OPTIMAL REACTIVE POWER PLANNING USING IMPROVED DIFFERENTIAL EVOLUTION INCORPORATING FACTS

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Abstract
This paper presents the relevance of Improved Differential Evolution (IDE) algorithm to solve the Reactive Power Planning (RPP) problem. Minimization of total cost of energy loss and cost of VAR source installments are taken as the objectives incorporating (RPP) problem. This paper compares the success of Evolutionary Programming (EP), Differential Evolution (DE), Improved Adaptive Genetic Algorithm and New Improved Differential Evolution (NIDE) to solve Reactive Power Planning (RPP) problem incorporating FACTS Controllers like Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Unified power flow controller (UPFC) considering voltage stability. With help of Fast Voltage Stability Index (FVSI), the critical lines and buses are identified to install the FACTS controllers. The optimal settings of the control variables of the generator voltages, transformer tap settings and provision and parameter settings of the SVC, TCSC, UPFC are considered for reactive power planning. The test and justification of the proposed algorithm are conducted on IEEE 30-bus system and 72-bus Indian system. The Simulation results of the proposed optimization approach is better than Evolutionary Programming and Differential Evolution (DE), Self Adaptive Differential Evolution, shows that the UPFC gives enhanced results than SVC and TCSC and the FACTS controllers diminish the system losses.

Keywords: FACTS Controllers, Differential Evolution, Improved Differential Evolution, Multi-objective optimization, RPP

INTRODUCTION
One of the most stimulating issues in power system research, Reactive Power Planning (RPP), Reactive power planning could be formulated with different objective functions [6] such as cost based objectives considering system operating conditions. Reactive power planning problem required the simultaneous minimization of two objective functions. The first objective deals with the minimization of real power losses in reducing operating costs and improve the voltage profile. The second objective minimizes the allocation cost of additional reactive power sources.
converters, well known Flexible AC Transmission Systems (FACTS), introduced by Hingorani,[11] are useful in taking fast control actions to ensure the security of power system. FACTS devices are capable of controlling the voltage angle and voltage magnitude[12] at selected buses and line impedances of transmission lines. In this paper, the maximum loadability is calculated using Fast Voltage Stability Index (FVSI). The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At this point, the connected load at the particular bus is considered as the maximum loadability. The smallest maximum loadability is ranked as the highest. This paper proposes the application of FACTS controllers to the RPP problem. The optimal location of FACTS controllers is identified by FVSI and an New Improved Differential Evolution (NIDE) is used to find the optimal settings of the FACTS controllers. The proposed approach has been used for the Indian 72 bus system which consists of 15 generator bus, 57 load buses.

**NOMENCLATURE**

List of Symbols

- $N_i$ = set of numbers of load duration levels
- $N_C$ = Set of numbers of possible VAr source installment bus
- $N_k$ = set of branch numbers
- $N_i$ = set of numbers of buses adjacent to bus $i$ including bus $i$ number of PQ buses
- $N_g$ = set of generator bus numbers
- $N_t$ = set of numbers of tap setting transformer branches
- $N_b$ = set of numbers of total buses
- $h$ = per unit energy cost
- $d_i$ = duration of load level $i$
- $g_k$ = conductance of branch $k$
- $V_i$ = voltage magnitude at bus $i$
- $\theta_{ij}$ = voltage angle difference between bus $i$ and bus $j$
- $e_i$ = fixed VAr source installment cost at bus $i$
- $C_{G_i}$ = per unit VAr source purchase cost at bus $i$
- $Q_{G_i}$ = VAr source installed at bus $i$
- $Q_i$ = reactive power injected into network at bus $i$
- $G_{ij} = $ mutual conductance between bus $i$ and $j$
- $B_{ij} = $ mutual susceptance between bus $i$ and $j$
- $G_{ii}, B_{ii} =$ self conductance and susceptance of bus $i$
- $Q_{gl} = $ reactive power generation at bus $i$
- $T_k =$ Tap of branch $k$
- $N_{lim} =$ set of numbers of branches in which voltage over limits
- $N_{Qlim} =$ set of numbers of branches in which reactive power over limits

**PROBLEM FORMULATION**

It is aimed in this objective function in Reactive Power planning, three objectives are considered in optimization model. The first objective is that minimizing of the real power loss ($P_{loss}$) in transmission lines of a power system. This is mathematically stated as follows.

$$W_C = h \sum d_i p_{loss,i}$$  \hspace{1cm} (1)

Where, ($P_{loss}$) denotes the network real power A loss during the period of load level $i$. It can be expressed in the following equation in the[6] duration $d_i$:

$$P_{loss} = \sum g_k (V_i^2 + V_i^2 - 2V_i V_i \cos \theta_{ij})$$ \hspace{1cm} (2)

The second term represents the cost of VAR source installments which has two components, namely, fixed installment cost and purchase cost:

$$I_{C_i} = e_i + C_{G_i} |Q_{gl}|$$ \hspace{1cm} (3)

Here $Q_{gl}$ can be either positive or negative depending on whether the installation is capacitive or reactive. Therefore absolute values are used to compute the cost.

The third term represents the cost of FACTS Controllers. Using Simens AG Data base, cost[14] function for SVC and TCSC are developed as follows.

$$C_{TCSC} = 0.0015 \delta^2 - 0.1735 \delta + 153.75$$
$$C_{SVC} = 0.0003 \delta^2 - 0.3051 \delta + 127.38$$
$$C_{UPFC} = 0.0003 \delta^2 - 0.2691 \delta + 188.22$$ \hspace{1cm} (4)

The objective function is expressed as

$$M_{in} F_C = W_C + C_{facts}$$ \hspace{1cm} (5)

The functions should satisfy the real and reactive power constraints (equality constraints)

(i) Load Flow Constraints:

$$0 = P_i - V_i \sum_{j} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$ \hspace{1cm} (6)

(ii) Generator Reactive Power Capability Limit

$$0 = Q_i - V_i \sum_{j} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$ \hspace{1cm} (7)

And also satisfy the inequality constraints like reactive power generation, bus voltage and FACTS controller installation as follows

(ii) Generator Reactive Power Capability Limit

$$Q_{gl}^{min} \leq Q_{gl} \leq Q_{gl}^{max}$$ \hspace{1cm} (8)

(iii) Voltage Constraints:

$$V_l^{min} \leq V_i \leq V_l^{max}$$ \hspace{1cm} (9)

(iv) FACTS Reactive Power Limit:
-100 \leq Q_{\text{facts}} \leq 100 \tag{10}

(v) FACTS Reactance Limit:

\begin{align*}
-0.8X_\text{Line} & \leq X_{\text{facts}} \tag{11}
\end{align*}

\(Q_{\text{facts}}\) can be fewer than zero and if \(Q_{\text{facts}}\) is chosen as a negative value, say in the light load period, variable inductive reactive power should be injected at bus \(i\) by the FACTS controllers. \(Q_{\text{facts}}\) act as a control variable. The load bus voltages \(V_{\text{load}}\) and reactive power generations \(Q_i\) are state variables, which are limited by adding them as the quadratic penalty terms to the objective function. Equation (5) is therefore changed to the following generalized objective function

\[
\begin{align*}
\text{Min} \quad & F_C = F_C + \sum_{i \in N_{\text{Qlim}}} (V_i - V_{\text{lim}})^2 + \sum_{i \in N_{\text{Vlim}}} (Q_{\text{glim}} - Q_{\text{glim}})^2 \\
\text{Subjected to} \quad & 0 = P_i - V_i \sum_{j \in N_{B-L}} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \\
& 0 = Q_i - V_i \sum_{j \in N_{PQ}} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})
\end{align*}
\]  

\[
\text{Min} \quad & F_C = F_C + \sum_{i \in N_{\text{Qlim}}} (V_i - V_{\text{lim}})^2 + \sum_{i \in N_{\text{Vlim}}} (Q_{\text{glim}} - Q_{\text{glim}})^2 \tag{12}
\]

Subjected to

\[
0 = P_i - V_i \sum_{j \in N_{B-L}} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})
\]

\[
0 = Q_i - V_i \sum_{j \in N_{PQ}} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})
\]

Where, \(\alpha\) and \(\beta\) are the penalty factors which can be increased in the optimization procedure; \(V_{\text{lim}}\) and \(Q_{\text{glim}}\) are defined in the following equations:

\[
V_{\text{lim}}^i = \begin{cases} 
  V_{\text{min}}^i & \text{if } V_i < V_{\text{min}}^i \\
  V_{\text{max}}^i & \text{if } V_i > V_{\text{max}}^i 
\end{cases}
\]

\[
Q_{\text{glim}}^i = \begin{cases} 
  Q_{\text{min}}^i & \text{if } Q_{\text{glim}}^i < Q_{\text{min}}^i \\
  Q_{\text{max}}^i & \text{if } Q_{\text{glim}}^i > Q_{\text{max}}^i 
\end{cases}
\]  

\[
V_{\text{lim}}^i = \begin{cases} 
  V_{\text{min}}^i & \text{if } V_i < V_{\text{min}}^i \\
  V_{\text{max}}^i & \text{if } V_i > V_{\text{max}}^i 
\end{cases}
\]  

\[
Q_{\text{glim}}^i = \begin{cases} 
  Q_{\text{min}}^i & \text{if } Q_{\text{glim}}^i < Q_{\text{min}}^i \\
  Q_{\text{max}}^i & \text{if } Q_{\text{glim}}^i > Q_{\text{max}}^i 
\end{cases}
\]  

MODELLING OF FACTS CONTROLLERS

SVC, TCSC and UPFC mathematical models are implemented by MATLAB programming. Steady state model of FACTS controllers in this paper are used for power flow studies [15,22]

TCSC

TCSC, the first generation of FACTS, can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line. A TCSC [11] is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. In this paper, TCSC is modeled by changing the transmission line reactance as below

\[
X_{ij} = X_{\text{ac}} + X_{\text{TCSC}} \tag{14}
\]

Where, \(X_{\text{line}}\) is the reactance of transmission line and \(X_{\text{TCSC}}\) is the reactance of TCSC. Rating of TCSC depends on transmission line where it is located. To prevent overcompensation, TCSC reactance is chosen between -0.8\(X_{\text{line}}\) to 0.2\(X_{\text{line}}\).

SVC

SVC can be used for both inductive and capacitive compensation. In this paper SVC is modeled as an ideal reactive power injection controller at bus \(i\)

\[
\Delta Q_i = Q_{\text{SVC}} \tag{15}
\]

UPFC

The decoupled model of UPFC is used to provide independent [10],[13] shunt and series reactive compensation. It is a combination of Static Synchronous compensator and Static Synchronous series compensator interconnected through a D.C. link. It has two control parameters a voltage source inserted in series with the line and the current source connected in shunt with the line. It is able to absorb or generate real and reactive power output depending on the rating of UPFC.

FVSI FORMULATION

The Fast Voltage Stability Index is resulting from the voltage quadratic equation at the receiving bus on a two-bus system [12,14,15,17]. The general 2-bus representation is illustrated in Figure 1.

\[
V_1 \quad B \quad P_1 \quad Bu \quad P_2 \quad V_2
\]

From the figure, the voltage quadratic equation at the receiving bus is written as

\[
V_2^2 - \frac{R}{X} \sin \delta + \cos \delta \left[ V_1 V_2 + (X + \frac{R^2}{X}) Q_2 \right] = 0 \tag{16}
\]

set the equation of discriminator be larger than or equal to zero yields

\[
\left( \frac{R}{X} \sin \delta + \cos \delta \right) V_1^2 - 4 (X + \frac{R^2}{X}) Q_2 \geq 0 \tag{17}
\]

Rearranging (2), we obtain

\[
\Delta \theta = Q_{\text{act}} \tag{6}
\]

Figure 1.Model of Two bus system
\[ \frac{4^2 Q X}{v^2(R \sin \theta + X \cos \theta)} < 1 \quad (18) \]

since "i" as the sending bus and "j" as the receiving end bus. Since \( \delta \) is normally very small, then, \( \delta = 0 \) \( R \sin \theta + X \cos \theta \approx 0 \) and \( X \) receiving bus, Fast Voltage Stability Index (FVSI) can be calculated

\[ \text{FVSI}_i = \frac{4^2 Q X}{v^2 X} \quad (19) \]

Where \( Z \), \( X \) are the Impedance and reactance of the line. Where as \( Q \), \( V \) are the Reactive power at the receiving end and the sending end voltage.

**PROCEDURE FOR DETERMINING THE MAXIMUM LOADABILITY FOR WEAK BUS IDENTIFICATION USING FVSI**

1. Using Newton Raphson method, Run the load flow program for the base case
2. Estimate Fast voltage stability Index value for all line in the system
3. Progressively increase the \( Q_i \) at chosen load bus until the load flow fails to give the results. Calculate Fast Voltage Stability Index Values for every load variation
4. Take out the line index that has the highest value be the most critical line with respect to a bus
5. Select another load bus repeat steps up to 4.
6. Obtain the voltage at the maximum computable FVSI prior to the divergence of the Load flow. It can be obtained from step 3. This determines the critical Voltage of a Particular bus
7. Take out the maximum \( Q_i \) loading for the maximum calculable FVSI for all test bus. It can be obtained from step 5. The greatest VAr loading is referred to as the most loadability of a Particular bus.
8. Sort the greatest loadability obtained from step 7 in ascending order and the least loadability Maximum is ranked the utmost imply the Weakest bus in the system
9. Select the feeble buses as the reactive power installation site for the Reactive Power Planning

**PROPOSED DIFFERENTIAL EVOLUTION (DE)**

Differential Evolution is first proposed over 1994-1996 by Storn and Price at Berkeley. Differential evolution (DE) is a population based stochastic search algorithm search algorithm that operate on the populations of the possible solution vectors \{ \( X_i^k \): \( i=1,2,3,\ldots, N_p \) \} at each generation \( G \) [8,10,11]. Each individual element of the solution vector is composed of \( D \)-parameters, namely \( X_i^k := x_{ij}^k : j=1,2,\ldots D \). Various steps in DE are mutation, crossover and selection. The outline of the DE algorithm is as follows:

1. Initialize the population:

2. Evaluate the population using an objective function.
3. Generate a new population where each new vector is created according to:

\[ v_i^G = x_i^G + P(x_m^G - x_n^G), i=1,2,\ldots,N_p \quad (20) \]

Where \( x_i^{g_{\text{BEST}}} \) represents the best solution and \{ \( x_m^G, x_n^G \) \} are two arbitrary vectors at generation \( G \) such that \{ \( x_m^G, x_n^G \) \} are mutually different. The constant \( P \) is a mutation factor. In this paper Differential Evolution Random Scale Factor is used. In Which the scaled parameter \( F \) is varied in random manner in the range of

(b) Crossover the trial vector and the current vector with crossover probability \( CR \) to deliver a baby vector \( u_i^G \) i.e.,

\[ u_i^G = \begin{cases} v_{ij}^G & \text{for} \frac{R_i}{f} < CR \\ x_{ij}^G & \text{otherwise} \end{cases} \quad (21) \]

(c) Evaluate the baby vector.
(d) Use the baby in the new generation if it is at least as good as the current vector; otherwise, the old vector is retained.

\[ x_i^{G+1} = \begin{cases} u_i^G & \text{for} (u_i^G) < f(x_i^G) \\ x_i^G & \text{otherwise} \end{cases} \quad (22) \]

4. Repeat step 3 until the termination condition is satisfied.

**5.4. PROBLEM REPRESENTATION:**

Generator bus voltages \( \left( V_g \right) \), transformer tap positions \( \left( t_k \right) \) and reactive power generation of
VAR sources \( (Q_c) \) are the optimization variables for the VSC-RPP problem. The generator bus voltages are represented as floating point numbers, whereas the transformer tap position and the reactive power generation of FACT Devices are represented as integers[21]. The transformer tap setting with tapping ranges of ±10% and a tapping step of 0.025 p.u is represented from the alphabet (0,1,….,8) and the VAR sources with limits of 1 and 5 p.u and step size of 1 p.u is represented from the alphabet (0,1,….,5).

With this representation, a typical chromosome of the RPP problem will look like the following:

\[
0.981 \quad 0.97 \quad … \quad 1.05 \quad 4 \quad 3 \quad … \quad 1 \quad -2 \quad +1 \quad … \quad +3
\]

V\(_1\), V\(_2\), Q\(_{FACTS1}\), Q\(_{FACTS2}\), Q\(_{FACTS3}\), t\(_1\), t\(_2\), t\(_3\), t\(_4\), t\(_5\)

**EVALUATION FUNCTION FOR MULTI-OBJECTIVE OPTIMAL REACTIVE POWER PLANNING PROBLEM**

In the optimal VAr planning problem, the objective is to minimize the total real power loss while satisfying the constraints. For each individual, the equality constraints are satisfied by running Newton-Raphson algorithm and the constraints on the state variables are taken into consideration by adding penalty function to the objective function. With the inclusion of the penalty factors, the new objective function using

\[
\text{Min } F_c = F_c + \sum_{i \in N} (V_i - V_{i,\text{lim}}^\text{min})^2 + \beta \sum_{i \in N} (Q_{gi} - Q_{gi,\text{lim}}^\text{min})^2 \tag{23}
\]

Where, \( \alpha \) and \( \beta \) are the penalty factors which can be increased in the optimization procedure; \( V_{i,\text{lim}}^\text{min} \) and \( Q_{gi,\text{lim}}^\text{min} \) are defined in the following equations:

\[
V_i^\text{lim} = \begin{cases} 
\alpha V_i^\text{min} & \text{if } V_i < V_i^\text{min} \\
\alpha V_i^\text{max} & \text{if } V_i > V_i^\text{max}
\end{cases}
\]

\[
Q_{gi}^\text{lim} = \begin{cases} 
\beta Q_{gi}^\text{min} & \text{if } Q_{gi} < Q_{gi}^\text{min} \\
\beta Q_{gi}^\text{max} & \text{if } Q_{gi} > Q_{gi}^\text{max}
\end{cases}
\tag{24}
\]

Where \( \alpha, \beta \) are the penalty factor.

**CASE STUDY**

A simplified Indian 400- kV transmission network with 72 buses (55 PV buses and 15 PQ buses) and is used for testing. One line diagram is shown in figure 2. FACTS locations are identified based on the FVSI technique. The greatest loadability and FVSI values for the real time system are given in Table I.
TABLE I: Bus Ranking and FVSI Values

<table>
<thead>
<tr>
<th>Rank</th>
<th>Bus</th>
<th>Qmax(p.u)</th>
<th>FVSI</th>
<th>Over loaded Branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>0.21</td>
<td>0.9837</td>
<td>38-53</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>0.27</td>
<td>0.9841</td>
<td>49 - 38</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>0.28</td>
<td>0.9964</td>
<td>51 - 53</td>
</tr>
<tr>
<td>4</td>
<td>53</td>
<td>0.35</td>
<td>0.9925</td>
<td>53-67</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>0.43</td>
<td>0.9843</td>
<td>35 - 36</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>0.45</td>
<td>0.9932</td>
<td>16-58</td>
</tr>
<tr>
<td>7</td>
<td>46</td>
<td>0.47</td>
<td>0.9972</td>
<td>46-18</td>
</tr>
<tr>
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</tr>
<tr>
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<td>28</td>
<td>0.56</td>
<td>0.9863</td>
<td>28-50</td>
</tr>
<tr>
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<td>27</td>
<td>0.57</td>
<td>0.9897</td>
<td>27-23</td>
</tr>
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<td>0.65</td>
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<td>17-66</td>
</tr>
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<tr>
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</tr>
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<td>0.98</td>
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<td>0.908</td>
<td>0.9999</td>
<td>24-57</td>
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<td>30</td>
<td>0.99</td>
<td>0.9931</td>
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<td>0.9976</td>
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<tr>
<td>36</td>
<td>40</td>
<td>1.13</td>
<td>0.998</td>
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<td>41</td>
<td>62</td>
<td>1.34</td>
<td>0.9795</td>
<td>62-69</td>
</tr>
<tr>
<td>42</td>
<td>69</td>
<td>1.354</td>
<td>0.9889</td>
<td>69 - 7</td>
</tr>
<tr>
<td>43</td>
<td>61</td>
<td>1.378</td>
<td>0.9567</td>
<td>61 - 32</td>
</tr>
<tr>
<td>44</td>
<td>20</td>
<td>1.39</td>
<td>0.9854</td>
<td>20-47</td>
</tr>
<tr>
<td>45</td>
<td>37</td>
<td>1.415</td>
<td>0.9912</td>
<td>37-41</td>
</tr>
<tr>
<td>46</td>
<td>31</td>
<td>1.42</td>
<td>0.9877</td>
<td>31 - 2</td>
</tr>
<tr>
<td>47</td>
<td>34</td>
<td>1.47</td>
<td>0.9945</td>
<td>34 - 9</td>
</tr>
<tr>
<td>48</td>
<td>21</td>
<td>1.54</td>
<td>0.9947</td>
<td>21-60</td>
</tr>
<tr>
<td>49</td>
<td>42</td>
<td>1.54</td>
<td>0.985</td>
<td>42-43</td>
</tr>
<tr>
<td>50</td>
<td>54</td>
<td>1.59</td>
<td>0.9857</td>
<td>54-30</td>
</tr>
<tr>
<td>51</td>
<td>48</td>
<td>1.61</td>
<td>0.9982</td>
<td>48-42</td>
</tr>
<tr>
<td>52</td>
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<td>1.75</td>
<td>0.9865</td>
<td>25-54</td>
</tr>
<tr>
<td>53</td>
<td>55</td>
<td>1.61</td>
<td>0.9789</td>
<td>55 - 8</td>
</tr>
<tr>
<td>54</td>
<td>57</td>
<td>1.88</td>
<td>0.9658</td>
<td>57-54</td>
</tr>
<tr>
<td>55</td>
<td>58</td>
<td>1.93</td>
<td>0.9687</td>
<td>58 - 5</td>
</tr>
<tr>
<td>56</td>
<td>56</td>
<td>1.98</td>
<td>0.9723</td>
<td>56-35</td>
</tr>
<tr>
<td>57</td>
<td>50</td>
<td>2.06</td>
<td>0.9834</td>
<td>50-39</td>
</tr>
</tbody>
</table>

From the Table, bus 38 has the smallest maximum loadability implying the critical bus and the branch 24 – 57 has the maximum FVSI value close to one indicates the critical line referred to bus 24. Hence, SVC is installed at bus 24, TCSC is installed in the branch 24 to 57.UPFC installed at midpoint of branch 24 - 57.

The parameters and variable limits are listed in Table II. All power and voltage quantities are per-unit values and the base power is used to compute the energy cost.Where h is per unit energy cost.

TABLE II:Parameters and Limits

<table>
<thead>
<tr>
<th>SB (MVA)</th>
<th>H ($/pWh)</th>
<th>e (€)</th>
<th>Caa (€/p.u.VAR)</th>
<th>dl</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6000</td>
<td>1000</td>
<td>3000000</td>
<td>8760</td>
<td>8760</td>
<td></td>
</tr>
</tbody>
</table>

Two cases have been studied. Case 1 is the light load. Case 2 is of heavy loads whose load is 125% as those of Case 1. The duration of the load level is 8760 hours in both the cases.

A. Initial Power Flow Results

The initial generator bus voltages and the loads are given as,

Case 1: Pload = 2.7821 and Qload = 1.1890
Case 2: Pload = 3.49865 and Qload = 1.4568

TABLE III: Optimal Generator Bus Voltages

<table>
<thead>
<tr>
<th>BUS</th>
<th>SVC</th>
<th>TCSC</th>
<th>UPFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0529</td>
<td>1.0771</td>
<td>1.0890</td>
</tr>
<tr>
<td>2</td>
<td>1.0696</td>
<td>1.0776</td>
<td>1.0899</td>
</tr>
<tr>
<td>3</td>
<td>1.0620</td>
<td>1.0824</td>
<td>1.0957</td>
</tr>
<tr>
<td>4</td>
<td>1.0694</td>
<td>1.0897</td>
<td>1.0997</td>
</tr>
<tr>
<td>5</td>
<td>1.0454</td>
<td>1.0796</td>
<td>1.0874</td>
</tr>
<tr>
<td>6</td>
<td>1.0773</td>
<td>1.0824</td>
<td>1.0954</td>
</tr>
<tr>
<td>7</td>
<td>1.0628</td>
<td>1.0723</td>
<td>1.0827</td>
</tr>
<tr>
<td>8</td>
<td>1.0536</td>
<td>1.0853</td>
<td>1.0939</td>
</tr>
<tr>
<td>9</td>
<td>1.0574</td>
<td>1.0861</td>
<td>1.0835</td>
</tr>
<tr>
<td>10</td>
<td>1.0556</td>
<td>1.0861</td>
<td>1.0700</td>
</tr>
<tr>
<td>11</td>
<td>1.0574</td>
<td>1.0638</td>
<td>1.0720</td>
</tr>
<tr>
<td>12</td>
<td>1.0450</td>
<td>1.0853</td>
<td>1.0945</td>
</tr>
<tr>
<td>13</td>
<td>1.0537</td>
<td>1.0835</td>
<td>1.0938</td>
</tr>
<tr>
<td>14</td>
<td>1.0535</td>
<td>1.0630</td>
<td>1.0832</td>
</tr>
<tr>
<td>15</td>
<td>1.0999</td>
<td>1.0999</td>
<td>1.0999</td>
</tr>
</tbody>
</table>

FACTS device settings, optimal generator bus voltages and optimal generation and power losses are obtained in as Table III to V
### TABLE IV: FACTS Device Settings

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FACTS Location</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>X&lt;sub&gt;TCSC&lt;/sub&gt;</td>
<td>24-57</td>
<td>-0.1672</td>
<td>-0.08006</td>
</tr>
<tr>
<td>Q&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Bus 44</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Q&lt;sub&gt;UPFC&lt;/sub&gt;</td>
<td>24-57</td>
<td>0.1974</td>
<td>0.29421</td>
</tr>
<tr>
<td>X&lt;sub&gt;TCSC&lt;/sub&gt;</td>
<td>24-57</td>
<td>-0.0432</td>
<td>-0.06732</td>
</tr>
</tbody>
</table>

### TABLE V: Optimal Generations and Power losses

<table>
<thead>
<tr>
<th>Method</th>
<th>P&lt;sub&gt;Loss&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;Loss&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolutionary Programming (EP)</td>
<td>14.8620</td>
<td>278103.26</td>
</tr>
<tr>
<td>Improved Adaptive Genetic Algorithm (IAGE)</td>
<td>15.76894</td>
<td>280274.61</td>
</tr>
<tr>
<td>Differential Evolution (DE)</td>
<td>16.6511</td>
<td>2950648.05</td>
</tr>
<tr>
<td>Improved Differential Evolution (IDE)</td>
<td>17.8201</td>
<td>3065206.40</td>
</tr>
</tbody>
</table>

The real power savings, annual cost savings and the total costs are calculated as,

\[
P_{\text{C Save}}\% = \frac{P_{\text{loss int}} - P_{\text{loss opt}}}{P_{\text{loss int}}} \times 100\% \quad (25)
\]

\[
W_{\text{C Save}} = \text{hd}_1 (P_{\text{loss int}} - P_{\text{loss opt}})
\]

The table VI gives the performance comparison. From the comparison FVSI Based New Improved Differential Evolution Reactive Power Planning approach gives more saving comparing EP, DE and IAGE approach.

### Fig. 4. Voltage profile improvement for case 1 using FACT Devices

From the above Figure 4 and Table VI, it is clearly seen that the Voltage profile using UPFC is far better in case of Improved Differential Evolution. Figure 4 & 5 gives the convergence and cost saving using UPFC for case 2.

### TABLE VI: Cost Comparison for Case-2 Study Incorporating UPFC controller

<table>
<thead>
<tr>
<th>Method</th>
<th>P&lt;sub&gt;C save&lt;/sub&gt;%</th>
<th>W&lt;sub&gt;C save&lt;/sub&gt; ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolutionary Programming (EP)</td>
<td>14.8620</td>
<td>278103.26</td>
</tr>
<tr>
<td>Improved Adaptive Genetic Algorithm (IAGE)</td>
<td>15.76894</td>
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</tr>
<tr>
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<td>17.8201</td>
<td>3065206.40</td>
</tr>
</tbody>
</table>

### CONCLUSION

In this Paper Improved Differential Evolution Algorithm with self tuned constraint has to useful to solve Reactive Power Planning in Indian 72 Bus system. FACTS controllers like SVC, TCSC and UPFC are situated in 72 Indian systems and their presentation are tabulated. New Improved Modified Differential Evolution and Fast Voltage Stability Index techniques played important role to locate the controllers and tune them to plan for reactive power. The individual maximum loadability obtained from the load buses are sorted in ascending order. The highest rank implies the critical bus in the system and the line with FVSI close to one indicates the most critical line corresponds to a bus. These are the possible locations for FACTS controllers to preserve stability of the system. Results show that the losses are reduced when using UPFC than using SVC and TCSC. By the Improved Modified Differential Evolution approach with Fast Voltage
Stability FVSI method, more savings on the energy and installment costs are achieved. Results shows that saving of annual cost is increased using UPFC than SVC and TCSC devices.

REFERENCES


