($/h)</td>
<td>801.8246</td>
<td>801.8582</td>
<td>801.8436</td>
<td>801.8024</td>
<td>801.8441</td>
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<tr>
<td></td>
<td>Total Generation(MW)</td>
<td>283.743</td>
<td>284.743</td>
<td>283.735</td>
<td>286.784</td>
<td>286.372</td>
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</table>
The Figures 6.4 and 6.5 shows the convergence characteristics of Voltage profile optimization of IEEE 30 system in case B with IPFC in MBFA and RBFA methods. The difference of voltage magnitude results show that the RBFA scheme coordination during loading condition is better. The line losses reduction and comparison using RBFA algorithm are given in the Figures 6.6 and 6.7. The comparison of line losses of RBFA algorithm are given in the Figure 6.8. The IPFC capacity against loading varying conditions is illustrated in Figure 6.9.

![Convergence Characteristics](image)

**Figure 6.3** Convergence Characteristics of IEEE 30 Bus system - Case B using RBFA
Figure 6.4 Voltage profile of IEEE 30 Bus system in Case-B with IPFC using MBFA

Figure 6.5 Voltage profile of IEEE 30 Bus in Case-B with IPFC using RBFA
Figure 6.6 Line losses of IEEE 30 Bus system in Case B without IPFC

Figure 6.7 Line losses of IEEE 30 Bus system in Case B with IPFC
Figure 6.8 Comparison of line losses without IPFC and with IPFC

Figure 6.9 IPFC Capacity Vs Percentage of load
From the simulation results, it is observed that, there is significant improvement in voltage profile, reduction in line losses and computation time with the help of IPFC scheme. The installation of IPFC enhances the performance of the power system than the other algorithms and the results of other FACTS devices. The IPFC coordination along with RBFA algorithm is much better during load varying conditions and optimal parameters of IPFC are obtained with the above mentioned criteria.

6.5.2 IEEE 57 Bus System

The IEEE 57 bus system with 80 transmission lines is simulated with RBFA algorithm and other algorithms for MO-OPD problem. The details of the data used for simulation are given in the Appendix A 1.2.

The MO-OPD problem with Multi-line FACTS devices, the voltage profile optimization and power losses are given in the Table 6.7. Most critical buses identified are bus 2 and 9 and lines are 2-3 and 54-55.

Using RBFA algorithm, the results show that loss reduction is 11.2601MW, which is much less than the other algorithms. The convergence obtained in voltage profile optimization shows considerable improvement.

Using other algorithms, the transmission losses is 11.98 MW in MBFA. It is compared with BFA and ACO algorithms. For larger system, the step length variation gives better performance and convergence rate is very high. The RBFA and MBFA algorithms varied according to the system dimensions. From the results of IEEE 57 bus system with IPFC, the multi-line FACTS devices are suitable for larger networks. Even with the load varying conditions, the IPFC is well suitable with RBFA technique. The results shows improvement in voltage profile and stability of power.
Table G.7 Results of Voltage Profile of the IEEE 57 Bus System

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Voltage Magnitude</th>
<th>Angle</th>
<th>Bus No.</th>
<th>Voltage Magnitude</th>
<th>Angle</th>
</tr>
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<tbody>
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<td>30</td>
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</tr>
<tr>
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<td>-0.8309</td>
<td>31</td>
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<td>-18.0679</td>
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<td>1.0509</td>
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<tr>
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<td>1.0582</td>
<td>-13.0346</td>
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</tr>
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<td>-12.0732</td>
</tr>
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<tr>
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<td>-17.7240</td>
<td>54</td>
<td>1.0965</td>
<td>-11.2633</td>
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<td>55</td>
<td>1.0308</td>
<td>-10.3529</td>
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</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission loss (MW)</td>
<td>13.2</td>
<td>12.29</td>
<td>11.98</td>
<td>11.2601</td>
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</table>
6.5.3 New England IEEE 39 Bus System

The New England IEEE 39 bus system is simulated for MO-OPD problem with IPFC devices using RBFA and other algorithms. The details of the data used for simulation are given in the Appendix A 1.3. The voltage profile for RBFA algorithm and transmission losses are reported in the Table 6.8.

Using RBFA algorithm, the weakest bus in New England IEEE 39 bus system is bus number 15 and 8, the critical lines are bus 8 to 9 and bus 26 to 27. The optimal placement of IPFC devices is carried out via RBFA algorithm, the result shows the improvement in voltage profile and the real and reactive power control action is enhanced corresponding buses. The IPFC placement in the critical identification line is 26-27 and transmission line power loss is 41.10 MW.

Using other algorithms, the transmission line power loss with UPFC device using MBFA algorithm is 41.15 MW. The value of transmission loss in MBFA algorithm is less than the other algorithms like ACO and BFA.

The voltage profile results of the ACO and BFA are almost similar to the MBFA technique. Hence, the proposed technique RBFA is compared with MBFA technique. The result shows that the IPFC devices are installed according to the critical operations. The power transfer capability is increased with the help of optimal placing of multi- the IPFC devices for multi-line compensation. Therefore, for the New England 39 bus system, there is no deviation in the voltage profile, even under load varying conditions, by using RBFA algorithm.
### Table 6.8 Results of Voltage Profile of the IEEE 39 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>MBFA</th>
<th>RBFA</th>
<th>Bus No</th>
<th>MBFA</th>
<th>RBFA</th>
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<td>1.0474</td>
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<td>1.0338</td>
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<td>1.0487</td>
<td>22</td>
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<tr>
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<td>1.0302</td>
<td>23</td>
<td>1.0465</td>
<td>1.0448</td>
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<td>25</td>
<td>1.0569</td>
<td>1.0576</td>
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<td>1.0013</td>
<td>1.0077</td>
<td>26</td>
<td>1.0532</td>
<td>1.0521</td>
</tr>
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<td>7</td>
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<td>1.0070</td>
<td>27</td>
<td>1.0396</td>
<td>1.0377</td>
</tr>
<tr>
<td>8</td>
<td>0.9904</td>
<td>1.0160</td>
<td>28</td>
<td>1.0509</td>
<td>1.0501</td>
</tr>
<tr>
<td>9</td>
<td>1.0254</td>
<td>1.0282</td>
<td>29</td>
<td>1.0506</td>
<td>1.0499</td>
</tr>
<tr>
<td>10</td>
<td>1.0134</td>
<td>1.0172</td>
<td>30</td>
<td>1.0475</td>
<td>1.0475</td>
</tr>
<tr>
<td>11</td>
<td>1.0082</td>
<td>1.0127</td>
<td>31</td>
<td>0.9820</td>
<td>1.0000</td>
</tr>
<tr>
<td>12</td>
<td>0.9961</td>
<td>1.0002</td>
<td>32</td>
<td>0.9831</td>
<td>1.0011</td>
</tr>
<tr>
<td>13</td>
<td>1.0106</td>
<td>1.0143</td>
<td>33</td>
<td>0.9972</td>
<td>1.0005</td>
</tr>
<tr>
<td>14</td>
<td>1.0087</td>
<td>1.0117</td>
<td>34</td>
<td>1.0123</td>
<td>1.0123</td>
</tr>
<tr>
<td>15</td>
<td>1.0157</td>
<td>1.0154</td>
<td>35</td>
<td>1.0493</td>
<td>1.0493</td>
</tr>
<tr>
<td>16</td>
<td>1.0340</td>
<td>1.0318</td>
<td>36</td>
<td>1.0635</td>
<td>1.0635</td>
</tr>
<tr>
<td>17</td>
<td>1.0355</td>
<td>1.0336</td>
<td>37</td>
<td>1.0276</td>
<td>1.0278</td>
</tr>
<tr>
<td>18</td>
<td>1.0327</td>
<td>1.0309</td>
<td>38</td>
<td>1.0263</td>
<td>1.0265</td>
</tr>
<tr>
<td>19</td>
<td>1.0510</td>
<td>1.0499</td>
<td>39</td>
<td>1.0290</td>
<td>1.0300</td>
</tr>
<tr>
<td>20</td>
<td>0.9922</td>
<td>1.0010</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission losses (MW)</td>
<td>AC0</td>
<td>BFA</td>
<td>MBFA</td>
<td>RBFA</td>
<td></td>
</tr>
<tr>
<td>42.51</td>
<td>43.72</td>
<td>41.15</td>
<td>41.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6.5.4 IEEE 6 Bus System

The IEEE 6 bus system is simulated with RBFA algorithm and other algorithms for MO-OPD problem with the optimal placement of IPFC devices. The details of the data used for simulation are given in the
Appendix A 1.4. The voltage magnitude, voltage angle and total losses are reported in the Table 6.9.

Using RBFA algorithm, the weak bus in IEEE 6 bus system is bus number 5 and the critical line is bus 2 to 5. The real and reactive power control action is enhanced corresponding lines. The optimal placement of IPFC devices is carried out via RBFA algorithm and the result shows the improvement in voltage profile. The transmission losses in RBFA algorithm is 6.32 MW, the voltage magnitude at bus 5 is 1.005 p.u during critical operations.

Using other algorithms, no violation in the constraints and security constraints are within the control level, voltage magnitudes (0.9<V<1.1 p.u) and line flows enhancement by IPFC devices. It is revealed that, the MBFA algorithms transmission loss is 6.820 MW and it is compared to ACO and MBFA algorithms. The Table 6.11 shows that the proposed approach has a considerably faster convergence compared to the other algorithms and the loss reduction level is very high.

Table 6.9 Results of IEEE 6Bus system with IPFC Devices

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Voltage magnitude</th>
<th>Voltage Angle</th>
<th>Bus No.</th>
<th>Voltage magnitude</th>
<th>Voltage Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.040</td>
<td>0.000</td>
<td>4</td>
<td>1.035</td>
<td>-0.209</td>
</tr>
<tr>
<td>2</td>
<td>1.049</td>
<td>2.005</td>
<td>5</td>
<td>1.005</td>
<td>-2.070</td>
</tr>
<tr>
<td>3</td>
<td>1.012</td>
<td>-2.694</td>
<td>6</td>
<td>1.001</td>
<td>-3.580</td>
</tr>
</tbody>
</table>

Comparison of System losses

<table>
<thead>
<tr>
<th>Method</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>System losses(MW)</td>
<td>9.101</td>
<td>8.83</td>
<td>6.820</td>
<td>6.32</td>
</tr>
</tbody>
</table>
6.5.5 IEEE 9Bus System

The IEEE 9 bus system is simulated with RBFA algorithm and other algorithms for MO-OPD problem with the optimal placement of IPFC devices. The details of the data used for simulation are given in the Appendix A 1.5.

The convergence results, voltage magnitude, voltage angle, line losses and total losses are detailed in the Table 6.10. The comparison of voltage magnitude and total losses are reported in the Table 6.11.

Using RBFA algorithm, the weak bus in IEEE 9 bus system is bus number 3 and the critical line is bus 5 to 6 and the optimal placement IPFC devices in critical line. The real and reactive power variation is detailed in the Table 6.10. The transmission loss is 2.729 MW and the voltage profile at bus 5 is improved (1.0840 p.u).

Using other algorithms, it is found that there is improvement in voltage profile in the other algorithms than without the IPFC case. The MBFA algorithm transmission loss is 3.816 compared to ACO and BFA algorithms. The voltage profile is 1.0212 p.u. compared to MBFA and BFA algorithms.

From the results, the RBFA scheme shows much reduction in the level of losses even under load varying conditions. The power transfer and compensation is improved by tuning the optimal parameters of IPFC devices. The losses are greatly reduced to 2.729 MW in IEEE 9 bus system. The control of real and reactive power flow is enhanced by multi-line FACTS devices based on the measure of critical conditions. It is observed that the voltage profile optimization is much in RBFA technique along with the IPFC devices.
### Table 6.10 Results of Convergence of IEEE 9Bus system using RBFA

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Voltage (pu)</th>
<th>Ang (deg)</th>
<th>Generation (MW)</th>
<th>Load (MW)</th>
<th>Loss (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mag</td>
<td>Ang</td>
<td>P (MW)</td>
<td>Q (Mvar)</td>
<td>P (MW)</td>
</tr>
<tr>
<td>1</td>
<td>1.0400</td>
<td>0</td>
<td>89.80</td>
<td>12.97</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.0970</td>
<td>4.817</td>
<td>134.32</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1.0870</td>
<td>3.243</td>
<td>94.19</td>
<td>-22.63</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>1.0947</td>
<td>-2.465</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>1.0840</td>
<td>-3.982</td>
<td>-</td>
<td>-</td>
<td>90.00</td>
</tr>
<tr>
<td>6</td>
<td>1.0129</td>
<td>0.603</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>1.0895</td>
<td>-1.196</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>1.0108</td>
<td>0.965</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>1.0725</td>
<td>-4.345</td>
<td>-</td>
<td>-</td>
<td>125.00</td>
</tr>
<tr>
<td>Total</td>
<td>318.31</td>
<td>-9.64</td>
<td>315.00</td>
<td>43.00</td>
<td>2729</td>
</tr>
</tbody>
</table>

### Table 6.11 Results of Comparison of IEEE 9Bus system with IPFC

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Without IPFC</th>
<th>With IPFC</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0400</td>
<td>0</td>
<td>1.0250</td>
<td>0.0762</td>
<td>1.0400</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>1.0250</td>
<td>9.280</td>
<td>1.0250</td>
<td>0.0267</td>
<td>1.0162</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>1.0258</td>
<td>4.6655</td>
<td>1.0023</td>
<td>0.0942</td>
<td>1.0134</td>
<td>0.0007</td>
</tr>
<tr>
<td>4</td>
<td>1.0225</td>
<td>2.217</td>
<td>0.9741</td>
<td>0.1957</td>
<td>0.9925</td>
<td>0.0927</td>
</tr>
<tr>
<td>5</td>
<td>0.9623</td>
<td>-3.982</td>
<td>1.0212</td>
<td>-0.0735</td>
<td>0.9523</td>
<td>-0.1978</td>
</tr>
<tr>
<td>6</td>
<td>1.0127</td>
<td>3.687</td>
<td>1.0155</td>
<td>0.0861</td>
<td>0.9645</td>
<td>0.0485</td>
</tr>
<tr>
<td>7</td>
<td>1.0258</td>
<td>3.720</td>
<td>1.0204</td>
<td>-0.0238</td>
<td>1.0040</td>
<td>-0.0652</td>
</tr>
<tr>
<td>8</td>
<td>1.0143</td>
<td>0.728</td>
<td>0.9927</td>
<td>0.1391</td>
<td>0.8656</td>
<td>0.0071</td>
</tr>
<tr>
<td>9</td>
<td>1.0257</td>
<td>1.967</td>
<td>0.9927</td>
<td>0.1391</td>
<td>1.0057</td>
<td>0.1319</td>
</tr>
</tbody>
</table>

| Trans. Losses (MW) | 4.641 | 4.640 | 3.816 | 2.729 |


6.5.6 Summary of IPFC Devices

The MO-OPD problem with IPFC device results, show that the IPFC device is powerful in complex power system. The OPD solution with the injection models of IPFC are easily incorporated into load flow program, the voltage profile at the network, bus voltage to which IPFC device is connected. There is a significant improvement in the system with the optimal placement of IPFC. The power flow control is enhanced through multi-line compensation method. The RBFA with IPFC results show superior features in Quality of solution, Voltage stability analysis and results comparable with other social behavior algorithms.

6.6 OVERALL COMPARISON OF RESULTS

The overall performance of the proposed method against Multi-objective Optimal Dispatch problem with optimal placement of various FACTS (single line and multi-line) devices is analyzed. The results of various FACTS devices are compared with the solution of MO-OPD problem with DG system.

The voltage profile for IEEE 30 bus system with the various FACTS devices are tabulated in the Table 6.12. The comparison is based on FACTS devices, UPFC devices, DG system, the Case -A IPFC placement and Case -B IPFC placement and the solution using proposed RBFA techniques.

The overall convergence results are listed in the Table 6.13. The convergences are objectives of MO-OPD problem, such as reduction in losses, generation cost, enhancing system stability via voltage profile optimization, minimize the voltage deviation. In addition, the convergence characteristics of computation time and the number of iteration are also considered.
### Table 6.12  Overall Comparisons of Voltage Profile Results for IEEE 30 Bus system

<table>
<thead>
<tr>
<th>Method / bus volatge</th>
<th>FACTS</th>
<th>UPFC</th>
<th>Case A IPFC</th>
<th>Case B IPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1.0500</td>
<td>1.0600</td>
<td>1.0200</td>
<td>1.0400</td>
</tr>
<tr>
<td>V2</td>
<td>1.0430</td>
<td>1.0430</td>
<td>1.0130</td>
<td>1.0430</td>
</tr>
<tr>
<td>V3</td>
<td>1.0199</td>
<td>1.02158</td>
<td>1.0100</td>
<td>1.0200</td>
</tr>
<tr>
<td>V4</td>
<td>1.0107</td>
<td>1.01295</td>
<td>1.0008</td>
<td>1.0108</td>
</tr>
<tr>
<td>V5</td>
<td>1.0100</td>
<td>1.0100</td>
<td>1.0000</td>
<td>1.0100</td>
</tr>
<tr>
<td>V6</td>
<td>1.0099</td>
<td>1.0121</td>
<td>1.0001</td>
<td>1.0101</td>
</tr>
<tr>
<td>V7</td>
<td>1.0022</td>
<td>1.0035</td>
<td>1.0023</td>
<td>1.0023</td>
</tr>
<tr>
<td>V8</td>
<td>1.0100</td>
<td>1.0100</td>
<td>1.0100</td>
<td>1.0100</td>
</tr>
<tr>
<td>V9</td>
<td>1.0399</td>
<td>1.0515</td>
<td>1.0402</td>
<td>1.0402</td>
</tr>
<tr>
<td>V10</td>
<td>1.0225</td>
<td>1.0453</td>
<td>1.0231</td>
<td>1.0231</td>
</tr>
<tr>
<td>V11</td>
<td>1.0820</td>
<td>1.0820</td>
<td>1.0500</td>
<td>1.0500</td>
</tr>
<tr>
<td>V12</td>
<td>1.0500</td>
<td>1.0576</td>
<td>1.0503</td>
<td>1.0503</td>
</tr>
<tr>
<td>V13</td>
<td>1.0710</td>
<td>1.0710</td>
<td>1.0710</td>
<td>1.0430</td>
</tr>
<tr>
<td>V14</td>
<td>1.0326</td>
<td>1.0428</td>
<td>1.0330</td>
<td>1.0330</td>
</tr>
<tr>
<td>V15</td>
<td>1.0259</td>
<td>1.0382</td>
<td>1.0263</td>
<td>1.0263</td>
</tr>
<tr>
<td>V16</td>
<td>1.0311</td>
<td>1.0452</td>
<td>1.0315</td>
<td>1.0315</td>
</tr>
<tr>
<td>V17</td>
<td>1.0197</td>
<td>1.0400</td>
<td>1.0202</td>
<td>1.0202</td>
</tr>
<tr>
<td>V18</td>
<td>1.0123</td>
<td>1.0286</td>
<td>1.0128</td>
<td>1.0218</td>
</tr>
<tr>
<td>V19</td>
<td>1.0075</td>
<td>1.0260</td>
<td>1.0080</td>
<td>1.0080</td>
</tr>
<tr>
<td>V20</td>
<td>1.0105</td>
<td>1.0301</td>
<td>1.0110</td>
<td>1.0110</td>
</tr>
<tr>
<td>V21</td>
<td>1.0094</td>
<td>1.0330</td>
<td>1.0102</td>
<td>1.0102</td>
</tr>
<tr>
<td>V22</td>
<td>1.0137</td>
<td>1.0336</td>
<td>1.0147</td>
<td>1.0147</td>
</tr>
<tr>
<td>V23</td>
<td>1.0099</td>
<td>1.0278</td>
<td>1.0105</td>
<td>1.0106</td>
</tr>
<tr>
<td>V24</td>
<td>1.0018</td>
<td>1.0223</td>
<td>1.0033</td>
<td>1.0033</td>
</tr>
<tr>
<td>V25</td>
<td>1.0091</td>
<td>1.0193</td>
<td>1.0125</td>
<td>1.0175</td>
</tr>
<tr>
<td>V26</td>
<td>0.9912</td>
<td>1.0017</td>
<td>1.0018</td>
<td>1.0019</td>
</tr>
<tr>
<td>V27</td>
<td>1.0223</td>
<td>1.0261</td>
<td>1.0240</td>
<td>1.0240</td>
</tr>
<tr>
<td>V28</td>
<td>1.0088</td>
<td>1.0108</td>
<td>1.0091</td>
<td>1.0091</td>
</tr>
</tbody>
</table>
Table 6.12 (Continued)

<table>
<thead>
<tr>
<th>Method/ bus voltage</th>
<th>FACTS</th>
<th>UPFC</th>
<th>Case A IPFC</th>
<th>Case B IPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>V29</td>
<td>1.0067</td>
<td>1.0063</td>
<td>1.0076</td>
<td>1.0076</td>
</tr>
<tr>
<td>V30</td>
<td>1.0000</td>
<td>0.9948</td>
<td>1.0005</td>
<td>1.0030</td>
</tr>
</tbody>
</table>

Table 6.13  Overall Best Convergence Results of MO-OPD problem for IEEE 30Bus system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TCSC, SVC and TCPAR</th>
<th>UPFC</th>
<th>Case A IPFC</th>
<th>Case B IPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>RBFA</td>
<td>RBFA</td>
<td>RBFA</td>
<td>RBFA</td>
</tr>
<tr>
<td>Total generation cost ($/hr)</td>
<td>801.842</td>
<td>801.842</td>
<td><strong>801.802</strong></td>
<td>801.844</td>
</tr>
<tr>
<td>Total line losses (MW)</td>
<td>8.267</td>
<td>4.9631</td>
<td>8.639</td>
<td>2.948</td>
</tr>
<tr>
<td>Simulation time (sec)</td>
<td>19.95</td>
<td>25</td>
<td>25</td>
<td>24.23</td>
</tr>
<tr>
<td>No. of Iterations</td>
<td>23</td>
<td>23</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Emission(ton/h)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Voltage deviation</td>
<td>0.1739</td>
<td>0.189</td>
<td>0.0010</td>
<td><strong>0.0009</strong></td>
</tr>
</tbody>
</table>

The voltage profile result shows that the voltage magnitude is within acceptable limits. However, the critical conditions and load varying conditions, the voltage profile in IPFC both cases are better than for other FACTS devices and the DG system. The installation of IPFC’s increase the voltage performance improvement (the best voltage profile at critical buses are, bus 26, 1.0019 p.u and at bus 30, 1.0030 p.u) in each bus and the total network against various operating conditions. From the overall voltage profile results, it is evident that the IPFC case shows voltage deviation level that is well connected and very strong. The maximum voltage deviation is
controlled, thereby, the voltage profile optimization is better. From the overall results, the minimum cost and minimum power loss of 801.802 ($/h), and 2.948 MW respectively is obtained by placing the IPFC devices using RBFA method.

6.7 DISCUSSION

From the Table 6.14, it is observed that the voltage profile improvement in the load bus is more than 10% during loading condition by IPFC device and it is compared with UPFC and other FACTS devices performance. In the voltage profile improvement is about more than 10% in IPFC device.

From the Table 6.15, it is observed that for IEEE 30 bus system, the line losses reduce by 82.93% (2.948 MW) with the optimal placement of IPFC in four sectors 1-2, 1-3, 27-30 and 29-30 by using RBFA algorithms and 50% of loss reduction in UPFC devices by using RBFA algorithm. In both the cases, the RBFA algorithms find better optimum solutions in MO-OPD problems. However, the RBFA with IPFC case, the loss reduction is obtained in 25 iterations and simulation time is 24 seconds, which is lesser than RBFA with UPFC devices.

The Figures 6.6 and 6.7 clearly indicates the loss reduction level in IPFC using the RBFA algorithms. The quality of solution is based on better voltage magnitude irrespective of operating conditions. The Figure 6.7 clearly indicates the IPFC capacity against increase of load. The loadability of the system is increased by the placement of IPFC. The generation cost reaches optimal level when considering the FACTS devices with RBFA algorithm. Nevertheless, in the IPFC device installation finds the simultaneous operation and better results against objectives. The generation cost in Case A of the IPFC scheme is 801.802 $/hr and for case B it is 801.8442$/h. The case B
produce better results with loss reduction along voltage profile improvement. However, the generation cost produces little difference with case A.

From the Table 6.16, it is observed that for IEEE 30 bus systems, the voltage profile is enhanced by 16% (in critical buses 26 and 30) with IPFC using RBFA than the other algorithms during critical conditions and all the bus voltages are within permissible limits. It is obvious that the obtained results using proposed RBFA algorithm with IPFC devices are better than that other FACTS devices and DG units. The Table 6.16 shows the voltage profile results of IEEE 30 bus system, the best results are reported, and it is based on RBFA. The best power flow results with IPFC using RBFA the Q injection are reported (23,300 MVAR) in the Appendix Table A.7.1, and sensitive index with control variables is shown in the Appendix Figure A.7.1

<table>
<thead>
<tr>
<th>Cases</th>
<th>$V_{MIN}$ Before Insertion</th>
<th>$V_{MIN}$ After Insertion</th>
<th>$V_{MAX}$ Before Insertion</th>
<th>$V_{MAX}$ After Insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC, TCSC</td>
<td>0.8953</td>
<td>0.9959</td>
<td>1.0056</td>
<td>1.0589</td>
</tr>
<tr>
<td>TCPAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UPFC</td>
<td>0.8915</td>
<td>0.9236</td>
<td>1.0004</td>
<td>1.0083</td>
</tr>
<tr>
<td>IPFC</td>
<td>0.9561</td>
<td>0.9738</td>
<td>1.0095</td>
<td>1.0586</td>
</tr>
</tbody>
</table>
Table 6.15  Summary of the Results of Best convergence of IEEE 30 Bus system

<table>
<thead>
<tr>
<th>Device / parameter</th>
<th>FACTS (SVC, TCSC and TCPAR)</th>
<th>UPFC</th>
<th>Case-A IPFC</th>
<th>Case-B IPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total generation cost ($/hr)</td>
<td>801.8426</td>
<td>801.842</td>
<td>801.802</td>
<td>801.8442</td>
</tr>
<tr>
<td>Total line losses (MW)</td>
<td>8.267</td>
<td>4.9631</td>
<td>8.639</td>
<td>2.948</td>
</tr>
<tr>
<td>Simulation time (sec)</td>
<td>19.95</td>
<td>25</td>
<td>25</td>
<td>24</td>
</tr>
<tr>
<td>No. of Iterations</td>
<td>23</td>
<td>27</td>
<td>24</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 6.16  Summary of the Results of Best voltage profile for IEEE 30 Bus system

<table>
<thead>
<tr>
<th>Device / Critical Bus no.</th>
<th>FACTS p.u</th>
<th>UPFC p.u</th>
<th>Case A IPFC p.u</th>
<th>Case B IPFC p.u</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>0.9912</td>
<td>1.0017</td>
<td>1.0018</td>
<td>1.0019</td>
</tr>
<tr>
<td>30</td>
<td>1.0000</td>
<td>0.9948</td>
<td>1.0005</td>
<td>1.0030</td>
</tr>
</tbody>
</table>

The Table 6.17 detailed the system losses and its loss reduction in IEEE 57 bus systems. The IPFC with RBFA algorithm produces minimum loss during the solution of MO-OPD problem. Therefore, the proposed RBFA algorithm is suitable for larger networks. From the overall results, the minimum cost and minimum power loss (11.2601 MW with IPFC using RBFA algorithm) is obtained by placing the IPFC devices, the end results show that the multiobjective problems are simultaneously optimized.
From the Table 6.18, it is seen that the transmission losses of New England IEEE 39 system, the IPFC with RBFA algorithm produce better results. During the pre-optimization and post-optimization stage, the critical operating conditions are identified under the loading conditions, the minimum loss is 41.10 MW with IPFC using RBFA algorithm.

Table 6.17  Summary of the Results of Best transmission loss for IEEE 57 Bus system

<table>
<thead>
<tr>
<th>Algorithm/Device</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPFC</td>
<td>13.2</td>
<td>12.29</td>
<td>11.98</td>
<td>11.201</td>
</tr>
<tr>
<td>UPFC</td>
<td>27.46</td>
<td>25.2456</td>
<td>24.2125</td>
<td>18.016</td>
</tr>
<tr>
<td>FACTS (SVC, TCSC and TCPAR)</td>
<td>27.06</td>
<td>27.7856</td>
<td>27.2125</td>
<td>26.016</td>
</tr>
</tbody>
</table>

Table 6.18  Summary of the Results of Best transmission loss for IEEE 39 Bus system

<table>
<thead>
<tr>
<th>Algorithm/Device</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPFC</td>
<td>42.51</td>
<td>43.72</td>
<td>41.15</td>
<td>41.10</td>
</tr>
<tr>
<td>UPFC</td>
<td>53.12</td>
<td>51.10</td>
<td>50.69</td>
<td>48.19</td>
</tr>
<tr>
<td>FACTS (SVC, TCSC, TCPAR)</td>
<td>43.71</td>
<td>41.845</td>
<td>41.823</td>
<td>41.821</td>
</tr>
</tbody>
</table>

From Table 6.19, it is evidence that the results of IEEE 9 bus system, the voltage stability and voltage profile optimization can be improved in critical lines (bus 5, 1.0840 p.u, bus 6, 1.0129 p.u) and it is because of real and reactive power management by IPFC scheme with the proposed RBFA algorithm.
In the Table 6.20, the results of IEEE 6 bus system are presented. The proposed RBFA algorithm with IPFC device shows better solution with considerable computational time and finding the minimal transmission losses of 6.32 MW.

Table 6.19  Summary of the Results of Best Voltage profile for IEEE 9 Bus system

<table>
<thead>
<tr>
<th>Device / Critical line number</th>
<th>FACTS device</th>
<th>UPFC device</th>
<th>IPFC device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Bus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>magnitude (p.u)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.9772</td>
<td>1.0000</td>
<td>1.0840</td>
</tr>
<tr>
<td>6</td>
<td>1.0821</td>
<td>1.0126</td>
<td>1.0129</td>
</tr>
<tr>
<td>angle (degree)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-2.721</td>
<td>-0.1978</td>
<td>-3.982</td>
</tr>
<tr>
<td>6</td>
<td>0.923</td>
<td>-0.0485</td>
<td>0.603</td>
</tr>
</tbody>
</table>

Table 6.20  Summary of the Results of Best Transmission loss for IEEE 6 Bus system

<table>
<thead>
<tr>
<th>Algorithm/Device</th>
<th>ACO</th>
<th>BFA</th>
<th>MBFA</th>
<th>RBFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission losses in MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPFC</td>
<td>9.101</td>
<td>8.83</td>
<td>6.820</td>
<td>6.32</td>
</tr>
<tr>
<td>UPFC</td>
<td>8.921</td>
<td>8.925</td>
<td>8.825</td>
<td>8.712</td>
</tr>
<tr>
<td>FACTS (SVC, TCSC, TCPAR)</td>
<td>8.92</td>
<td>8.91</td>
<td>8.82</td>
<td><strong>8.716</strong></td>
</tr>
</tbody>
</table>

From the overall results, it is interesting to note that the RBFA is useful for Power system problems when it is needed to apply a multi-objective solution and it is very accurate in simultaneous optimization connected with the global optimal solution and handling of control variables.
During the analysis, the foraging behavior of bacteria is better in the way of handling multiple objectives and control variables at any desired operating conditions. It is proved by active and reactive power control with help of Multiline FACTS devices.

68 SUMMARY

In the present chapter, the optimal analysis of IPFC scheme is compared with the various FACTS devices and with DG units. Comparison of simulink analysis with IPFC scheme is performed. The results of both the validity analysis and the performance of IPFC scheme are better against the critical operating and load varying conditions. The objectives and control of MO-OPD problem, the voltage profile improvement, the real power control and loss reduction, and reactive power control and level of compensation are well under control and suitable for power system operating conditions. Economic operations and effective levels of stable operating conditions are thereby enhanced.